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Literature Review and Industry Survey of Recycled Fibers from Novel and Existing Source Materials for Concrete Use

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Literature Review and Industry Survey of Recycled Fibers from Novel and Existing Source Materials for Concrete Use

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Partnered Pavement Research Center (PPRC) Project Numbers 4.86 (DRISI Tasks 2709 and 3194):
Toward Implementation of Recycled Fibers from Novel and Existing Source Materials in Concrete Pavements

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16. ABSTRACT
Research has demonstrated the multiple benefits of fibers for the early and late-age performance of concrete pavements and bridge decks. Many research studies have also shown that the expected enhancements in properties of concrete with recycled fibers could be commensurate with those of concrete reinforced with virgin fibers. However, compared with virgin polymeric fibers and steel fibers from primary steel, recycled fibers and fibers from natural sources are not as commonly implemented in construction due to several barriers. Some of these obstacles include a lack of research on recycled fibers, leading to gaps in technical performance data, case studies, test tracks, and pilot projects. The primary reason for the lack of research is related to gaps in information regarding the quality of recycled fibers compared to virgin fibers. To help overcome some of these barriers, this study included a comprehensive survey of concrete fiber suppliers. Those suppliers with recycled fiber and natural fiber manufacturing lines were identified and interviewed. The categories of fibers included in this report are recycled polymeric fibers, natural fibers mainly from cellulose, recycled steel fibers, carbon and glass fiber-reinforced polymer composites (for example, from end-of-life windmill blades), recycled carbon fibers, and glass and basalt fibers. The information gathered from the manufacturers is summarized in this report and includes the feedstock material, recycling process, geometric properties of fibers, recommended load for concrete flatwork applications, performance data (if available), cost, and environmental product declaration, if available. In addition to manufacturers' surveys, a synthesis of performance in concrete is provided based on published technical literature for each fiber type. The topics included in the literature review are fiber dispersion and the impacts of fibers on the workability of concrete, plastic and drying shrinkage, strength and post-cracking performance, and durability of concrete. Based on this comprehensive review, many fibers from recycled and natural sources were identified for each source material. These fibers are already available on a large scale in the market, and several have been successfully implemented in concrete applications. In the case of steel and carbon fibers, recycled fibers are available at a fraction of the cost of virgin fibers, making this product more feasible in construction. Cellulosic fibers appear to have great potential to reduce plastic shrinkage cracking in concrete. Glass and basalt fibers are from natural silica sources and offer many structural advantages to the performance of concrete. These fibers are recommended for laboratory testing in the next phase of the project.

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PROJECT OBJECTIVES

This project aims to develop guidance for Caltrans to incorporate fiber-reinforced concrete (FRC), using virgin fibers, and recycled fiber-reinforced concrete (rFRC), using recycled fibers, technologies into structural concrete design and construction, which will include identifying recycled fiber technologies with a viable supply chain to support the concrete industry in California. The project will have a technical advisory group led by the Caltrans Office of Concrete Pavements (OCP) with information sharing with the Materials Engineering and Testing Services (METS) and Construction divisions of Caltrans. The objectives of this study will be achieved through the following tasks:

Phase I

- Task 1: Practice and literature review

Go/No-Go point

Phase II

- Task 2: Source material sampling, characterization, and fiber production
- Task 3: Laboratory testing to optimize recycled fiber size and loads
- Task 4: Durability evaluation of selected rFRC
- Task 5: Phase II report

Go/No-Go point

Phase III

- Task 6: Small-scale field testing (to be done after laboratory testing and simultaneously with full-scale testing)
- Task 7: Full-scale field testing (falling weight deflectometer and heavy vehicle simulator loading)
- Task 8: Mechanistic-empirical pavement design for FRC
- Task 9: A pavement design tool
- Task 10: Project summary report

This report is the result of Task 1, the practice and literature review.

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ASTM D7508	Standard Specification for Polyolefin Chopped Strands for Use in Concrete
ASTM D7611	Standard Practice for Coding Plastic Manufactured Articles for Resin Identification
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LIST OF ABBREVIATIONS

AR	Alkali resistant
ASR	Alkali-silica reactivity
BG	Basalt glass
CFRP	Carbon fiber-reinforced polymer
CMOD	Crack mouth opening displacement
CNT	Carbon nanotubes
CTOD	Crack tip opening displacement
EOL	End of life
EPD	Environmental product declaration
FC	Fiber count
FRC	Fiber-reinforced concrete
FRP	Fiber-reinforced polymer
FSS	Fiber-specific surface area
GFRC	Glass fiber-reinforced concrete
GFRP	Glass fiber-reinforced polymer
GHG	Greenhouse gas
GWP	Global warming potential
HDPE	High-density polyethylene
HRWR	High-range water reducer
HYFRC	Hybrid fiber-reinforced concrete
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LCIA	Life cycle environmental impact assessment
ISF	Industrial virgin steel
MOR	Modulus of rupture
PAN	Polyacrylonitrile
PC	Plain concrete
PE	Polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
PUR	Polyurethane
PVA	Polyvinyl alcohol
PVC	Polyvinyl chloride
PVE	Polyvinyl ethers

rFRC	Recycled fiber-reinforced concrete
rGFRP	Recycled glass fiber-reinforced polymer
RIC	Resin Identification Code
rPE	Recycled polyethylene
rPET	Recycled polyethylene terephthalate
rPP	Recycled polypropylene
SCC	Self-compacting concrete
SEM	Scanning electron microscope
SG	Silica glass
SFRC	Steel fiber-reinforced concrete
w/c	Water-to-cement ratio
w/cm	Water-to-cementitious materials ratio

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
LENGTH				
in.	inches	25.40	millimeters	mm
ft.	feet	0.3048	meters	m
yd.	yards	0.9144	meters	m
mi.	miles	1.609	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.09290	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac.	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
VOLUME				
fl. oz.	fluid ounces	29.57	milliliters	mL
gal.	gallons	3.785	liters	L
ft^3	cubic feet	0.02832	cubic meters	m^3
yd^3	cubic yards	0.7646	cubic meters	m^3
MASS				
oz.	ounces	28.35	grams	g
lb.	pounds	0.4536	kilograms	kg
T	short tons (2000 pounds)	0.9072	metric tons	t
TEMPERATURE (exact degrees)				
°F	Fahrenheit	(F-32)/1.8	Celsius	°C
FORCE and PRESSURE or STRESS				
lbf	pound-force	4.448	newtons	N
lbf/in^2	pound-force per square inch	6.895	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
LENGTH				
mm	millimeters	0.03937	inches	in.
m	meters	3.281	feet	ft.
m	meters	1.094	yards	yd.
km	kilometers	0.6214	miles	mi.
AREA				
mm^2	square millimeters	0.001550	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac.
km^2	square kilometers	0.3861	square miles	mi^2
VOLUME				
mL	milliliters	0.03381	fluid ounces	fl. oz.
L	liters	0.2642	gallons	gal.
m^3	cubic meters	35.31	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
MASS				
g	grams	0.03527	ounces	oz.
kg	kilograms	2.205	pounds	lb.
t	metric tons	1.102	short tons (2000 pounds)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C + 32	Fahrenheit	°F
FORCE and PRESSURE or STRESS				
N	newtons	0.2248	pound-force	lbf
kPa	kilopascals	0.1450	pound-force per square inch	lbf/in^2

*SI is the abbreviation for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2021)

1 INTRODUCTION

1.1 Background

Concrete is the most widely used construction material worldwide. Some of its favorable attributes are the local availability of its prominent constituent materials (sand and rock) at relatively low costs; its workability and flowability, allowing it to be cast in the desired shape; and its ability to gain strength in a few days to form a hardened structure *(1,2)*. However, it is well known that concrete is weak in tension and has low resistance to cracking under tensile stresses owing to its brittle nature *(3)*. Cracks can develop due to volumetric changes from the hydration of portland cement (autogenous shrinkage), loss of moisture to the environment (chemical and drying shrinkage), temperature changes, and mechanical stresses. In the case of concrete flatwork (for example, pavements and bridge decks), the large surface-area-to-volume ratio increases the chances of shrinkage cracking due to moisture loss from the large surface compared to other concrete structures such as beams and columns.

Fibers have proven to enhance the performance of concrete pavements and bridge decks in several ways. According to the American Concrete Institute (ACI) Committee 544's *Report on Fiber Reinforced Concrete*, depending on the type, fibers can add to the flexural strength, crack resistance, resistance to impact and abrasion, shrinkage, expansion, fire resistance, and toughness of concrete *(4)*. Fibers come in various sizes and shapes and are made from a wide range of materials.

Essential properties of fibers that affect their performance are their dimensions, mechanical properties (tensile strength and elastic modulus), elongation, and surface chemistry for bonding with the cementitious matrix *(5)*. The most common fiber materials used for concrete are steel, alkali-resistant glass, polymeric, carbon, and natural fibers. These fibers are then subdivided into two general size classes: microfibers and macrofibers. Microfibers have diameters less than 0.012 in. (0.3 mm) with a high aspect ratio (length-to-diameter ratio) and are usually less than 0.7 in. (18 mm) long *(6)*. Macrofibers have diameters larger than 0.012 in. (0.3 mm) and are generally longer than 0.7 in. (18 mm). Macrofibers are also sometimes referred to as structural fibers *(6)*.

Of the commonly used fibers for concrete, the most prevalent are macrofibers made from steel, polypropylene, or polyethylene. Polypropylene or polyethylene fibers can be either monofilament or fibrillated. Monofilament fibers, as the name suggests, consist of just a single, continuous strand. The definition from ACI 544.1R is "any single filament of a manufactured fiber, usually of a denier higher than 14. Instead of a group of filaments being extruded through a spinneret to form a yarn, monofilaments generally are spun individually" *(4)*. Fibrillated fibers are bundles of fine fiber strands and are defined as "slit film fiber where sections of the fiber peel away, forming branching fibrils" according to ACI 544.1R *(4)*. Macrofiber dosages in concrete vary depending on the fiber properties and the specific application. A typical range is 0.2 vol% to 1 vol%. Macrofibers used specifically for structural concrete applications can potentially reduce slab thickness and allow for larger joint spacing. For instance, steel fibers can significantly increase the flexural strength of concrete (30% to 50% improvement was reported), and, therefore, a thinner slab (13% reduction) would be required over the design life *(7)*.

Compared to macrofibers, microfibers are very fine (small diameter) and are used primarily to control plastic shrinkage cracking, which occurs at early ages and develops when the concrete surface evaporation rate is faster than the rate of water migration to the surface (bleeding). Microfibers are used in small dosages ranging from 0.03% Vol to 0.1% Vol or 0.5 to 1.5 lb/yd^3 (0.3 to 0.9 kg/m^3). In addition, microfibers have been shown to control drying shrinkage cracks during curing/hardening and over the pavement service life *(6)*.

Microfibers and macrofibers can be produced from virgin materials, such as primary steel and various types of polymers. However, opportunities exist for the recycling of industrial byproducts, post-consumer waste streams, and end-of-life (EOL) products as well as more use of natural and renewable source materials for concrete fibers. Research shows that many industrial byproducts (steel sheets and shavings, carbon fibers), post-consumer waste streams (old carpets, tires, and brake pads, paper/magazine waste, plastic bottles), and EOL products (parts of wind turbine blades, planes, automobiles, boats) can be recycled into high-quality recycled fibers for concrete applications *(8,9)*. Furthermore, natural fibers from wood and nonwood plants are inexpensive, and the source material is abundant. However, these fibers are not as commonly used in concrete construction.

Recycled fibers could be produced at a lower cost than virgin fibers depending on the recovery and recycling process, based on a survey of fiber producers conducted as part of this study (which will be discussed in more detail in Chapter 5). One example is steel fibers produced from industrial scraps and waste streams, which have much lower costs than their counterparts from primary steel, resulting in more economical and implementable products for concrete. The price of recycled steel fibers can start from as low as $0.75 per lb. ($0.35 per kg), while primary steel fibers may cost $2.50 per lb. ($1.13 per kg) or more, according to several steel fiber suppliers *(10–12)*. The recycled carbon fibers price starts at $35 per lb. ($16 per kg) versus a starting price of $53 per lb. ($24 per kg) for virgin carbon fibers, according to conversations with Zoltek Corporation.

Another advantage of recycled fibers compared with their virgin counterpart fibers is potential differences in global warming potential (GWP) from greenhouse gas (GHG) emissions and other environmental impacts from production. For example, steel production from primary steel is energy and carbon-intensive, contributing to GHG emissions and other environmental concerns *(13)*. Steel fibers used by the construction sector are typically from primary steel, which requires a large amount of steel production (0.33 million US tons [0.3 million metric tons]) sold annually *(8)*—this large amount of steel fiber production results in GHG emissions from the construction industry. The environmental advantages of recycled steel fibers are especially significant as most concrete steel fibers are made from old tires with no or minor thermal treatment. Other scrap steel or steel byproducts, such as brake pads and steel wires that can be recycled into concrete fibers with minimum thermal treatment, were identified in the industry survey of this study. Based on a life cycle assessment (LCA) study, the GWP of recycled steel fibers from waste tires was found to be 0.0695 kg CO_2eq per kg of fibers produced (69.5 kg CO_2eq/tonne of fibers) *(14)* and 54.74 kg CO_2eq for recycled steel fibers (from tires) based on another study *(15)*. These GWP amounts are lower compared with the GWP of 1 tonne of industrial steel fibers from primary steel, reported to be approximately 1,096 kg CO_2eq for 1 tonne of fibers *(15)*.

In addition to the potential for reduction of environmental impacts, recycling creates a reuse route for industrial byproducts, waste streams, and EOLs that currently do not have a recycling path and reuse application. This reuse route promotes a circular economy and reduces waste, and it can reduce landfill use and preserve raw materials resources. On the other hand, recycled materials are typically associated with high variability in composition and physical properties, depending on their sourcing and processing. Recycled fibers can also be contaminated with impurities, requiring washing, drying, thermal, and/or chemical treatments. The washing, drying, thermal, and chemical treatments may have large negative environmental and economic impacts due to the use of water, chemicals, and energy, and they may have other environmental impacts, such as air pollution and noise. Transportation, storage requirements, and waste streams from the processing of recycled materials should also be considered.

Recycled fibers must have the required attributes for use in concrete: they are dispersible in concrete, they have appropriate and controlled geometric configurations, and they have good mechanical properties. The recovery process may also degrade the properties of the primary material. As a result, recycled fibers may experience reduced mechanical properties, affecting their suitability for concrete applications. Therefore, when assessing the suitability of recycled fibers for concrete applications, a comprehensive evaluation is required, taking into account multiple factors such as technical performance and the environmental impacts and cost of the recycling process.

Using natural source materials such as cellulose to create fibers for the concrete industry presents another potential strategy for enhancing the sustainability of fiber-reinforced cement-based products. Natural fibers offer distinct advantages over synthetic fibers, such as the abundance of the source materials, renewability, and cost-effectiveness. Natural fibers are sourced and processed from plants and animal sources. This report will specifically focus on natural fibers sourced from plants.

The underlying structure of natural fibers is composed of cellulose microfibrils within a matrix of lignin and hemicellulose *(3)*. These fibers exhibit a heterogeneous nature, and their properties are largely influenced by the specific plant source. Among the most commonly employed natural fibers in concrete are sisal, flax, hemp, jute, sugarcane, coconut, and cellulosic fibers derived from wood. Natural fibers have several favorable engineering properties compared to the other commonly used fibers in concrete: low density, high modulus-to-weight ratio, and a low-carbon footprint *(3)*. When used in concrete, these fibers improved mechanical performances—mostly tensile strength, flexural strength, and the impact resistance of concrete. However, some inherent characteristics of natural fibers—lower reliability because of variability in composition, the solubility of constituents in the cementitious solution, and moisture susceptibility—must be addressed to implement natural fibers in concrete successfully *(3)*. Proper surface treatment techniques can be applied to make the natural fibers compatible and durable for use in cementitious materials.

Another category of fibers from naturally occurring sources is glass and basalt fibers. Glass fibers were first used in cement mortar in 1931 *(16)*. Glass and basalt fibers are primarily sourced from silica glass and basalt rock *(17)*. Alkali-resistant glass fibers were developed for concrete due to the susceptibility of pure silica glass fibers to deterioration in alkaline environments *(19)*. Subsequent research has mostly focused on alkali-resistant silica glass fibers instead of pure silica glass fibers. The specifications for alkali-resistant silica glass fibers intended for use in glass fiber-reinforced concrete (GFRC) are outlined in ASTM C1666. Research has shown that both silica and basalt glass fibers contribute to the strength and fracture properties of concrete with increasing fiber dosages *(18)*; however, high temperatures of 1400°C to 1600°C required for melting and forming the material into fiber shapes contribute to the environmental burdens of these fibers *(19)*. Therefore, similar to recycled fibers, the implementation of natural fibers in concrete should be evaluated based on their technical performance as well as consideration of the environmental and cost aspects.

This report presents a review of recycled fibers and fibers from natural materials produced at an industrial scale using information that could be found to evaluate their suitability for concrete with respect to the issues previously discussed. Information was gathered on the physical and chemical properties, costs, and environmental impacts of the recycling process and the performance of recycled and natural fibers in concrete.

1.2 Problem Statement

The following problem statements have been identified:

- Many recycled fibers have shown an equivalent structural performance when compared to virgin fibers. Fibers from naturally occurring sources such as cellulose, silica, and other minerals have also shown great enhancements to concrete performance. However, fiber-reinforced concrete (FRC) with these types of fibers is not commonly used owing to incomplete or outdated information regarding variability, performance data, and a lack of standard specifications and tools to consider them in pavement design methods. An assessment is needed to provide updated and more comprehensive information.

- Fibers from recycled and natural sources that are available on the market and those with a high chance of developing a robust supply chain to support the concrete pavement market need to be identified and evaluated for structural, constructability, environmental, and economic performance.
- For fibers that are found to provide benefits and that are being produced at an industrial scale or are capable of reaching that scale, pavement design methods need to be updated to permit the design of structures to meet design life requirements so that life cycle environmental and cost evaluations of recycled fiber-reinforced concrete (rFRC) versus FRC and conventional concrete materials can be done in the project delivery process. Inclusion in design methods will motivate designers and the concrete pavement industry to consider rFRC technology for life cycle cost analysis (LCCA) and environmental life cycle assessment (eLCA) comparison, which cannot currently be done. There is a potential for cost savings and reduced life cycle environmental burdens of concrete pavements if rFRC allows the use of thinner slabs or produces longer lives for the same thickness.

1.3 Project Objective/Goal

This project aims to develop guidance for Caltrans to incorporate FRC (using virgin fibers) and rFRC (using recycled fibers and natural fibers) technologies into structural concrete design and construction, including identifying recycled fiber technologies with a viable supply chain to support the structural concrete industry in California. The project will have a technical advisory group led by the Office of Concrete Pavements (OCP) with information sharing with the Materials Engineering and Testing Services (METS) and Construction divisions of Caltrans. This objective will be achieved through the following tasks:

- **Phase I**
    - Task 1: Practice and literature review (Go/No-Go Point)

- **Phase II**
  - Task 2: Source material sampling, characterization, and fiber production
  - Task 3: Laboratory testing to optimize recycled fiber size and loads
  - Task 4: Durability evaluation of selected rFRC
  - Task 5: Phase II report (Go/No-Go Point)
- **Phase III**
  - Task 6: Small-scale field testing (to be done after laboratory test at the same time as full-scale testing)
  - Task 7: Full-scale field testing (falling weight deflectometer and Heavy Vehicle Simulator loading)
  - Task 8: Mechanistic-empirical pavement design for FRC
  - Task 9: Pavement design tool
  - Task 10: Project summary report

This technical memorandum presents the results of Task 1.

1.4 Report Layout

The report is presented in sections based on the fiber material type. The following fiber types are included in the report: recycled fibers from steel, plastic fibers, recycled metallic (steel) fibers, carbon fibers, and carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer composites (GFRP). Natural fibers from cellulose, silica, and basalt were also included. For each fiber type, major suppliers of concrete fibers were surveyed, and those suppliers with a recycled fiber production line were identified for further information gathering.

Detailed information was gathered for the recycled fiber, including properties (size and morphology), recommended dosage in concrete, expected performance outcome in concrete, feedstock supplies, the production process, performance data, case studies, the availability of an environmental product declaration (EPD), and the cost range.

In addition to the survey of concrete fiber suppliers, a review of the scientific literature was performed for each fiber type, and a literature synthesis was provided for each fiber type.

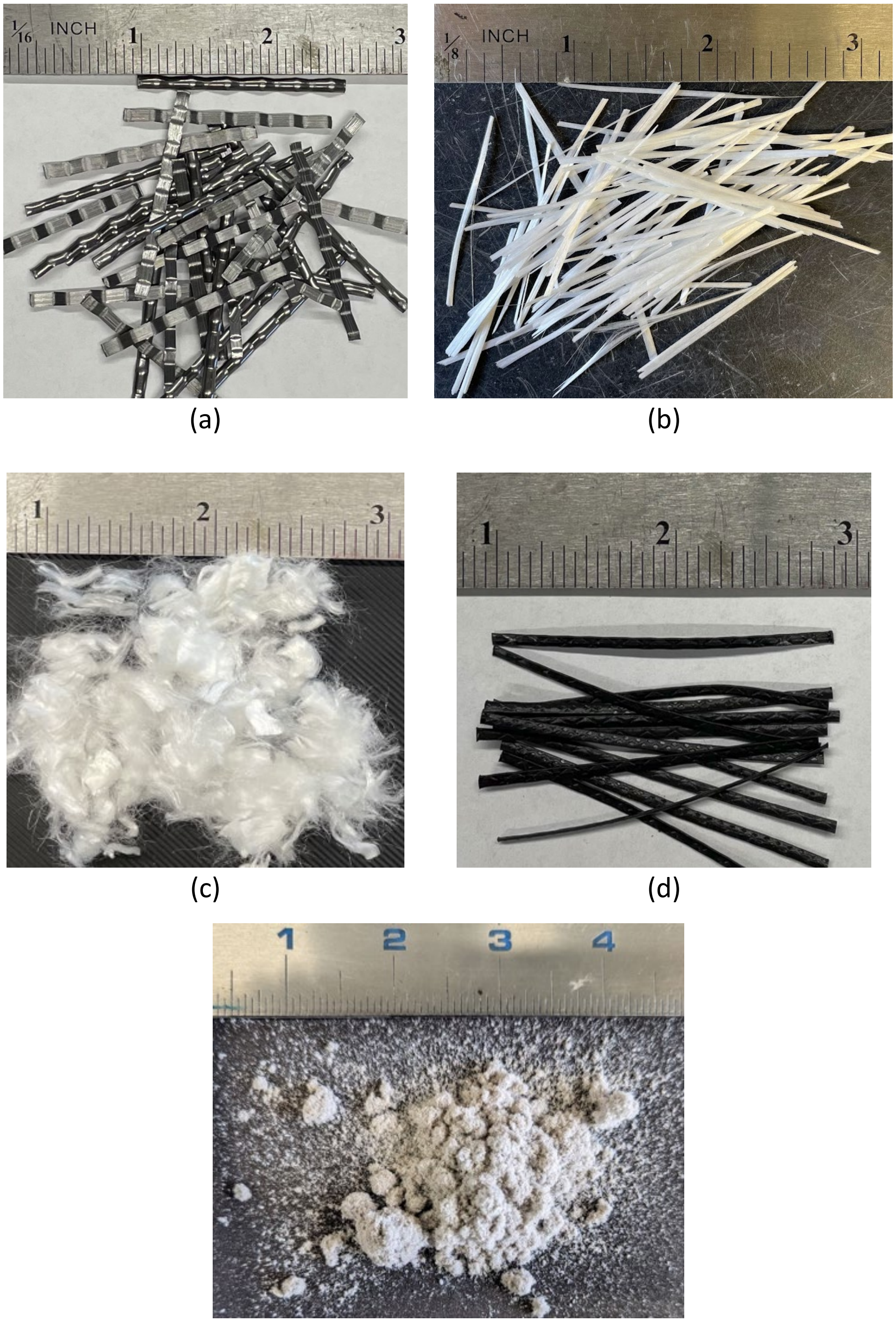
1.5 Measurement Units

In this report, both English and metric units (provided in parentheses after the English units) are provided in the general discussion.

2 MATERIALS AND TESTING BACKGROUND

Fibers are often classified based on their origin material according to the ASTM C1116M standard. Major fiber classifications are steel (Type I), shown in Figure 2.1a, glass (Type II), shown in Figure 2.1b, synthetic (Type III), shown in Figure 2.1c and Figure 2.1d, and natural fibers (Type IV), shown in Figure 2.1e. Each of these types of fibers enhances a different property of concrete based on the fiber type's specific physical, chemical, and mechanical properties.

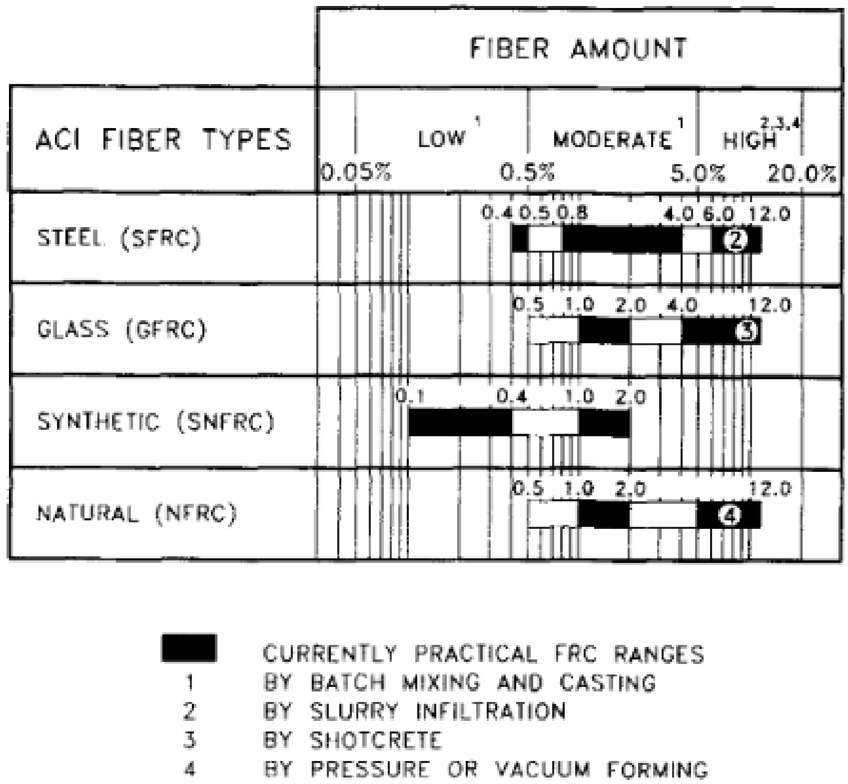
Steel and glass fibers can significantly enhance the flexural and tensile strength and post-cracking functional performance of concrete owing to their energy-absorbing and crack-control capabilities. Natural fibers from wood and nonwood plants (cotton, sisal, coconut, sugarcane bagasse, etc.) can enhance the hydration of cement by improving internal curing, reducing bleeding and early-age shrinkage, and improving the finishability of concrete. Synthetic fibers can be made from polyolefin, acrylic, aramid, and carbon materials, with polyolefin being the most used source. These fibers generally control plastic shrinkage cracking and provide post-cracking performance *(20)*.



(a) (b) (c) (d) (e)

Figure 2.1: (a) Recycled steel fibers by Sika (Novocon XR), (b) silica glass fibers by Owens Corning (Anti-CRAK HP 67/36), (c) recycled synthetic microfiber (Euclid Chemicals), (d) recycled synthetic macrofiber (Barchip R50), and (e) cellulose fibers (CreaFill Fibers).

Depending on fiber type, different dosages are used in concrete applications. Figure 2.2 shows the range of fiber amount based on low, medium, and high application dosages per fiber material types.



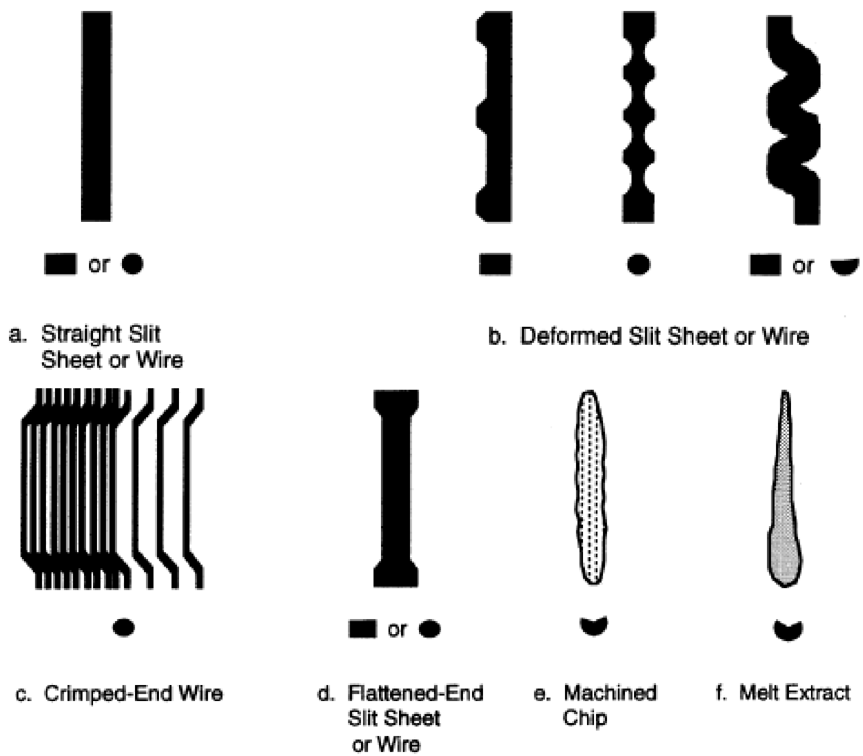
Source: Zollo (1997) *(21)*.

Figure 2.2: Fiber types and amount used by volume percent of the cement matrix.

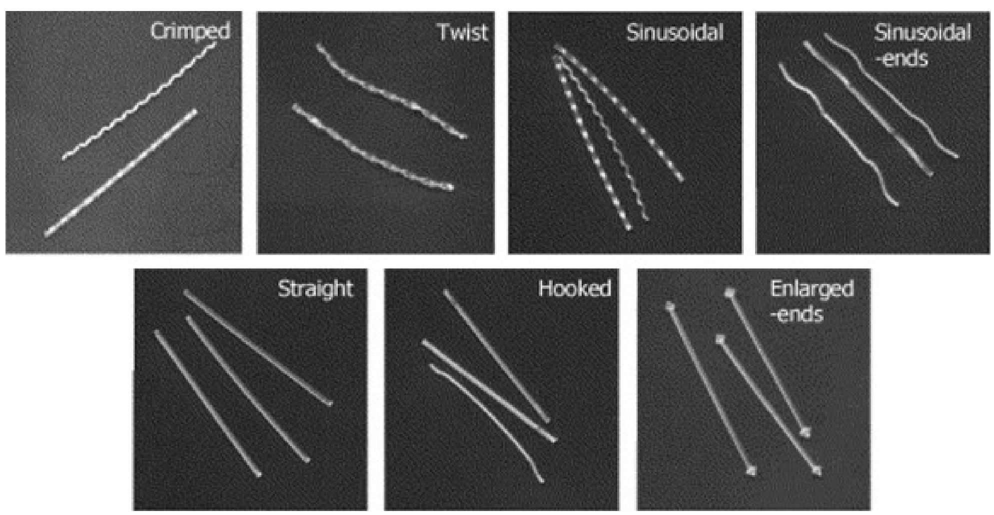
Another subclassification of fibers is based on fiber dimensions. The diameter cutoff between microfibers and macrofibers is 0.012 in. (0.3 mm), according to ACI 544.4R-18 *(6)*. Typically, microfibers are less than 0.7 in. (18 mm) in length. Synthetic microfibers are often added to concrete to control plastic shrinkage and sometimes drying shrinkage, and macrofibers are added to enhance the flexural performance and fracture toughness of concrete. At a much smaller scale, nanofibers (nanosize in one dimension) are sometimes used to modify the properties of cement composites, but nanofibers' dosage and functional mechanisms are different from those of microfibers and macrofibers and, therefore, are not included in this report.

Aspect ratio is an important term used to characterize fibers and is defined as the ratio of the length to the width of the fibers, generally ranging from 20 to 100 for concrete fibers. Microfibers with very fine diameters have a large aspect ratio, while macrofibers, typically greater than 0.3 mm in diameter, have a smaller aspect ratio *(5)*.

Based on cross-section shapes, fibers may be subdivided into prismatic (rounded or polygon cross-section with a smooth surface or deformed throughout or only at the end), irregular (cross-section varies along the length), or collated (which can be further subdivided into multifilament or monofilament) *(21)*. Figure 2.3a and Figure 2.3b show steel and polymeric fibers varying in cross-sections and surface texture.



(a)



(b)

Source: ACI Committee 544 (1997) *(4)*; Frazão et al. (2022) *(15)*.

Figure 2.3: Various configurations of (a) steel fibers and (b) polymeric fibers.

Another term used to characterize fibers is the equivalent diameter of a fiber, defined as the diameter of a circle having the same area as that of the average cross-sectional area of an actual fiber. The aspect ratio can then be defined as the ratio of the length to the equivalent diameter of an individual fiber. The equivalent diameter of a fiber can be calculated per Equation 2.1 *(21)*:

$$\boldsymbol{d = f\left(\frac{d}{SG}\right)^{\frac{1}{2}}} \quad \textbf{(2.1)}$$

Where:

d = equivalent diameter

f = 0.0120 for d in mm

D = fiber denier

SG = specific gravity of fiber

Fiber denier—a term usually used in the textile industry—is defined as the weight of fiber in a 5.6 mi. (9,000 m) fiber length, and it is different for bundled (collated) versus multifilament fibers *(21)*. The significance of the term fiber denier is that it considers the change in the form of bundled fibers before and after being mixed into concrete. Sufficient mechanical shearing energy is required to break up the bundled fibers during mixing concrete. The post-concrete mixing fiber denier is used to calculate the equivalent diameter in Equation 2.1. Depending on the type of fiber and the form in which it was introduced into concrete, fiber denier becomes a necessary material specification for FRC *(21)*. Thus, synthetic fiber manufacturers usually specify this information in their product technical data sheets. Fiber volume or amount in a concrete mix varies according to its material type.

Other important parameters are fiber count (FC) and fiber-specific surface area for a unit length of fiber (FSS). FC is the number of fibers in a unit volume of FRC, and FSS is the total surface area of fibers in a unit volume of FRC, which can be calculated using Equation 2.2 and Equation 2.3 *(21)*.

$$FC = \left[\frac{7.5{*}DRT{*}\,10^{-4}}{l{*}\,d^{2}{*}SG}\right] = \left[\frac{5.08{*}V{*}SG{*}\,10^{6}}{l{*}PoMD}\right] \quad \textbf{(2.2)}$$

$$FSS = FC * \pi * d * l \quad \textbf{(2.3)}$$

Where:

DTR = fiber dosage rate (lb./yd^3)

V = unit volume of FRC

l = fiber length (in.)

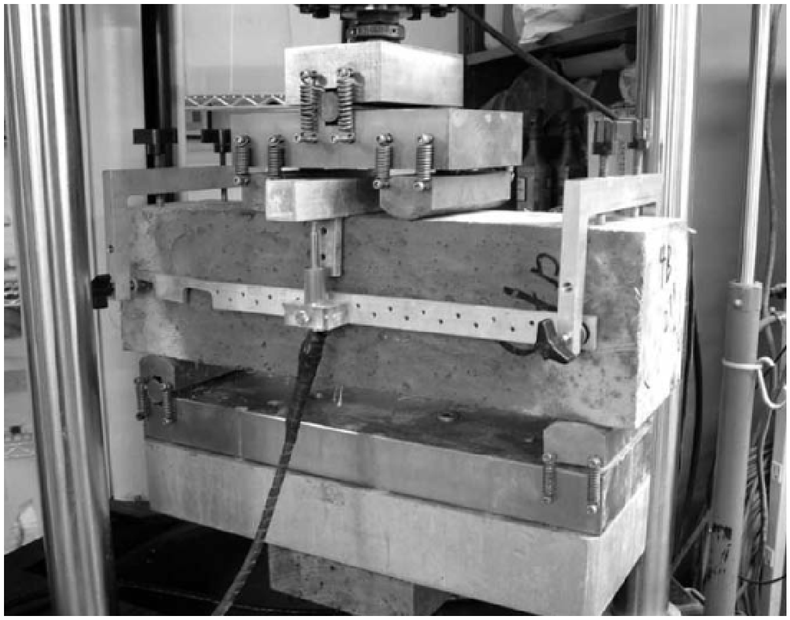
d = fiber equivalent diameter (in.)

SG = specific gravity of fiber material

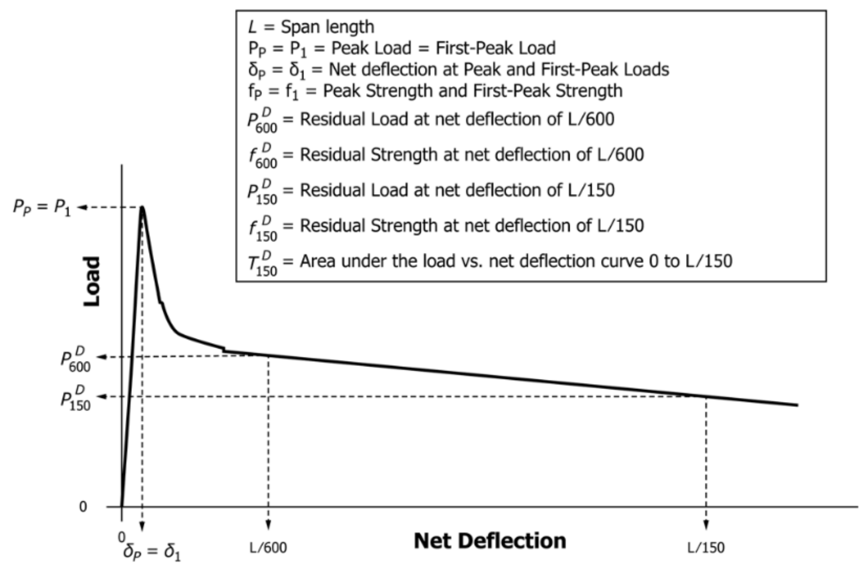
$PoMD$ = post-mix denier

FC = fiber count

The ASTM C1609 test procedure, specifically developed for testing FRC, is used to determine the impact of fiber on the flexural strength and residual flexural strength of fiber-reinforced concrete. This test provides a standardized method for evaluating the performance of concrete containing fibers under flexural loading conditions. The typical test setup for ASTM C1609 flexural testing is shown in Figure 2.4a. Figure 2.4b shows the resulting load-deflection plot from the test, which indicates how well the fibers perform in post-cracked FRC.



(a)



(b)

Source: ASTM C1609/C1609M-19a.

Figure 2.4: (a) Residual strength test setup and (b) test analysis plot showing load versus net deflection.

The various parameters calculated based on the load-deflection graph are as follows. Peak strength (f_p) calculated by Equation 2.4:

$$f_p = \frac{PL}{bd^2} \quad \textbf{(2.4)}$$

Where:

P = peak load in N

L = flexural span length

b = width of the specimen in mm

d = depth of specimen in mm

The flexural toughness (T_{150}), as outlined in ASTM C1609, is calculated as the energy (area under the load-deflection graph) required to deflect the test beam to the $L/_{150}$ point of its span. The residual strengths, f_{600} and f_{150}, are the flexural stresses at the midpoint deflection of $L/_{150}$ and $L/_{600}$, respectively. Finally, the equivalent flexural strength ratio (%) is calculated by R_{150}, where f_1 is the first crack strength.

$$R_{150} = \frac{150T_{150}}{f_1 bd^2} \times 100 \quad \textbf{(2.5)}$$

Where:

T_{150} = flexural toughness required to deflect a beam specimen to the $L/_{150}$ point

f_1 = first crack strength

b = width of the specimen in mm

d = depth of specimen in mm

The fibers identified in this literature review report will be systematically assessed based on the properties of FRC materials discussed in Section 2. The aim will be to evaluate the enhancements from fibers to the concrete matrix and to determine any potential tradeoffs between the enhanced performance attributed to fibers and their added cost and environmental burdens, focusing on recycled fibers and natural fibers.

3 RECYCLED POLYMERIC FIBERS

3.1 Introduction

Synthetic polymeric fibers are designed according to the ASTM D7508 standard and are primarily made of polyolefin materials, such as polypropylene (PP) and polyethylene (PE) *(22)*. Fibers from other types of polymers, such as polyacrylonitrile (PAN), polystyrene, polyvinyl chloride (PVC), polycarbonate, nylon, and polyvinyl ethers (PVE) are also used in concrete *(23)*. These are usually virgin-sourced fibers and generally consist of alkene monomers. While not as common, recycled synthetic fibers are also manufactured for concrete. These fibers are usually composed of PP, PE, or polyethylene terephthalate (PET), commonly known as polyester. The focus of this report is these three polymer types. The following abbreviations are used for polymeric fibers throughout this report:

- Virgin polypropylene (PP)
- Virgin polyethylene (PE)
- Virgin polyester (PET)
- Recycled polypropylene (rPP)
- Recycled polyethylene (rPE)
- Recycled polyester (recycled polyethylene terephthalate [rPET])

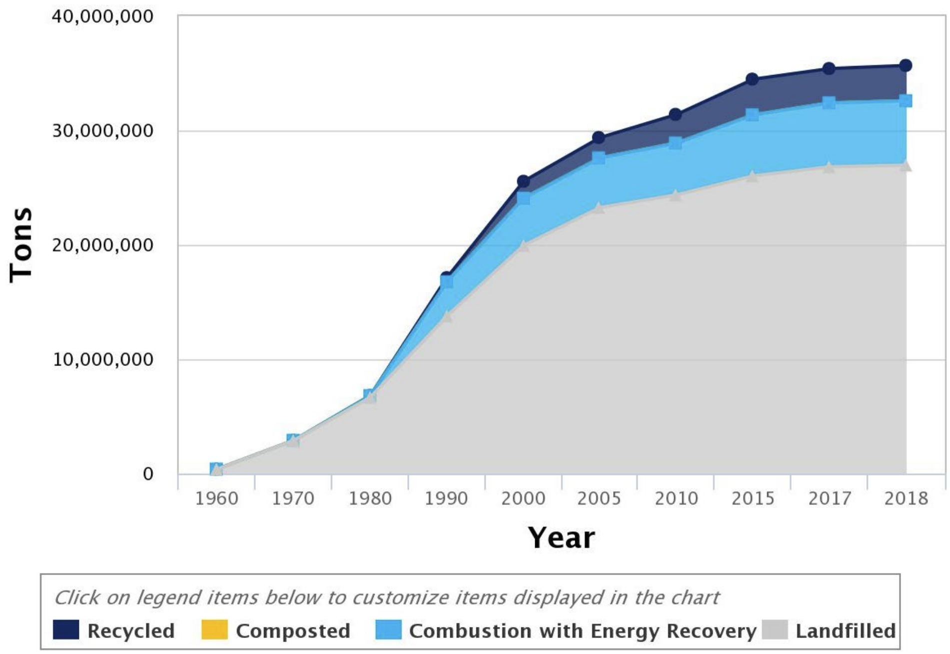
The main purpose of polymeric microfibers is to mitigate plastic shrinkage cracking *(24)*. In comparison, polymeric macrofibers such as PP and PE do not add to the mechanical strength properties, and their main purpose is to provide post-crack performance as they create a network that prevents microcrack propagation *(22,25)*.

Post-consumer and industrial plastic wastes remain in the ecosystem for long periods of time, leading to long-term environmental pollution or landfill space occupation from waste accumulation *(9)*. Recycled fibers from post-consumer or industrial plastic waste can potentially reduce demand for new plastic generation and divert plastic waste from the ocean and landfills or incineration plants, helping to mitigate the associated environmental and social impacts of plastic waste. In this direction, there is an increasing interest in the fiber manufacturing industry and among researchers to study the feasibility of using recycled polymeric fibers in concrete *(9)*.

There are seven plastic recycling codes per the Resin Identification Code (RIC) system created by and for the Plastics Industry Association in 1988, as outlined in ASTM D7611: (1) polyethylene terephthalate (PET), (2) high-density polyethylene (HDPE), (3) polyvinyl chloride (PVC), (4) low-density polyethylene (LDPE), (5) polypropylene (PP), (6) polystyrene (PS) and (7) other plastics.

Based on the internal chemistry, plastics can be subdivided into thermoplastics and thermosets. The main difference between these two is that thermoplastics do not undergo the thermo-chemical transformation that thermosets do *(26)*. As a result, thermoplastics can be remolded by heat and recycled easily compared to thermosets, which require complex chemical recycling *(26)*. The plastics in recycling Code 1 (most post-consumer bottles are in this group) can be thermally molded and recycled into polyester fibers as these are predominantly thermoplastics. The same applies to PP and PE plastic groups *(27)*. Polyurethane (PUR) is a commonly used thermoset and is challenging to recycle *(26)*.

According to the US Environmental Protection Agency (EPA), plastics in municipal solid waste amounted to approximately 14.5 million US tons (13.2 million metric tonnes) in 2018 *(28)*. PET and HDPE plastic contributed to most of this amount. Figure 3.1 shows the amount of plastic waste managed from 1960 to 2018. Figure 3.1 shows that the bulk of the total plastic waste is landfilled, and a small amount is recycled, composted, or used in energy recovery, according to the EPA *(28)*. While plastic recycling increased since 2005, the rate of increase has been slow with respect to total generated plastic waste.



Source: US Environmental Protection Agency (2017) *(28)*.

Figure 3.1: Summary of plastic waste management from 1960 to 2018.

3.2 Feedstock Description: Recycled Polymers

Recycled polymeric fibers can be derived from various polymer types and recycling methods. One study compiled and summarized previous research on recycled polymeric fibers *(9)*. The findings are presented in Table 3.1. This table includes studies between 1998 and 2017 that examined the use of recycled polymeric fibers in concrete, with some studies also investigating their application in asphalt. Most of these studies employed recycled polymeric fibers in infrastructure projects, primarily pavements. Based on the information in Table 3.1, the reviewed studies used recycled polymeric fibers manufactured from post-consumer PET bottles and PP from carpet and other domestic and industrial waste. These recycled fibers are discussed in greater detail in the next section.

Table 3.1: Recycled Polymeric Fibers from Different Sources

Title	Concrete Type	Fiber Type	Recycling Source Material	Application	Reference Material for Comparison	Technical or Environmental or Economical Aspects Considered
Yazdanbakhsh et al. (2017) *(29)*	Fiber-reinforced polymer (FRP)	Needles from bar scraps	—	FRC	—	Tech
Pereira et al. (2017) *(30)*	Concrete	Polyester (PET)	PET bottles	—	—	Tech/Env
Kurup and Kumar (2017) *(31)*	Fiber-reinforced concrete (FRC)	PVC cable	Electronics	—	Normal concrete	Tech/Env
Vishnu et al. (2017) *(32)*	Plastic fiber-reinforced concrete (PFRC)	PET	Bottles	—	–	Tech/Env
Sodhi and Salhotra (2017) *(33)*	Concrete	Plastic	–	—	–	Tech/Env/Eco
Dar and Salhotra (2017) *(34)*	Concrete	PET	Bottles	—	Natural coarse aggregate concrete	Tech/Env
Hama (2017) *(35)*	Lightweight aggregate concrete	Plastic	Bottles	—	Reference mix without plastic fibers	Tech/Env
Kurup and Kumar (2017) *(36)*	FRC	Outer casing insulation of wire	Electronic	—	Normal concrete	Tech/Env
Karanth et al. (2017) *(37)*	Waste plastic fiber-reinforced concrete	Plastic	Doors	—	—	Tech
Cheng et al. (2017) *(38)*	Lightweight wet-mix shotcrete	PET; PP (not specified if recycled)	Agriculture/ bottles	Roadway support as lightweight shotcrete	Plain concrete (PC)	Tech/Env
Dinesh and Hanumantha Rao (2017) *(39)*	FRC	Plastic	—	—	Conventional concrete	Tech/Env
Khalid et al. (2017) *(40)*	Ring-shaped PET (RPET) fiber in concrete	PET	Bottles	—	RPET	Tech/Env
Rinu Isah and Shruthi (2017) *(41)*	FRC	PET	Bottles	—	Ordinary concrete, steel-reinforced concrete	Tech
Al-Hadithi and Hilal (2016) *(42)*	Self-compacting Concrete (SCC)	Waste plastic fibers	Cut beverage bottles	—	—	Tech

Title	Concrete Type	Fiber Type	Recycling Source Material	Application	Reference Material for Comparison	Technical or Environmental or Economical Aspects Considered
Pešić et al. (2016) *(43)*	FRC	Simply extruded recycled high-density polyethylene (HDPE)	—	—	—	Tech/Env
Yin et al. (2016) *(44)*	FRC	PP	—	Footpaths, precast panels	—	Tech
Foti (2016) *(45)*	FRC	PET	—	—	—	Tech
Gu and Ozbakkaloglu (2016) *(46)*	Concrete	Plastic	—	—	—	Tech/Env
Borg et al. (2016) *(47)*	FRC	PET	Bottles	—	—	Tech
Sharma and Bansal (2016) *(48)*	Concrete	Waste plastic	–	—	—	Tech/Env
Usman et al. (2016) *(49)*	Neat asphalt concrete mixture	PET	–	Asphalt concrete	—	Tech/Env
Guendouz et al. (2016) *(50)*	Sand concrete	PET; Low-density polyethylene (LDPE)	Manufacturing of bags	Sand concrete	—	Tech
Choudhary and Aggarwal (2016) *(51)*	Polypropylene fiber-reinforced fly ash concrete	PP	Various	—	—	Tech/Env
Jandiyal et al. (2016) *(52)*	FRC	PET	Bottles	—	—	Tech
Yin et al. (2015) *(20)*	FRC	PP	Industrial waste	—	Recycled vs. nonrecycled	Tech
Otuoze et al. (2015) *(53)*	Asphalt concrete	PP	—	Pavement	—	Tech
Ghernouti et al. (2015) *(54)*	SCC	Plastic	Plastic bags	—	—	Tech
Khaloo et al. (2015) *(55)*	High-performance concrete	Polymer fibers	Discarded car timing belts	—	—	Tech
Abdul Awal et al. (2015) *(56)*	FRC	PP carpet	Waste carpet	—	—	Tech
Yin et al. (2015) *(57)*	FRC	PP processed	—	Concrete footpaths	—	Tech

Title	Concrete Type	Fiber Type	Recycling Source Material	Application	Reference Material for Comparison	Technical or Environmental or Economical Aspects Considered
Nibudey et al. (2015) *(58)*	FRC	PET	Bottles	—	—	Tech
Karthikeyan and Vennila (2015) *(59)*	FRC	PET	Bottles	—	—	Tech
Subramaniaprasad et al. (2015) *(60)*	Stabilized mud masonry blocks	Plastic	Mineral water bottles, carry bags	Soil masonry blocks	Raw specimen	Tech
Fraternali et al. (2014) *(61)*	Recycled polyethylene terephthalate fiber-reinforced concrete (RPETFRC)	PET	—	—	—	Tech
Karthik and Maruthachalam (2014) *(62)*	Hybrid fiber-reinforced concrete (HYFRC) beams	Scrim bled steel (non- recycled); recycled PET and PP	—	—	—	Tech
Spadea et al. (2014) *(63)*	Recycled PET fiber-reinforced concrete	PET	—	—	—	Tech
Kandasamy and Murugesan (2011) *(64)*	FRC	Domestic waste plastic	Domestic waste plastic	—	—	Tech/Env
Koo et al. (2014) *(65)*	Concrete mixed with short, recycled PET fibers	PET	PET bottles	Construction applications	—	Tech/Env
Foti and Paparella (2014) *(66)*	FRC	PET	PET bottles	Road; airport pavements	—	Tech/Env
Foti (2013) *(67)*	RFRC	PET	Bottles	–	—	Tech/Env
Ozger et al. (2013) *(68)*	Nylon FRC	Nylon	Carpet	Thermal energy storage	Traditional concrete	Tech/Env
Pelisser et al. (2012) *(69)*	RFRC	PET	Bottles	—	—	Tech/Env
Bhavi et al. (2012) *(70)*	FRC	HDPE	—	—	—	Tech/Env
Dai et al. (2011) *(71)*	FRP	PET	PET bottles	—	—	Tech
Foti (2011) *(72)*	FRC	PET	PET bottles	—	—	Tech/Env

Title	Concrete Type	Fiber Type	Recycling Source Material	Application	Reference Material for Comparison	Technical or Environmental or Economical Aspects Considered
Fraternali et al. (2011) *(73)*	Recycled PET FRC	PET	PET bottles	—	—	Tech
Dhariwal (2010) *(74)*	FRC	Plastic	—	—	—	Tech/Env
Kim et al. (2010) *(75)*	Structural concrete	PET	PET bottles	—	PP fiber-reinforced concrete	Tech/Env
Asokan et al. (2009) *(76)*	Concrete	Glass fiber-reinforced plastic (GFRP) waste	–	—	—	Tech/Env
Alhozaimy and Shannag (2009) *(77)*	FRC	LDPE	Plastic bottles	—	Plain concrete	Tech/Env
Anurag et al. (2009) *(78)*	Asphalt	Roofing polyester waste fibers	Building roofing	Hot mix asphalt	—	Tech/Env/Eco
Schmidt and Cieślak (2008) *(79)*	Fiber reinforced concrete	Polyamide (PA); PP	Carpet	—	—	Tech/Env
Ochi et al. (2007) *(80)*	Fiber reinforced concrete	PET	PET bottles	Gateway support; pavements	—	Tech
Ogi et al. (2005) *(81)*	Carbon fiber-reinforced plastic reinforced concrete	Recycled and crushed carbon fiber-reinforced plastic	—	—	—	Tech
Lee et al. (2005) *(82)*	Fiber-reinforced asphalt concrete	Nylon	Carpet	—	—	Tech
Auchey (1998) *(83)*	Portland cement concrete	HDPE	—	—	Virgin PP fibers	Tech/Eco

Notes: FRC = fiber-reinforced concrete; FRP = fiber-reinforced polymer; GFRP = glass fiber-reinforced plastic; HDPE = high-density polyethylene; HYFRC = hybrid fiber-reinforced concrete; PET = Polyester; LDPE = low-density polyethylene; PC = plain concrete; PP = polypropylene; PVC = polyvinyl chloride; PFRC = plastic fiber-reinforced concrete; RPET = ring-shaped polyester; SCC = self-compacting concrete.

Source: Merli et al. (2020) *(9)*.

3.3 Description of Recycling, Production, and Processing Method

In one study, rPET fibers were prepared from used plastic bottles (*86*). The process involved melting pellets derived from plastic bottles, extruding them through a nozzle, and drawing them into fibers while they were still warm. This manufacturing method resulted in the alignment of polymer chains in a longitudinal direction, imparting greater tensile strength to the rPET fibers. These recycled polymeric fibers exhibited a smooth texture with a circular cross-section. As part of their research, they also developed a fiber-cutting apparatus to roughen the surface texture of the fibers. This modification aimed to prevent the fibers from pulling out of the cement matrix.

Another study used corrugated surface post-consumer 68 fl. oz. (2 liters) PET bottles to produce rPET reinforcement grids *(66)*. The bottles were manually cut to produce rPET fibers. These fibers were then incorporated into concrete slabs and subjected to impact-loading tests to simulate the loading conditions in airport pavements, roadways, and piers. Figure 3.2 shows the 2 ft. x 2 ft. x 0.2 ft. (80 cm x 80 cm x 5.8 cm) slab with the rPET reinforcement grid used in the study.

Source: Foti and Paparella (2014) *(72)*.

Figure 3.2: Concrete cast over an rPET grid.

Another study tested 0.5 vol% to 2.0 vol% rPET fibers in concrete *(84)*. The rPET fibers were cut at a length and width of 2 in. (50 mm) and 0.2 in. (5 mm), respectively. The findings indicated that adding rPET fibers reduces workability and compressive strength. However, the splitting tensile strength increased by 10% compared to the plain concrete mixture when adding 1.0 vol% of rPET fibers. Recycled PET fibers from post-consumer PET bottles also found application in thermal insulation panels in buildings *(85)* as well as fine aggregates *(86)* and sand *(87)* in concrete.

One study produced recycled high-density polyethylene (rHDPE) fibers from plastic milk containers *(83)*. The preprocessing involved washing and rinsing milk containers with liquid dishwashing soap and fresh water. Once cleaned, the containers were sheared into fibers of approximately 0.75 to 1.50 in. (20 to 40 mm) in length. The method of shearing was not mentioned in the study. Dog bone-shaped specimens were tested to determine the tensile strength of the rHDPE fibers. Compared to a commercially available virgin PP fiber, the tensile strength of the rHDPE fibers was lower by approximately 1,500 psi (10,350 kPa).

For one study, rPP fibers were produced in the laboratory using a melt-spinning and hot-drawing process *(57)*. The source of PP fibers in this study was commercially available plastic granules. The rPP fibers produced in this process had lower tensile strength compared to virgin PP fibers. In another study, rPP fibers derived from waste carpets were used in concrete at 0.5 vol% to 2.0 vol% *(56)*. A few other studies were also found that used recycled polymeric fibers in concrete flatwork applications *(57,66,80)*.

3.4 Physical and Chemical Properties of Recycled Polymeric Fibers

Virgin polypropylene fibers exhibit a tensile strength ranging from 60 to 110 ksi (400 to 760 MPa), Young's modulus of 500 to 600 ksi (3.5 to 4.1 GPa), and specific gravity of 0.9 to 0.95 *(88,89)*. Bolat et al. *(90)* reported that the maximum elongation of PP fibers was 10%, which was approximately 2% higher than that of PET fibers. Polypropylene and PE fibers have been shown to be highly resistant in the alkaline environment of concrete. However, their hydrophobic nature results in weak fiber-matrix bond strength in cementitious systems *(17)*. Polypropylene fibers can be in micro or macro dimensions and manufactured as both fibrillated multifilament (common as micro) and monofilament (common as macrofibers). The pullout strength of macrofibers in the concrete matrix is derived from their surface texture and shape. The various shapes include crimped, twisted, hooked, sinusoidal, and others, shown previously in Figure 2.3 *(91)*.

Virgin PET fibers can be up to 1 in. (30 mm) long with a specific gravity of 1.36 and tensile strength of 60 to 115 ksi (400 to 800 MPa) *(25)*. The final elongation of PET fibers is less than 8%, and water absorption is less than 0.4% by weight *(90)*. A study reported that rPET fibers produced from waste plastic bottles had a specific gravity of 1.34, a diameter of 0.03 in. (0.7 mm), a length of 1 to 1.5 in. (30 to 40 mm), and a tensile strength of 65 ksi (450 MPa) *(86)*. Recycled PET fibers generally have higher alkali resistance than virgin PP fibers, which affects the long-term tensile strength of the fibers when used in concrete.

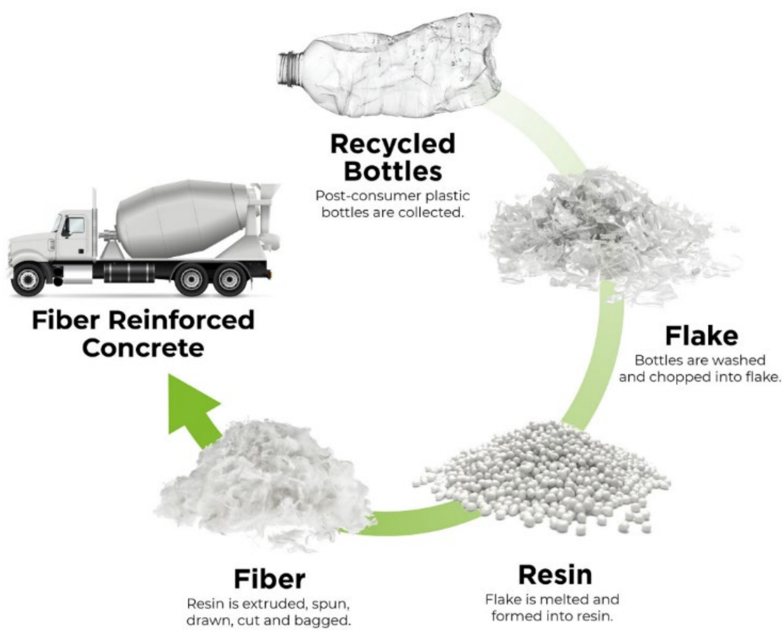
3.5 Identified Suppliers of Recycled Polymeric Fibers for Concrete Applications

The following subsections (Section 3.5.1 to Section 3.5.3) provide information gathered from three major recycled polymeric fiber manufacturers in the United States. In addition to the identified recycled polymeric fibers, one virgin PP fiber from GCP Advance Technologies was included as a baseline comparison for recycled polymeric fibers in terms of technical performance in concrete.

3.5.1 *Recycled PE Microfibers by Euclid Chemical (Cleveland, Ohio)*

Euclid Chemical manufactures rPET fibers from post-consumed PET clear water bottles, sports drinks, and soda bottles. The manufacturing process starts with shredding the bottles and removing labels and papers. Next, the bottles are washed, dried, and chipped into flakes. Lastly, the flakes are melted back to a resinous state, which becomes the raw material for this fiber. PSI FIBERSTRAND REPREVE 225 is the commercial name for this recycled fiber (Figure 3.3), and the manufacturing process is described in Figure 3.4 in a flow diagram.

Figure 3.3: PSI FIBERSTRAND REPREVE 225 rPET fibers.



Source: Image courtesy of Euclid Chemical.

Figure 3.4: Manufacturing process of PSI FIBERSTRAND REPREVE 225.

This rPET fiber is a straight, fine denier, synthetic monofilament fiber with a smooth surface. The length of this fiber is 0.25 in. (6 mm), and the fiber denier is 2.25. The specific gravity of this fiber is 1.34. The typical dosage of this fiber in concrete is 0.5 lb./yd^3 (0.3 kg/m^3), but for pavement applications, a higher dosage of 1 to 3 lb./yd^3 (0.6 to 1.8 kg/m^3) may be required. PET or polyester has a higher tensile strength compared to PP. However, further research is required to establish the effects of this fiber on the properties of hardened concrete. At the recommended dosage, this fiber is beneficial in preventing plastic shrinkage of concrete. It is recommended that this fiber be used without any fine aggregate replacement from the concrete mix and be added early in the mixing process. A superplasticizer admixture is recommended to achieve the desired workability. PSI FIBERSTRAND REPREVE 225 has negligible water absorption and is highly alkaline resistant, meeting ASTM C1116 requirements. There are no fiber pullout or bond strength test data available as the product is relatively new. The cost of this fiber is $4.50/lb.

3.5.2 *Recycled PP Macrofibers by Barchip Inc. (Charlotte, North Carolina)*

Barchip Inc. produces a commercially available rPP fiber called Barchip R50. Based on communications with the manufacturer, the polymer used to make this fiber is the high-quality PP scrap material left from its production lines. Barchip R50 conforms to ASTM C1116, Type III (Polyolefin) fibers. The continuous embossed surface helps these fibers anchor in the concrete. An image of a sample of this synthetic macrofiber, at 2 in. (48 mm) length, is shown in Figure 3.5, and the cost is $0.95/lb. The recommended application is in concrete as a replacement for steel reinforcement structures such as track slabs (reinforced concrete slabs to support railway tracks), tunnels, and thin concrete pavements. However, laboratory evaluation is required to confirm the performance and durability of these fibers in concrete compared with their virgin counterpart fibers.

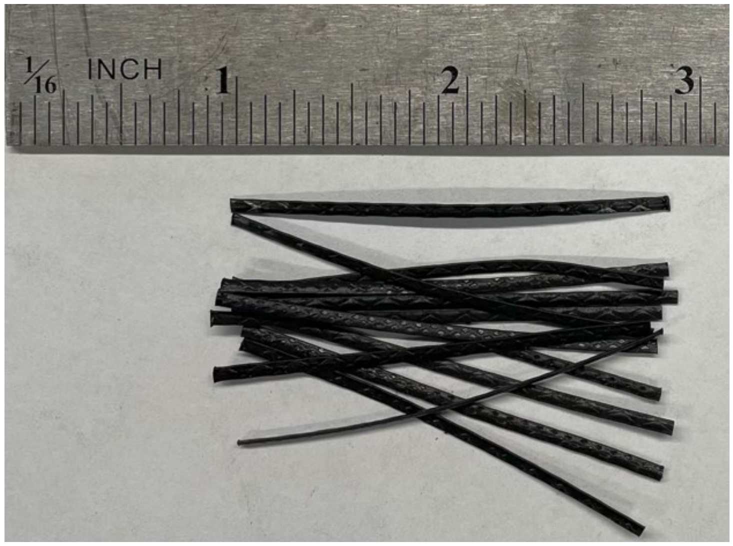


Figure 3.5: Barchip R50 rPP fibers.

3.5.3 *Recycled Polymeric Fibers by Forta Concrete Fibers (Grove City, Pennsylvania)*

Forta Concrete Fibers produces recycled macrofibers and microfibers. FORTA FERRO-GREEN is a blended macro-synthetic fiber, and FORTA GREEN-NET is a synthetic microfiber. FORTA FERRO-GREEN is a blend of monofilament macro virgin copolymer and fibrillated rPP microfibers (Super Net). The source of the recycled portion of the fiber is waste PP. Information regarding the recycling process or the exact source of the PP waste was not found. This fiber has a specific gravity of 0.91 and is available in lengths of 0.75 to 2.25 in. (19 to 54 mm). The tensile strength of this fiber is 83 to 96 ksi (570 to 660 MPa), and it is alkali resistant and does not absorb water. It conforms to ASTM C1116 and ASTM D7508 requirements.

FORTA FERRO-GREEN is expected to provide post-crack toughness, impact resistance, and freeze-thaw resistance in concrete. The suggested dosage in concrete is 3 to 12 lb./yd^3 (1.7 to 7.0 kg/m^3), depending on the application of the concrete. Proper mixing procedures should be followed to avoid fiber balling issues. The fiber should be added to the mixer with the aggregates so the aggregate can shear and separate the fibers. For ready-mix concrete, to achieve no fiber balling, standard practices involving using a newer truck and not overloading the truck should be followed. The cost of FORTA FERRO-GREEN is $7 to $8/lb. ($15.50 to $17.50 per kg) plus delivery cost.

FORTA GREEN-NET is a 100% rPP collated fibrillated microfiber. The specific gravity of this fiber is 0.91, and the length is between 0.75 to 2.25 in. (19 to 54 mm). Like FORTA FERRO-GREEN, the GREEN-NET is manufactured from a waste PP source. However, further details about the source and manufacturing process were not available. This fiber is alkali resistant and does not absorb water. It can reduce plastic shrinkage and drying shrinkage and increase the strength, fatigue resistance, and toughness of concrete. The suggested dosage in concrete is 1.5 to 3.0 lb./yd^3 (0.9 to 1.8 kg/m^3). This fiber has no impact on setting time, and at elevated dosages, it can reduce the bleeding rate of concrete. The cost of this fiber is less than $7/lb. ($15.5/kg) plus delivery cost. Images of samples of FERRO-GREEN and GREEN-NET are shown in Figure 3.6.

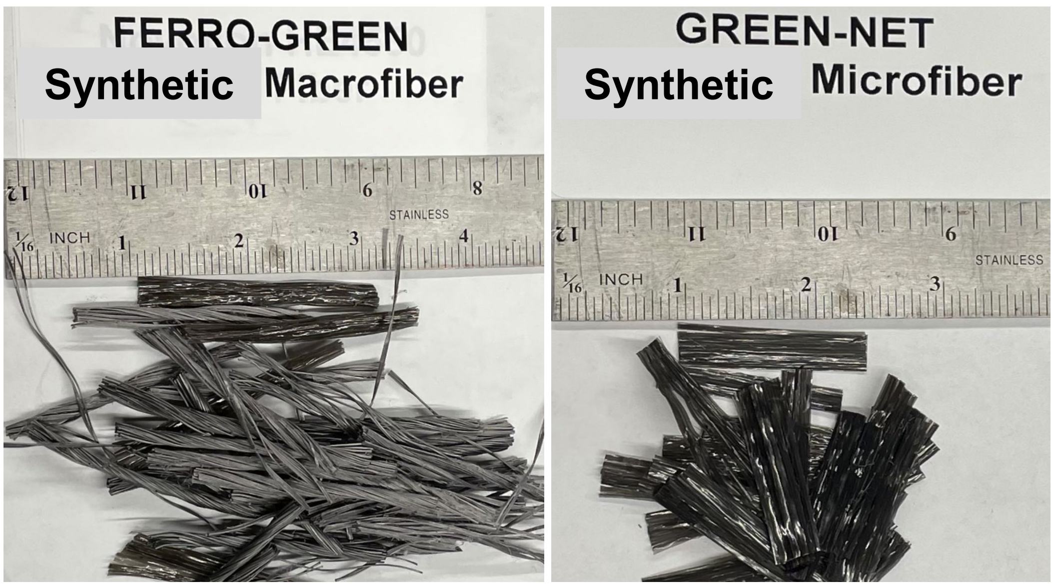


Figure 3.6: FERRO-GREEN (left) and GREEN-NET (right) rPP fibers.

3.5.4 *Summary of Findings from Recycled Polymeric Fibers Suppliers*

After reaching out to most major concrete fiber manufacturers in the United States, the three suppliers previously mentioned were found to be the significant producers of recycled polymeric fibers on a large scale. When asked about their production capacity for the recycled fibers, exact quantities were unavailable. However, the suppliers were confident that their supplies of recycled fibers could meet the market demand of the concrete industry in California. Table 3.2 summarizes the pertinent information gathered from the interviewed manufacturers that have manufacturing lines for recycled polymeric fibers.

Table 3.2: Summary of Properties of Identified Recycled Polymeric Fibers in This Study

Fiber Supplier/Property	GCP Advanced Technologies (Virgin PP Macrofiber)	Euclid Chemical (Micro)	Barchip Inc. (Macro)	Forta Concrete Fibers (Micro and Macro)
Source material	100% PP and PE blend	rPET from post-consumer PET bottles	rPP from melted PP bottles	Macro: a blend of virgin and rPP Micro: 100% rPP from PP waste
Fiber length	Macro: 1.55 in. (40 mm) Micro: 0.75 in. (19 mm)	0.25 in. (6 mm)	2 in. (48 mm)	Macro: 0.75-2.25 in. (19-54 mm) Micro: 0.75-2.25 in. (19-54 mm)
Aspect ratio	Macro: 90; Micro: Not available	Not available (Denier-2.25)	Not available	Not available
Fiber diameter	Macro: 0.017 in. (0.43 mm) Micro: Not available	Not available	Not available	Not available
Specific gravity	0.92	1.32	Not available	0.91
Ultimate tensile strength	Macro: 90 ksi (620 MPa) Micro: 42 ksi (290 MPa)	Not available	Not available	Macro: 83-96 ksi (570-660 MPa)
Advantage to concrete as per manufacturer	Macro: crack width control, drying shrinkage resistance Micro: reduce plastic shrinkage cracking	Prevents plastic shrinkage	Replacement to steel reinforcement, crack width control	Macro: increase post-crack toughness, impact resistance, and freeze-thaw durability Micro: reduce plastic shrinkage, drying shrinkage
Cost per pound (cost per kg) excluding shipping cost	$10 ($22)	$4-5 ($9-11)	$0.95 ($2)	Macro: $7-8 ($15-17.50) Micro: <$7 (<$15)

3.6 Performance of Polymeric Fibers in Concrete Based on Technical Literature

Both PP and PET fibers have been extensively tested in laboratory studies worldwide. Some studies have also evaluated PP and PET fibers in field applications as secondary reinforcement in slabs-on-ground applications or concrete pavements.

3.6.1 *Dispersion of Fibers in Concrete*

A uniform dispersion of fibers in concrete is essential for fiber performance and depends on the aspect ratio, material type, fiber dosage, concrete mixture, and mixing method *(80)*. PP macrofibers are often better dispersed in the matrix compared to steel fibers *(92)*. However, the dispersion of PP fibers in the matrix is not as good as nylon or PAN fibers *(89,93)*. According to one study, the dispersion of PP fibers is a function of the water-to-cementitious materials (w/cm) ratio of the concrete *(94)*. Also, fibers will likely agglomerate when used in amounts higher than the optimum fiber dosage *(95)*.

Some information regarding the method of mixing the fibers into concrete was found in the literature. One study used a three-axis mechanical force mixer to help disperse reticular PP fibers properly in laboratory mixes when applied at a dosage rate of 1.2 vol% in concrete *(96)*. Another study reported that it was difficult to completely disperse PE fibers in the cement matrix with conventional mixing procedures due to their hydrophobic surfaces *(97)*. In another study, it was found that rPET fibers were evenly dispersed in the concrete matrix using hand mixing and machine mixing *(*86*)*. In field applications, rPET fibers may be mechanically agitated and then combined with the concrete in the ready-mix truck *(80)*.

3.6.2 *Impact of Fibers on the Workability of Concrete*

Polypropylene fibers generally decrease the concrete slump when applied at dosages higher than 1 vol% *(20,89,90,98,99)*. The water demand of fibers has been known to be similar to fine aggregates in concrete, and water demand should also be accounted for in the mix design *(10)*. Superplasticizers added to the concrete can increase flowability loss from adding fibers *(88,99)*. The low slump of PP FRC is due to the development of a network structure *(100)* or a three-dimensional web in concrete *(101)*, which restrains the concrete mixture from flowing. In addition, PP fibers orient themselves parallel to the formwork wall surface and perpendicular to the flow direction, thus inhibiting the free flow of concrete *(25)*. Apart from this, a significant amount of mortar paste adheres to the surface of the fibers, reducing workability *(102)*.

Studies have shown that recycled HDPE and PET FRC had higher workability compared to PP FRC *(80,83)*. For rHDPE, a fiber dosage of 0.2 vol% resulted in a slump value of 3.5 in. (9 cm), compared to a slump value of 2 in. (5 cm) at the same fiber dosage for virgin PP FRC *(83)*. On the other hand, rPET FRC had a slump of 6 in. (16 cm) at 0.5 vol% dosage *(80)*. A moderate content of polyolefin fibers, 5 to 10 lb./yd^3 (3 to 6 kg/m^3) in concrete, did not significantly affect the concrete slump *(103)*.

3.6.3 *Impact of Fibers on Plastic and Drying Shrinkage of Concrete*

Polypropylene and PE fibers reduce early-age volume change and thereby reduce plastic shrinkage cracks in concrete *(83)*. The crack arrest is a result of the mechanical blocking action of the fibers *(99)*. Polypropylene microfibers have the ability to arrest microcracks and bridge capillary pores *(17,88,89,104,105,106)*.

In one study, hybrid PP fibers, containing monofilament and staple fibers, reduced the drying shrinkage of concrete by proper distribution throughout the mortar mix and around the coarse aggregate particles *(100)*. Another study tested PP FRC prisms for drying shrinkage. It was found that the fibrillated PP FRC had 40% less drying shrinkage at 28 days compared to the non-fiber-reinforced control mix when applied at a dosage rate of 0.1% to 0.15% volume fraction. This reduction in drying shrinkage was attributed to the better stability of the matrix by the fiber network *(99)*.

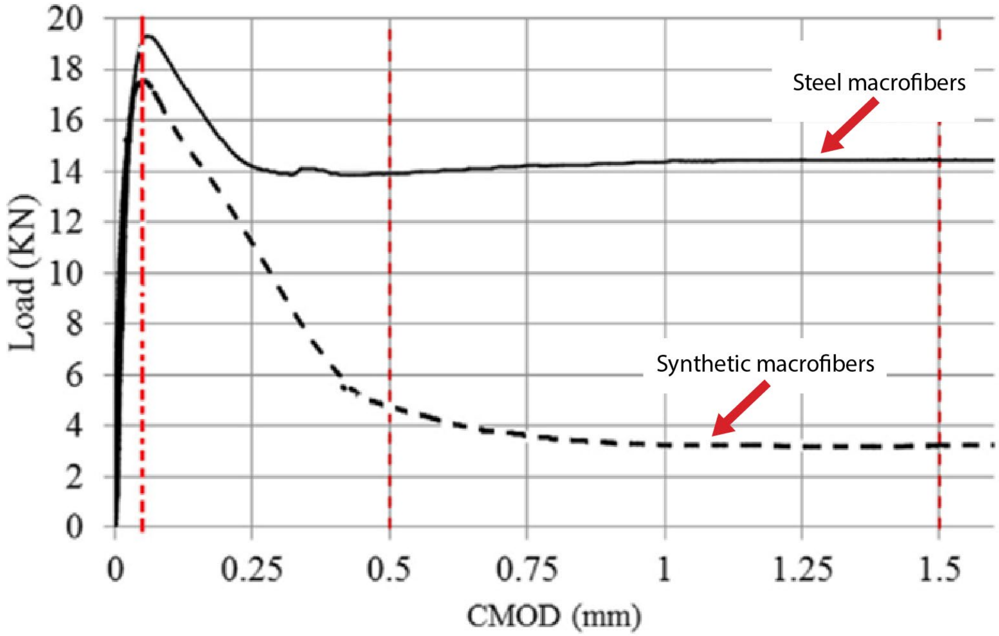
3.6.4 *Impact of Fibers on Strength and Toughness of Concrete*

The strength and toughness of FRC are affected by the test equipment and measurement devices used, test specimen dimensions, and fiber properties *(24)*. Adding PP fibers typically does not affect the compressive strength of concrete but can improve the tensile strength of concrete from 10% to 50% *(88,89,95,103,107,108)*. The improved tensile strength is because fibers help transfer tensile stresses by bridging across the split portion once the splitting occurs. A few studies indicated PP fibers contribute to both compressive and tensile strength *(98,100,109)*. However, these studies used hybrid fiber-matrix systems involving silica fume or some other pozzolanic materials, and the sole contribution of fibers to compressive strength is not isolated in these studies.

The first crack impact and impact failure resistance improved when PP fibers were added along with pozzolans in concrete *(88)*. The first crack impact resistance improved by 12%, and the impact failure resistance by 17% when plain concrete was reinforced with PP fibers at a dosage rate of 0.04 lb./ft^3 (0.6 kg/m^3) *(89)*.

3.6.5 *Impact of Fibers on Residual Strength or Post-Crack Strength of Concrete*

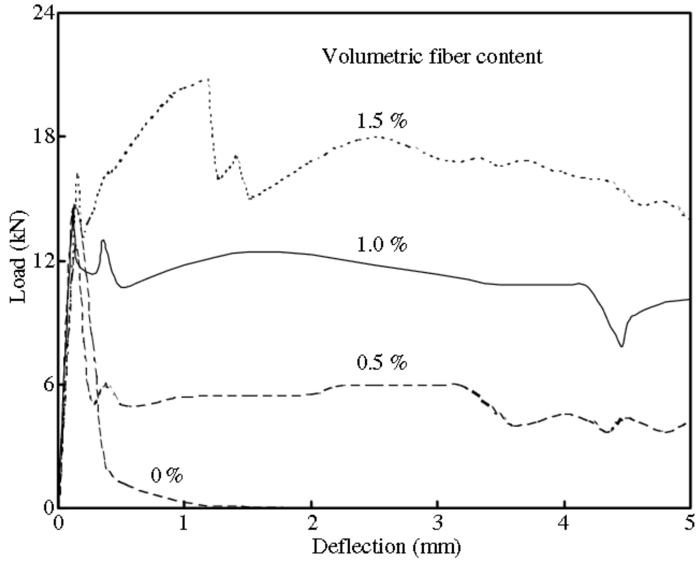
Residual strength refers to the strength of FRC after the initial cracking event *(21)*. In one study, the effects of adding 0.4 vol% of synthetic fibers to ground granulated blast-furnace slag concrete were investigated *(110)*. The findings showed that adding macro-PP fibers increased the post-crack toughness of the concrete. The study also examined the residual flexural strength of the concrete after cracking, which was measured by the crack mouth opening displacement (CMOD) ranging from 0.02 to 0.15 in. (0.5 mm to 3.5 mm). Figure 3.7 shows the load versus CMOD graph for FRC with steel fibers and FRC with synthetic PP macrofibers. The graph demonstrates that PP fibers provide some post-crack strength, which is low compared to steel fibers *(110)*. Similar results were obtained in another study, where macro-PP fibers provided some post-crack performance at 0.5 vol% fiber dosage in roller-compacted concrete *(102)*. At 0.04 in. (1 mm) CMOD, the fiber-reinforced roller-compacted concrete specimens were able to carry 112 lbf (500 N) load.



Source: Fuente-Alonso et al. (2017) *(110)*.

Figure 3.7: Load versus crack mouth opening displacement (CMOD) for fiber-reinforced concrete.

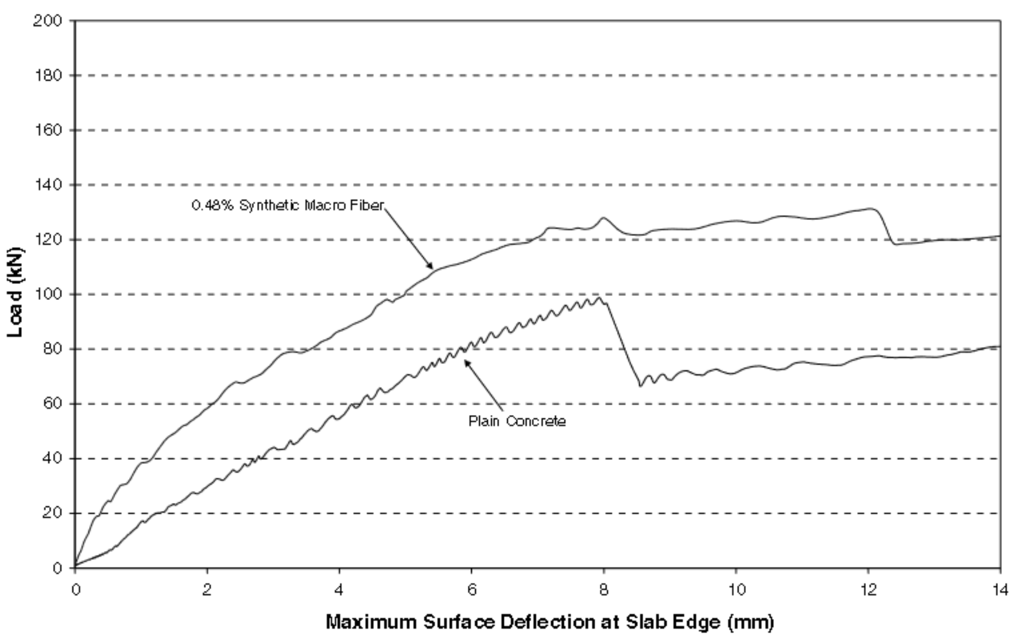
Recycled PET FRC increased flexural strength by approximately 30% compared to plain concrete when applied at a dosage rate of 1.5 vol% *(80)*. The load-deflection behavior of rPET FRC is shown in Figure 3.8, where the peak load for plain concrete occurs at about 0.012 in. (0.3 mm) deflection, after which a steep decline occurs in the load. However, as the fiber dosage increases, the deflection at which the peak load occurs also increases, and more load than plain concrete is carried post-peak. In addition, the post-crack load-carrying capacity is a function of the fiber dosage, and the 1.5 vol% shows a strain-hardening behavior.



Source: Ochi, Okubo, and Fukui (2007) *(80)*.

Figure 3.8: Load-deflection curve for rPET fiber-reinforced concrete.

Polypropylene macrofibers were used in previous studies *(111,112)* at 0.48 vol% for a concrete pavement slab under monotonous loading. Figure 3.9 shows that adding 0.48 vol% synthetic macro-PP fibers improves the flexural and ultimate cracking loads compared to the plain concrete by about 25 % to 70% *(112)*.



Source: Altoubat et al. (2008) *(112)*.

Figure 3.9: Load-deflection curve for center-loaded concrete slabs-on-ground.

These added enhancements from fibers were not accounted for in the previously available design guidelines for slabs-on-ground. So, this study adopted an effective strength approach to take into account the additional post-peak strength or residual strength of fibers in the design *(118)*. Based on extensive small- and large-scale laboratory testing, researchers proposed an equivalent flexural strength ratio ($R_{e,3}$) to quantify the increased flexural strength capacity of FRC pavements, shown in Equation 3.1. This method increases the flexural strength of FRC by some percentage and thereby accounts for the increased flexural resistance *(118)*.

$$F_{cr,fiber} = F_{cr,plain} \left(1 + \frac{R_{e,3}}{100}\right) \quad \textbf{(3.1)}$$

Where:

$F_{cr,fiber}$ = Cracking load of the fiber-reinforced slab

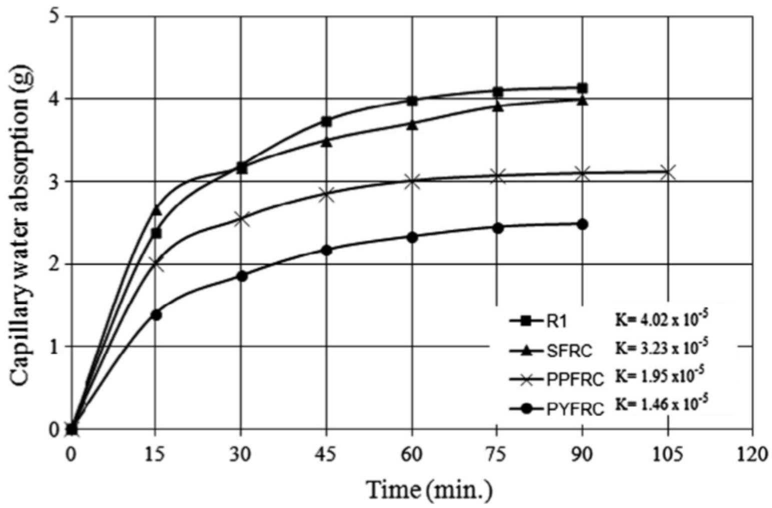
$F_{cr,plain}$ = Cracking load of plain concrete

$R_{e,3}$ = Flexural strength modification factor: the ratio of equivalent flexural strength to the modulus of rupture (MOR)

The equivalent flexural strength can be obtained by the ASTM C1609 test specifically developed for FRC. The numerical equation to calculate the equivalent flexural strength ratio was mentioned before in Equation 2.5.

3.6.6 *Impact of Fibers on the Durability of Concrete*

Recycled PP fibers have high resistance to alkali attacks. One study tested the durability of rPP fibers in different alkaline solutions for 28 days *(113)*. The tensile strength and modulus of elasticity of the rPP FRC did not change significantly before and after exposure to the alkaline solutions. Adding PE fibers at a dosage of 1.5 vol% increased the freeze-thaw durability of concrete by reducing the multiple crack development behavior *(97)*. Another study showed that polymeric fibers (PET and PP) could effectively reduce the water absorption of concrete when applied at a dosage rate of 4.25 vol%, shown in Figure 3.10 *(90)*.



Notes: R1 = reference concrete; SFRC = steel fiber-reinforced concrete; PPFRC = polypropylene fiber-reinforced concrete; PYFRC = polyester fiber-reinforced concrete.

Source: Bolat et al. (2014) *(90)*.

Figure 3.10: Capillary water absorption of concrete mixtures with different types of fibers.

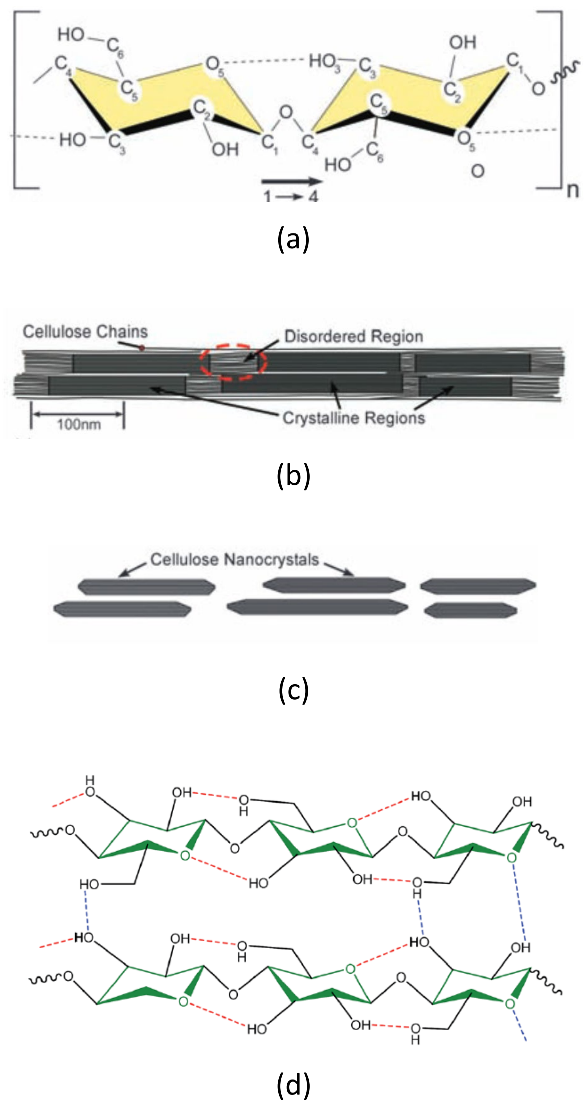
4 CELLULOSE FIBERS

4.1 Introduction

Cellulose is the most abundant natural polymer on Earth, with many advantages for replacing petroleum-derived polymers *(114)*. The most common use of cellulose is to produce products such as pulp, paper, board, and tissue *(115)*. Compared to steel, glass, and petroleum-based synthetic fibers, cellulose fibers are less studied and marketed for use in concrete.

4.2 Feedstock Description: Cellulose

Cellulose is a natural biopolymer formed by repeating glucose units *(116)*. The repeat unit has two anhydrous glucose rings covalently bonded through oxygen that share C1 of one glucose ring and C4 of the other ring *(117)* (Figure 4.1). Hydrogen bonding between rings stabilizes the linear structure of cellulose *(117)*. Cellulose has six different polymorphs. Cellulose I is a natural polymorph with two variants, Iα and Iβ. The two have a similar skeleton but different hydrogen bonding patterns. Cellulose Iα is a metastable phase with one chain, while Iβ has two chains in the monoclinic unit and can be derived from Iα. Cellulose units contain many hydroxyl groups, allowing hydrogen bonding between cellulose chains, which causes polymerization of cellulose chains and forms microfibrils.



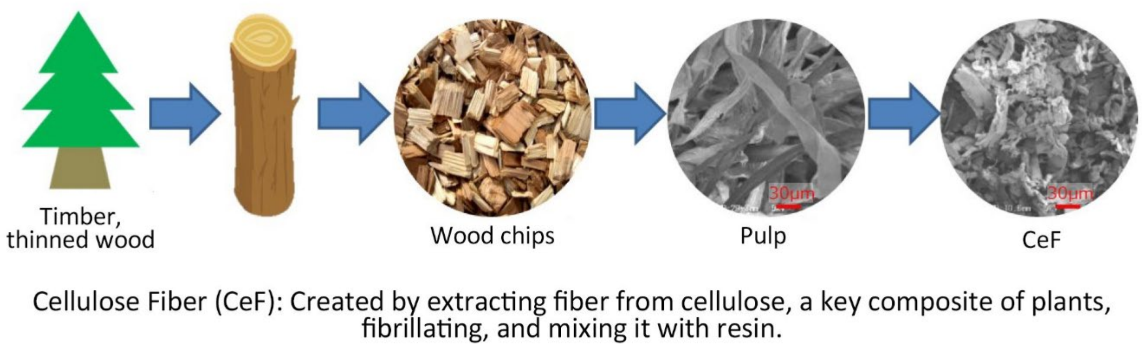
Source: Shaghaleh, Xu, and Wang (2018) *(116)*; Moon et al. (2011) *(117)*.

Figure 4.1: (a) Unit of cellulose chain (n=10000-15000), (b) cellulose microfibrils, (c) cellulose nanocrystals derived by acid hydrolysis, (d) intramolecular and intermolecular hydrogen bond in cellulose fiber.

Cellulose fibers can be derived from wood, nonwood plants, tunicates, algae, and bacteria. Cellulose fiber properties largely depend on the cellulose sources. Wood and plant sources are the most abundant and have established facilities for extraction for paper, textiles, and other industries.

4.3 Description of Recycling, Production, and Processing Method

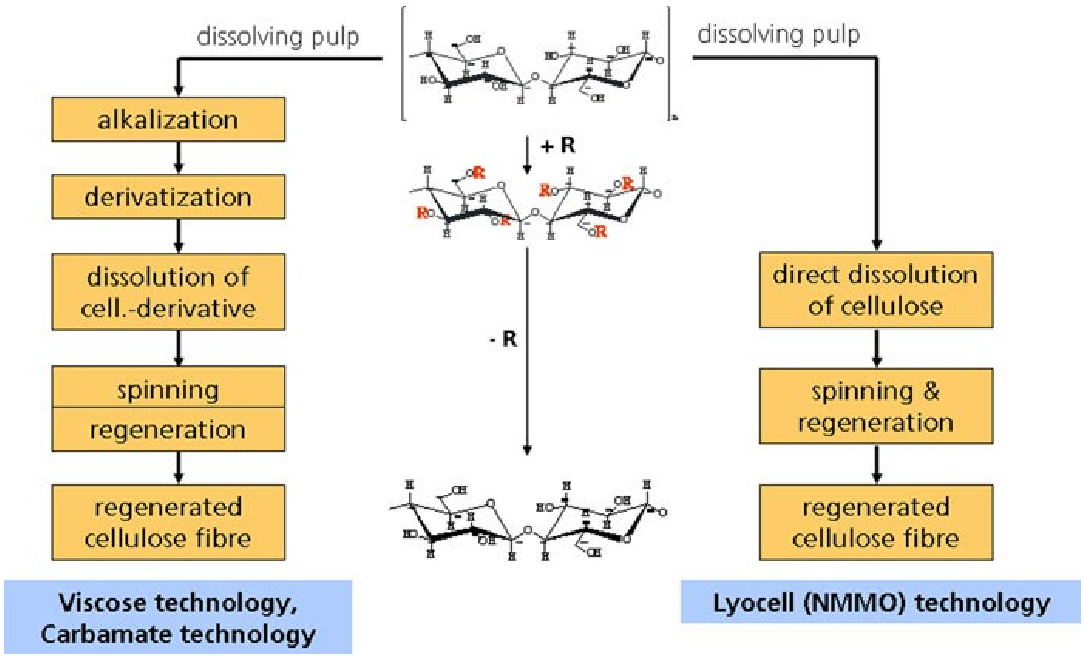
Cellulose fiber production from the raw materials (wood and nonwood sources, such as cereal straw, reeds, esparto grass, jute, flax, cotton, and sisal) includes preparation of the raw material to produce pulp, pulp production, and fiber extrusion from the pulp (Figure 4.2). For cellulose fibers from wood sources, trees are cut into logs, processed into wood chips, and sorted. Pulp is produced through the chemical, mechanical, or semichemical processes of separating fibers by removing lignin. The pulp is then washed and bleached, and fibers are produced from the pulp *(118)*.



Source: Panasonic Group (2020) *(119)*.

Figure 4.2: Production of cellulose fiber from woods.

Manufactured cellulose fibers are produced from dissolving grade pulp to remove lignin, resins, and a large amount of hemicellulose *(120)*. The chemical pulping process degrades other parts of the wood structure (hemicellulose) from the pulp to obtain the cellulose fibers. The dissolving pulp production can follow either the kraft or acid sulfite process. The kraft process is the most common chemical pulping method, where wood chips are treated with a hot mixture of water, sodium hydroxide, and sodium sulfide (also known as white liquor) that breaks the bonds linking the lignin, hemicellulose, and cellulose. The technology consists of several steps, both mechanical and chemical. In the acid sulfite process, lignin and hemicellulose are dissolved in sulfurous acid or bisulfites, removed from the wood pieces, and then dissolved in spent sulfite acid liquor. The resulting stock further goes through some purification steps (alkali extraction or bleaching) to produce dissolving pulps *(121)*. Figure 4.3 shows two production processes for manufacturing cellulose fibers from pulp *(122)*.



Source: Fink, Ganster, and Lehmann (2014) *(122)*.

Figure 4.3: Cellulose fiber production technology.

Several factors—such as resource efficiency, byproduct management, high demand for wood, scarcity in some regions, and deforestation—require using residues from wood processes, such as sawmill residues, for pulp production. Sawmill residue can be in the form of chips, sawdust, cross-cut ends, edgings, and trimmings *(123)*. Other sources of cellulose fibers are agricultural residues. For example, one study successfully produced cellulose fiber from agro-industrial residues of corn, grape, pomegranate, strawberry-tree fruit, and fava *(124)*.

In a few cellulose fiber-reinforced cement and concrete studies, cellulose fibers were produced at the laboratory scale for cementitious materials. For instance, researchers used two processes (a semichemical process and a chemical process using NaOH and ethanolamine at different temperatures and times) to produce cellulose fibers *(125)*. First, they used hemp core fiber to obtain hemp pulp. The chemical process was performed in a heat exchanger under a controlled pressure system (5 to 7 bars). The liquid-to-solid content was 6:1, and two different cooking conditions were used (180°C temperature, 90 minutes pulping time, and 155°C temperature, 30 minutes pulping time). Next, the core fiber was processed in a NaOH solution with a catalyst for the semichemical process. The process conditions were 180°C, 90 minutes pulping time, and

155°C, 30 minutes pulping time. Next, the resultant pulp was defibered using a hydra pulper, and a vibratory screen with a 0.006 in (0.15 mm) slot size was used to screen the pulps. Afterward, the screened pulp was washed, pressed, crumbled, and stored at 4°C *(125)*. Another study used the mechanical high-pressure steam technique to produce cellulose fibers from rice straw *(126)*. In this process, the rice straw was cut into 4 to 5 cm lengths after drying at 60°C for 16 hours, and it was then passed through the 0.031 in (0.8 mm) screen. The resulting powder was ground in a ball mill for 4 hours and soaked in water for 24 hours. Next, steam at 160°C and 2 bar was applied at a water-to-rice straw ratio of 50:1 for different treatment periods (9, 18, 27, 36, 45, and 54 hours). Finally, the resulting stream solution was filtered, washed, distilled with water and ethanol, and dried for 16 hours at 60°C.

4.4 Physical and Chemical Properties of Cellulose Fibers

Cellulose microfibrils have crystalline and amorphous regions; the crystalline phase is highly ordered, whereas the amorphous region has no definitive shape or form *(127)*. High crystallinity gives cellulose high strength, stiffness, durability, and biocompatibility. In addition, the presence of the hydroxyl group makes cellulose hydrophilic, biodegradable, highly reactive, and chemically modifiable to hold the desired functional groups for dispersibility in cement systems *(116)*. The production process of fibers from the raw materials affects the properties, especially the surface chemistry of the fibers. The chemical process yields shorter and less coarse fibers than the semichemical process. The semichemical process using NaOH removes amorphous constituents (e.g., hemicellulose, pectic). However, the chemical process is more effective for lignin, hemicellulose, and pectin removal, even at lower conditions (temperature, time, and concentration of chemicals). Table 4.1 shows the effect of different cooking processes on the properties of the pulp produced from hemp core. P1 was produced from the cooking condition of 180°C, 90 minutes, and 25% NaOH, and P2 was produced at 140°C, 30 minutes, and 15% NaOH. Pulp P3 and P4 were produced using the organosolv process with conditioning of 180°C, 90 minutes, and 60% ethanolamine and 155°C, 30 minutes, and 40% ethanolamine, respectively.

Table 4.1: Morphological Characterization of Pulp Produced Using Different Processes

Process	Semichemical		Organosolv		Kraft
Process	P1	P2	P3	P4	P5
Number of fibers (10^6/g)	32	61.2	45.2	28.5	10.8
Arithmetic length (um)	356	389	345	352	456
Average width	19.2	29	24	27.3	25.5
Coarseness (mg/m)	0.08	0.4	0.06	0.10	0.18
Microfibrils (%)	1.38	1.66	1.68	1.48	1.62
Fines number	13,149	30,470	8,947	15,474	49,192

Source: Jarabo et al. (2012) *(128)*.

Polymerization and the amount of cellulose and lignin greatly influence the setting time and strength gain. Protective measures (waterproofing and chemical treatment of fibers) can be applied. However, their effectiveness for the desired performance due to these treatments needs to be carefully considered.

Mechanical high-pressure steam treatment was applied to rice straw in another study *(129)*. This method can partially remove hemicellulose and lignin and increase the cellulose content. The crystallinity is increased, and the fiber is expected to have better stability and strength than the untreated rice straw fiber. The cellulose content or the reduction of hemicellulose and lignin depends on the treatment time. With increasing treatment time, the hemicellulose and lignin removal increases. The treatment process increases the surface area of the fibers, which makes polysaccharides more receptive to hydrolysis *(130)*.

The source material also impacts the properties of the fibers. Besides wood, natural fibers can be produced from other plant-based sources. The major properties of several natural fibers compared to wood fibers from kraft pulp are shown in Table 4.2, according to ACI 544-1R-96 *(4)*.

Table 4.2: Properties of Natural Fibers (ACI 544-1R-96)

Fiber Type/Property	Wood Fiber (kraft pulp)	Sisal	Coconut	Bamboo	Jute	Hemp
Fiber length, mm	2.54-5.1	N/A	51-102	N/A	178-305	0.345-0.389
Fiber diameter, mm	0.025-0.076	N/A	0.10-0.41	0.05-0.41	0.10-0.20	0.02-0.03
Specific gravity	1.5	N/A	1.12-1.15	1.5	1.02-1.04	
Modulus of elasticity, GPa	N/A	13-26	19-26	33-40	26-32	60
Tensile strength, MPa	700	276-568	120-200	350-500	250-350	750
Elongation at peak, %	N/A	3-5	10-25	N/A	1.5-1.9	N/A
Water absorption, %	50-75	60-70	130-180	40-45	N/A	N/A

Source: Buch, Rehman, and Hiller (1999) *(131)*.

Hemp was also used as the feedstock for cellulose fibers, and it was shown to reduce some of the shortcomings, including low modulus of elasticity, high moisture absorption, susceptibility to alkali, and biological attack of fibers from pine *(128)*. Hemp fibers have high strength, low density, and durability and are biodegradable and environmentally friendly.

One study compared cellulose fibers' properties with polypropylene and nylon, shown in Table 4.3. The comparison revealed that cellulose fibers have favorable properties in terms of size, morphology, bonding, elastic modulus, and durability for use in cement-based systems. On the other hand, they have some disadvantages, including variability of sources, low elastic modulus compared to steel fibers, low alkaline resistance of untreated fibers, higher water absorption, and compatibility in composite matrices. At an earlier stage of cement hydration, natural fibers can provide cohesion and reduce plastic and drying shrinkage. However, over time, fibers will lose their application as a reinforcing element due to chemical degradation *(132)*.

Table 4.3: Comparison of Cellulose, Polypropylene, and Nylon Fibers

Property	Preferred	Cellulose	Polypropylene	Nylon
Elastic modulus, GPa	High	60	4	4
Bond strength, MPa	High	1.5	0.4	N/A
Tensile strength, MPa	High	500	600	700
Effective diamater, mm	Low	0.015	0.1	0.05
# of fibers/g	High	2,000,000	12,000	45,000
L/D ratio	High	200	120	200
Surface characteristics	Hydrophilic	Hydrophilic	Hydrophobic	Hydrophilic
Density, g/cc	Medium	1.5	0.9	1.1
Alkali resistance	High	High	High	High
Fiber spacing, mm	Low	0.53	2.8	1.7
Fiber count, l/cc	High	90	0.6	3.3
Specific surface	High	0.13	0.033	0.052

Source: Buch, Rehman, and Hiller (1999) *(131)*.

As mentioned previously, natural fibers, depending on the processing level, could contain hemicellulose, lignin, starch, and sugar, which can retard setting and strength development in the cement system. The chemical composition of natural fibers (cellulose, hemicellulose, and lignin) highly affects the mechanical properties of the fiber *(129)*. Water solubility and absorption cause strength reduction and reduced durability, which may worsen in the alkaline conditions of the cement composites. Cement alkaline conditions can cause embrittlement of sisal fiber within months in cement composites in tropical weather *(132)*. However, natural fibers were found to be intact in a carbonated environment.

4.5 Identified Suppliers of Cellulose Fibers for Concrete Applications

Cellulose fiber suppliers that produce fibers engineered explicitly for concrete at large scale were identified and interviewed. The gathered information is summarized and discussed in the following sections.

4.5.1 *Kraft Pulp Fibers by International Paper*

International Paper Global Cellulose Fiber has two cellulose fiber products suitable for cement/concrete use: Matrix Performance and Matrix Impact (Figure 4.4:). Matrix Performance is suitable for fiber cement and calcium-silicate boards. It is used in fiber cement boards for building sidings up to 16 ft. (4.87 m) in length and in calcium-silicate boards for house siding. It reduces autogenous shrinkage, and the fibers in the cement mix help capture particles and add temporary reinforcement, strength, and toughness. These fibers are short-lived and used to prevent autogenous shrinkage. For long-term reinforcement, steel rebar is used in the cement board.

Matrix Impact is marketed for concrete applications. The fiber length is 0.12 in. (3 mm), and the aspect ratio is 100:1; these fibers are treated to be alkali resistant. Matrix Impact is used for shrinkage reduction in concrete. Matrix Impact fibers reduce plastic shrinkage in plain and reinforced concrete and reduce drying shrinkage and cracking in plain concrete. Each gram contains millions of fibers, and they have a good affinity for cement. This fiber has good pullout strength and does not break during the pullout. The producers make the fiber with the right sugar level, not delaying the setting time. The suggested mix dose is 0.1% by mass of the mix.

The feedstock for these fibers is southern softwood bleached kraft pulp, and the factory is based in Georgia. International Paper has a production capacity of millions of tons annually. The density of the pulp is 33.71 lb./ft^3 (0.54 g/cm^3), and it has a moisture content of 9.2%. These fibers are alkali resistant, but the process of making them alkali resistant is a trade secret. Fibers are usually produced in the form of sheets to be transported. However, the producers stated they are well dispersed when mixed with cementitious materials.

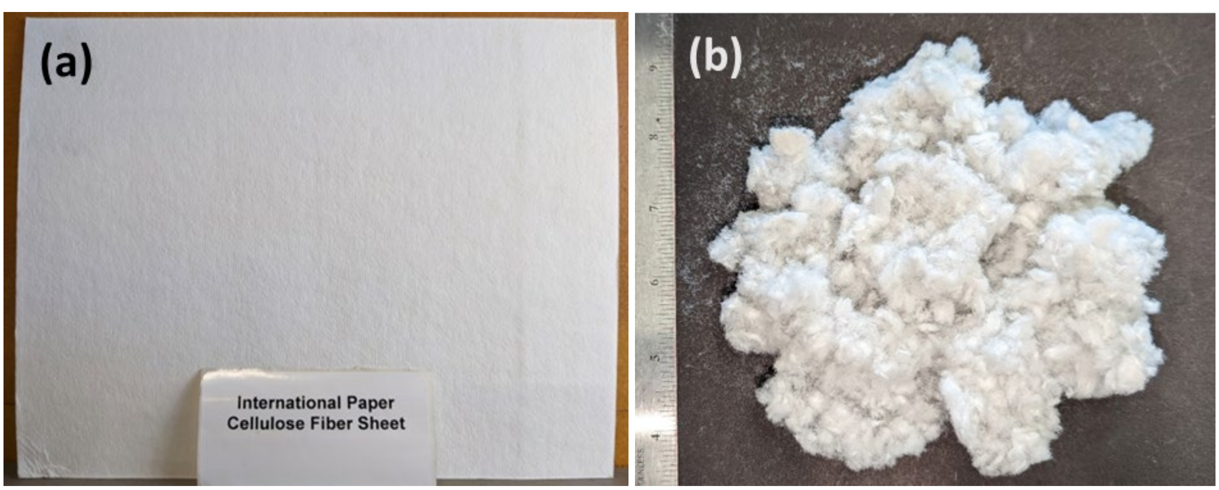


Figure 4.4: Matrix Impact (a) as-received fiber sheet and (b) after mixing in a blender for 30 seconds.

4.5.2 *CreaFill Fibers Corporation (Chestertown, Maryland)*

CreaFill Fibers Corporation has been producing cellulose fibers for more than 30 years, with two different cellulose fiber products shown in Figure 4.5. One is the virgin fiber product CreaTech, and the other is a recycled fiber product sourced from wastepaper, branded as CreaMix.

CreaMix is a gray-colored fiber with a cellulose content of more than 75%. The loose density of the fiber is 2.8 to 4.36 lb./ft^3 (0.045 to 0.075 g/cm^3). The product has a moisture content of less than 6%, and 90% of the fibers are less than 0.031 in. (800 µm) in length. The average length of the fiber is 0.022 in. (560 µm), and the diameter is 20 µm.

CreaTech is white with more than 99.6% cellulose content and low ash content (<0.4%). The loose fiber density is 2.49 lb./ft^3 (0.040 g/cc), and 98% of the fibers are less than 0.008 in. (200 µm). The average length is 0.006 in. (155 µm), and the diameter is 0.0008 in. (20 µm). The fibers are not compressed for better dispersion, and they are nonabrasive. The suggested dosage in concrete is 0.3% to 10% by weight.

CreaMix and CreaTech cellulose fibers are hydrophilic. Therefore, they hold water and support the hydration of the cement by releasing water. In addition, the fibers are beneficial in cracking and shrinkage control.

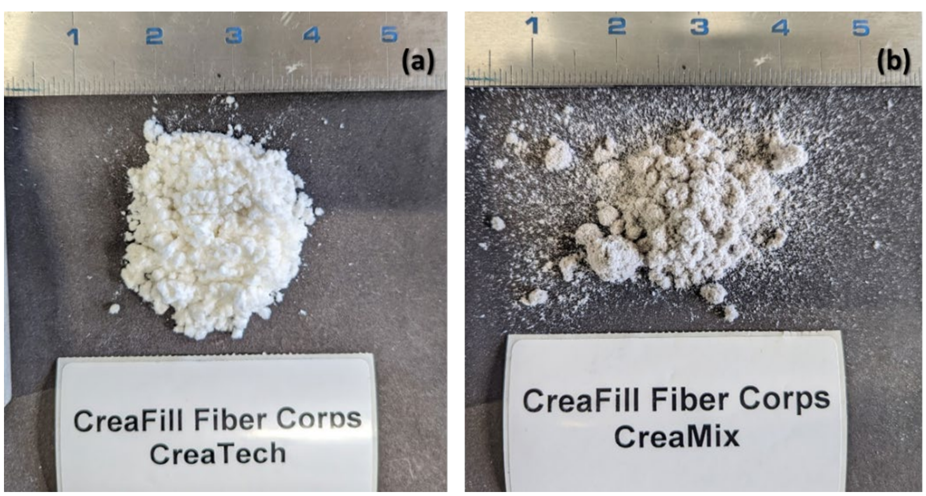


Figure 4.5: CreaFill cellulose fiber products: (a) CreaTech, virgin cellulose fiber (b) CreaMix, recycled cellulose fibers.

4.5.3 *Solomon Colors Inc. (Rialto, California)*

Solomon Colors produces cellulose fiber used as reinforcement in the concrete industry. The fiber feedstock is sourced from forest materials, specifically from pine trees. The fiber product for concrete use is marketed with the brand name UltraFiber 500 (Figure 4.6). The product is suitable for different uses, including commercial and industrial slabs, composite metal decks, paving, pervious paving, curb and gutter, slip form, architectural and decorative uses, shotcrete, wall, and white topping applications. The fiber is alkali resistant, and it has an average length of 0.083 in. (2.1 mm) and a diameter of 0.0007 in. (18 µm). The apparent density of the fiber is 68.67 lb./ft^3 (1.1 g/cc), and the surface area is 12,206 ft^2/lb. (25,000 cm^2/g). It has a higher fiber count of 770 million/lb. and better tensile strength (90 to 130 ksi [620 to 896 MPa]) compared to polypropylene fibers (30 to 70 ksi [207 to 483 MPa]). The UltraFiber 500 can absorb more than 85% of its weight in water, and due to this hydrophilic nature, it can create good bonding and compatibility with cementitious materials. This fiber can reduce fiber clumping and balling and shows good dispersibility in the cementitious matrix, thus providing good finishing. The fiber provides better compressive strength in concrete than synthetic PP fiber and reduces plastic shrinkage and temperature cracking by 80%.

Figure 4.6: Solomon Colors cellulose fiber UltraFiber 500.

4.5.4 *J. Rettenmaier USA LP (Schoolcraft, Michigan)*

J. Rettenmaier USA LP produces ROAD-CEL cellulose fibers suitable for road construction (Figure 4.7). The company has two manufacturing facilities for cellulose fibers in the United States. According to the manufacturer, the fiber is environmentally safe and manufactured using uncirculated, recycled material. The cellulose fiber product is a stabilizing and functional addition to road construction. It provides internal curing, reduced noise and rutting resistance, and superior functioning in low temperatures *(133)*.

Source: J. Rettenmaier USA LP *(133)*.

Figure 4.7: ROAD-CEL cellulose fiber produced by J. Rettenmaier USA LP.

4.5.5 *FibreZone India (Gujarat, India)*

The cellulose fiber product from FibreZone India has a minimum of 75% cellulose in its raw material base, with an ash content of 3% to 7%. The fibers are gray-colored and suitable for use in various building and industrial applications. The loose density of the fiber is 1748 lb./ft^3 (28 g/l). The fiber is thixotropic and can be used for cracking, shrinkage, and setting control. The fiber is acid and alkali resistant. The recommended dose of fiber is 0.3% to 10% by weight *(134)*.

4.5.6 *Summary of Findings from Cellulose Fiber Suppliers*

A summary of the properties of the identified commercially available cellulose fibers for concrete applications is provided in Table 4.4. The table outlines information about the four identified fiber suppliers: International Paper, CreaFill Fibers Corporation, Solomon Colors Inc., J. Rettenmaier USA LP, and FibreZone India. They use different source materials, including pinewood, wood from

Maryland, paper waste, and recycled materials. Fiber lengths range from 0.56 to 3 mm, with fiber diameters from 0.018 to 0.03 mm and densities from 0.060 to 1.1 g/cc. Ultimate tensile strength data are not available for all suppliers. Manufacturers claim benefits such as plastic shrinkage control, cracking reduction, internal curing, improved finishing of concrete, and reduced noise.

Table 4.4: Summary of Properties of Kraft Pulp Fibers from Identified Suppliers

Fiber Supplier/Property	International Paper	CreaFill Fibers Corporation	Solomon Colors Inc.	J. Rettenmaier USA LP	FibreZone India
Source material	Pinewood	Wood from Maryland and paper waste	Pinewood	Recycled materials	N/A
Fiber length, mm	2.9-3	0.56	2.1	N/A	N/A
Fiber diameter, mm	0.03	0.020	0.018	N/A	N/A
Density, g/cc	0.54	0.060-0.083	1.1	N/A	0.028
Ultimate tensile strength, MPa	N/A	N/A	620-896	N/A	N/A
Advantage for concrete	Plastic shrinkage control	Cracking reduction and internal curing	Secondary reinforcement improves finishing of concrete	Internal curing, reduced noise	Craking, shrinkage and setting control

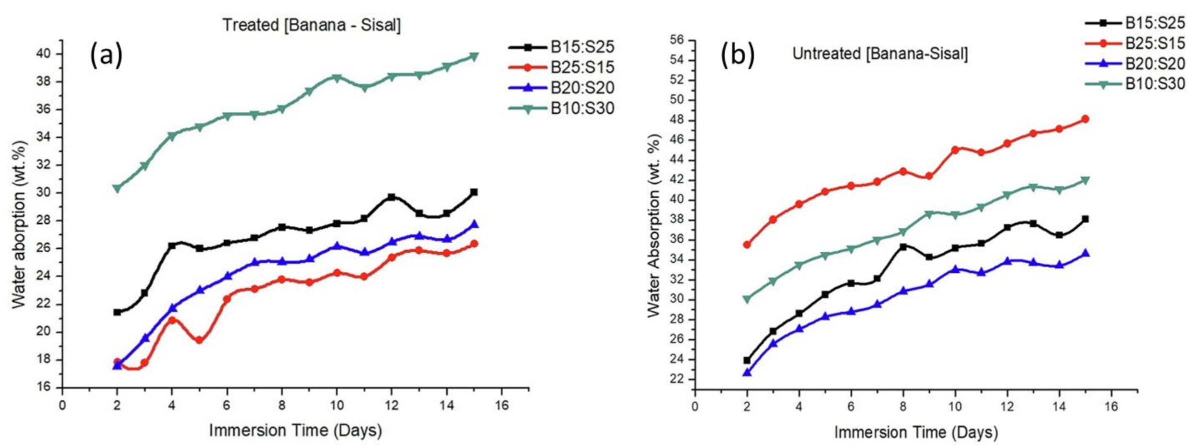
4.6 Performance of Cellulose Fibers in Concrete Based on Technical Literature

4.6.1 *Dispersion*

Uniform dispersion of cellulose fibers is crucial for the desired performance of FRC materials. One study used cellulose fibers in the cement paste, mortar, and concrete at 1 wt% of cement. Fibers were added to the water first and mixed for 10 to 20 minutes in a planetary mixer to aid in dispersion. For paste and mortar samples, clumps were found in some mixes, which means fibers were not completely breaking during the mixing process. However, for concrete samples, clumps were not visible *(135)*. In another study, no dispersion issues were noted with cellulose fibers using regular mixing operations in planetary mixers. The conclusion was that fiber dispersion is not dependent on the cement’s rheological properties and yield stress at 0.5 wt% in cement paste and mortar *(136)*.

4.6.2 *Fresh Properties, Setting Time, and Rheology*

Fibers affect the fresh-state properties of the concrete. The influence on the fresh properties—workability, setting time, and rheology—depends on the fiber type, surface chemistry, size, and shape characteristics. Cellulose fibers are hydrophilic and absorb water as high as 85% of their weight *(137)*. Figure 4.8 shows water absorption by treated and untreated banana and sisal fibers over time. Within 15 days, the absorbance increased by 8% to 10% for treated banana-sisal fibers (Figure 4.8a) and 12% to 14% for untreated banana-sisal fibers (Figure 4.8b). Additionally, the desorption rate of the natural fibers is slow, which means that when the fiber comes into contact with water, it absorbs available water for cement particles from the mix and affects the workability of the cementitious composites *(138)*. Hence, during the mixing process, the fibers can absorb water that might otherwise be available to the cement, reducing the workability of the cement mix.

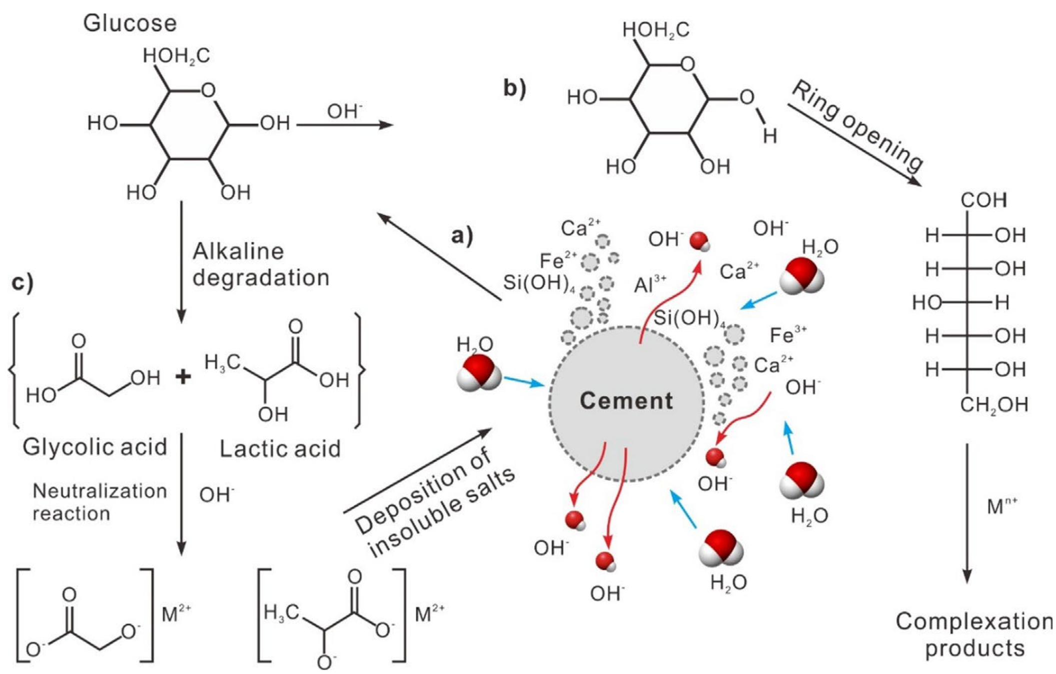


Note: The datasets show different dose (10-30 wt%) combinations of banana (B) and sisal (S) fibers.
Source: Badyankal et al. (2021) *(139)*.

Figure 4.8: Water absorption of cellulosic fiber: (a) treated banana-sisal fibers and (b) untreated banana-sisal fibers composites over time.

Cellulose fibers reduced slump by 53% due to their hydrophilic nature, which absorbed water during the mixing process, reducing the workability of the mix *(140)*. Another study also reported a decreased concrete slump with cellulose fibers. This decrease was attributed to the water retention capacity of the cellulose fiber. Moreover, a portion of the cement paste is involved in the coating of the fiber surface *(131)*.

Glucose in cellulose fibers may retard the early hydration reactions of the cement. One study examined the effect of jute and hemp fibers on the setting time of cement composites *(129)*. It found that increasing doses of jute and hemp cellulose fibers increased the initial and final setting times of cementitious composites. The doses of hemp and jute fibers used were 0.25%, 0.5%, 1%, and 2% of cement mass. The initial and final setting times were delayed by 9.16 and 13.35 hours, respectively, with 2% hemp fiber. For 0.25% hemp fiber, the delay in initial and final setting times were 0.48 and 1.14 hours, respectively. For jute fiber, the delay in initial and final setting times was 1.88 and 2.77 hours, respectively. The hydroxyl group in glucose reacts with clinkers in two different ways: alkali degradation and ring opening. The alkaline deposition process produces insoluble salts after some chemical reactions and deposits on cement particles. Similarly, the ring-opening process produces insoluble metal complexes after the reaction between OH^- and metal ions, which deposit on cement particles and impede the hydration reaction, shown in Figure 4.9 *(129)*.

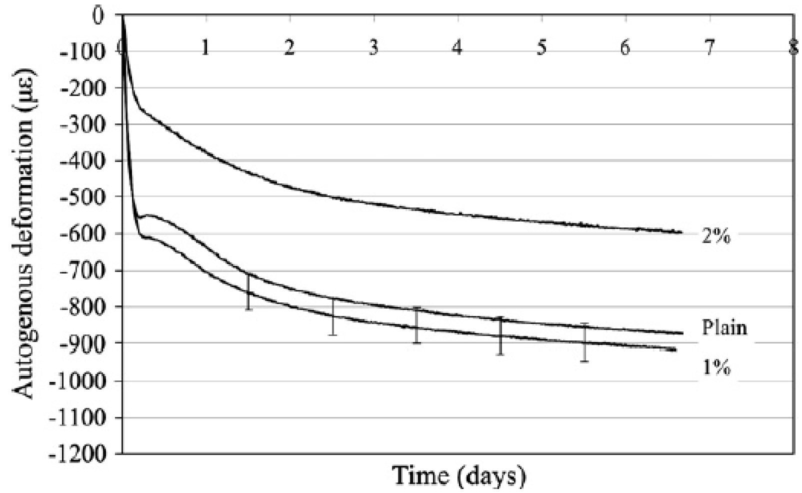


Source: Choi and Choi (2021) *(129)*.

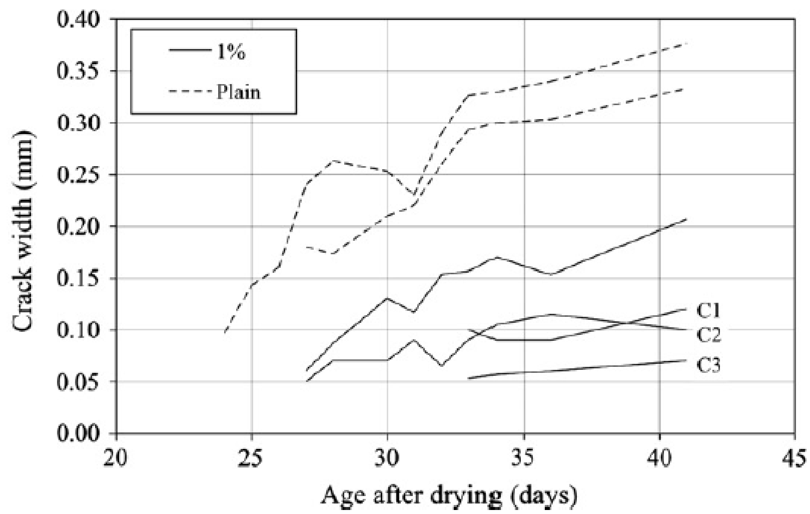
Figure 4.9: Effect of glucose (polysaccharide) on setting time delay.

4.6.3 *Early-Age Shrinkage and Drying Shrinkage*

Fiber reinforcement has shown a positive effect on the shrinkage reduction of concrete. One of the major benefits of using cellulose fibers is internal curing because of their water retention capacity. Most cellulose fiber manufacturers assert that their fiber products are effective in shrinkage cracking. One study evaluated the performance of cellulose fiber on plastic shrinkage and drying shrinkage of concrete. Cellulose fibers reduced the crack area under restrained shrinkage by 44% compared to the control. The first crack in the control specimen appeared on the tenth day after casting, whereas cracks were not visible until 14 days for the cellulose FRC specimen. Cellulose FRC had 28% less plastic shrinkage, and the maximum crack width was reduced to 0.004 in. (0.1 mm) compared to 0.012 in. (0.3 mm) for the control *(131)*. Another study reported a statistically significant decrease in plastic shrinkage with specialty cellulose fibers. The researchers achieved a 78% and 40% reduction in plastic shrinkage with 0.21 wt% and 0.18 wt% (1.5 lb./yd^3 or 0.9 kg/m^3), respectively, of cellulose fibers in plain and ultra-high-performance concrete. A study reported a decrease in autogenous shrinkage with a 2 wt% dose compared to plain mortar *(135)*. However, 1 wt% dose could not produce better autogenous shrinkage reduction compared to the control mortar, which was attributed to the clumping of fibers. Even though clumping happened at 2 wt%, higher internal curing was possible with higher doses. The same study reported about a 57% reduction in crack width under restrained drying shrinkage for mortar and 84% for concrete, shown in Figure 4.10. The researchers also reported a significant reduction in crack width with cellulose fibers and concluded that an optimum fiber volume is present for the best performance above, while adding more fibers does not provide additional benefits *(136)*.



(a)



(b)

Note: C1, C2. and C3 denote multiple cracks in the ring.

Source: Kawashima and Shah (2011) *(135)*.

Figure 4.10: (a) Autogenous deformation of mortar specimens with and without cellulose fibers, (b) crack widths under drying conditions with and without cellulose fibers for concrete specimens.

4.6.4 *Impact of Cellulose Fibers on Strength and Toughness of Concrete*

Cellulose fibers have high tensile strength and elastic modulus and contain many fibers per unit volume *(141)*. Cellulose fibers contain highly crystalline regions, which may also benefit the strength properties of the cellulose fiber-reinforced cementitious systems. Cellulose fibers are also compatible with the cementitious system due to their hydrophilic and good bonding characteristics in the cement matrix *(137)*.

One study reported a 10% increase in compressive strength with 0.15 vol% cellulose fibers, shown in Figure 4.12(a) *(131)*. Another study also found a positive effect of cellulose fiber on compressive strength, while polyvinyl alcohol (PVA) fiber had a negative impact, and polyolefin fiber did not show any significant effects *(142)*. A study used different types of cellulosic fibers with up to 3 vol% of doses with 0.5% intervals *(143)*. All fibers showed higher compressive strength compared to the control concrete, with a maximum increase of 20.2% at 0.5 vol% of fibers (Figure 4.11). The increasing trends were seen up to 2 vol% doses, which decreased afterward. The trend for compressive strength was jute > sisal > coconut > sugarcane for all doses tested. The increase in the compressive strength was attributed to the mixture composition, and a further increase in fiber doses beyond optimum content caused voids and irregularities in the concrete, reducing compressive strength. The difference in the performance with different types of cellulose fiber was due to their mechanical strength. Jute (69.6 ksi [480 MPa]) and sisal fibers (55.26 ksi [381 MPa]) have higher tensile strength than coconut (25.38 ksi [175 MPa]) and sugarcane (9.86 ksi [68 MPa]), and hence show better compressive strengths.

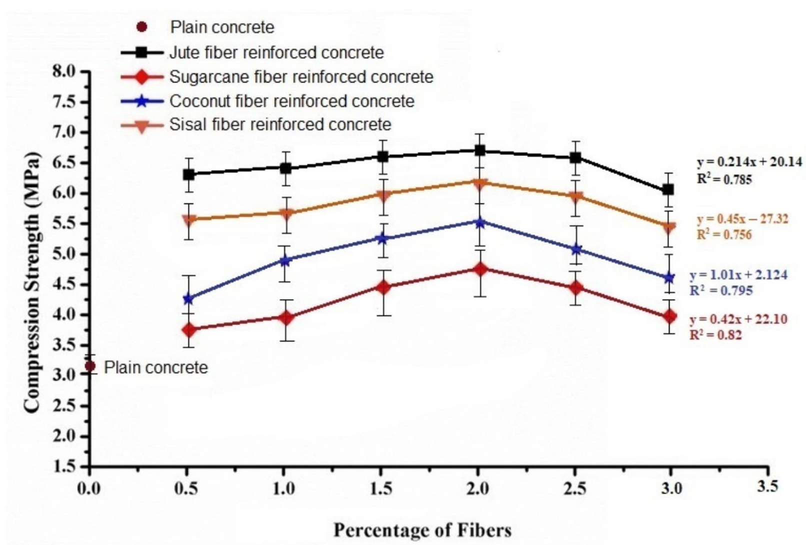
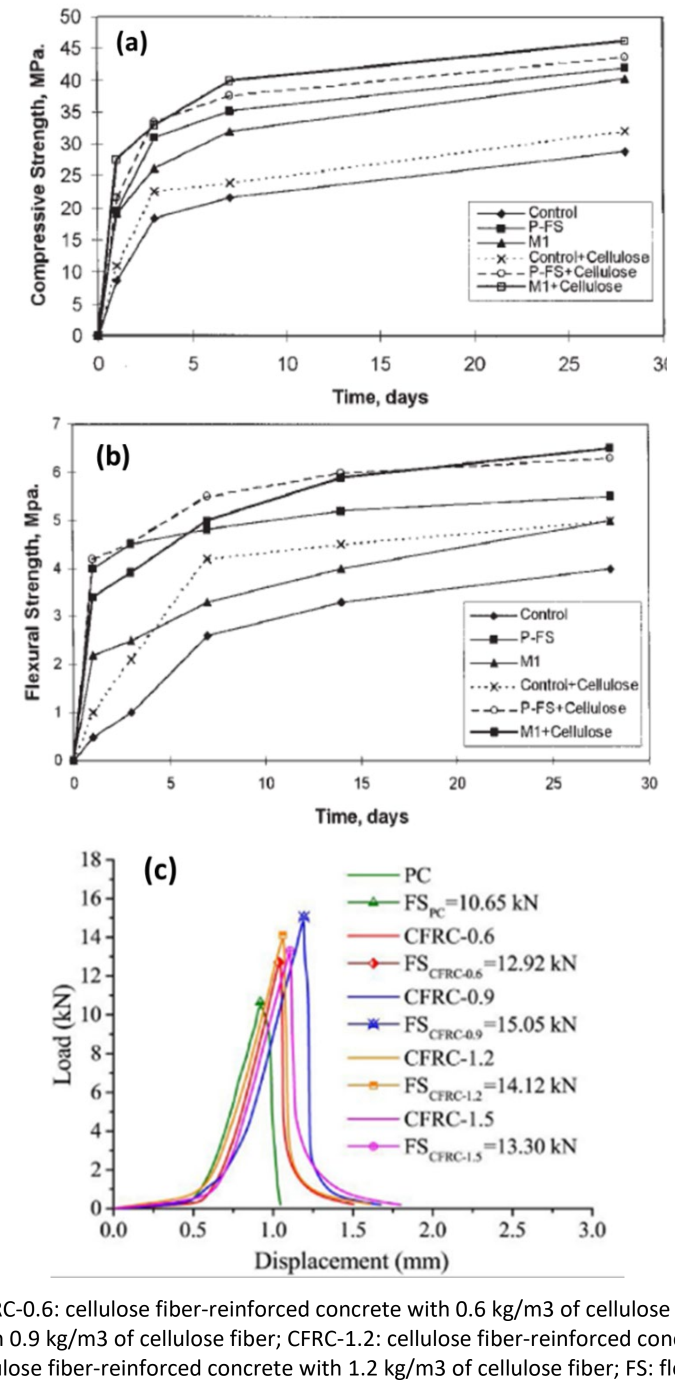


Figure 4.11: Compressive strength of different cellulose fiber-reinforced concrete.

The production process may have an influential impact on the strength activity of cellulose fiber-reinforced concrete. One study examined the effect of the cellulose fiber production process and found that the hemp fibers produced from the chemical process showed the best mechanical performance in terms of flexural strength, modulus of elasticity, and specific energy and closely matched with the reference cement slurry, which was made of pine kraft fiber *(125)*. Pine kraft fiber was the refined fiber that contained more microfibrils and degraded surface than hemp fibers, which resulted in better fiber-matrix interaction. The conclusion was that production methods and the resulting morphology of fibers greatly influence the performance of the hemp fibers in the composites. Another study used different doses (1.01 [0.6], 1.52 [0.9], 2.02 [1.2], and 2.52 [1.5] lb./yd^3 [kg/m^3] of concrete) of cellulose fibers in concrete and compared them with a control mixture. The compressive strength increased until 1.52 lb./yd^3 (0.9 kg/m^3) dose by a maximum of 18.5%, then decreased with higher doses of cellulose fibers. Therefore, for maximum mechanical performance based on compressive strength, the optimum dose was 0.056 lb./ft^3 (0.9 kg/m^3). The increase in compressive strength was attributed to the internal curing functionality of the fibers, as cellulose fibers can hold water and provide water during cement hydration. The decrease at higher doses was due to the mineralization of fibers, voids created by excessive fibers, and inadequate workability of the fresh mix.

Another study reported a 37% decrease in compressive strength at 14 days and 26% at 28 days, at 0.5 vol% of fiber, with cellulose fiber inclusion, which was attributed to the reduced workability of the mix. At 28 days, the decrease was less than 14 days because the cellulose fiber worked as an internal curing agent by releasing water at later ages *(140)*. One study of cellulose fibers showed the same effect on the split tensile strength of concrete as compressive strength *(142)*. The maximum improvement for jute, sisal, coconut, and sugarcane fibers in another study was 137%, 104%, 74%, and 34%, respectively, for 2 wt% fiber doses *(*150*)*. Flexural strength also showed improvement with the incorporation of cellulosic fibers. For flexural strength, the greatest improvement of 72% was found at a 1.5 wt% dose. At doses greater than 1.5 wt%, flexural strength decreased; however, flexural strengths were higher than the control at all doses *(143)*. Figure 4.12(b) from another study reported a 25% increase in flexural strength with cellulose fibers compared to the plain concrete *(131)*.

A study reported an increase of 32% in splitting tensile strength and 41% in flexural strength with 1.5 lb./yd^3 (0.9 kg/m^3) of cellulose fibers, shown in Figure 4.12 (c) *(144)*. Cellulose fiber, due to its good bonding with the cement matrix and higher tensile strength compared to the matrix, enhanced the flexural strength of the composites *(140)*. Another study reported an 8% increase in flexural strength and a significant increase in maximum deflection at failure at 28 days with cellulose fibers that bridge and transfer loads across cracks *(142)*. Other research examined the individual and synergic effects of cellulose fiber, PVA, and PO fiber in cement composite. The study found a weakening effect on split tensile strength and shear strength of concrete with fiber inclusions *(142)*.

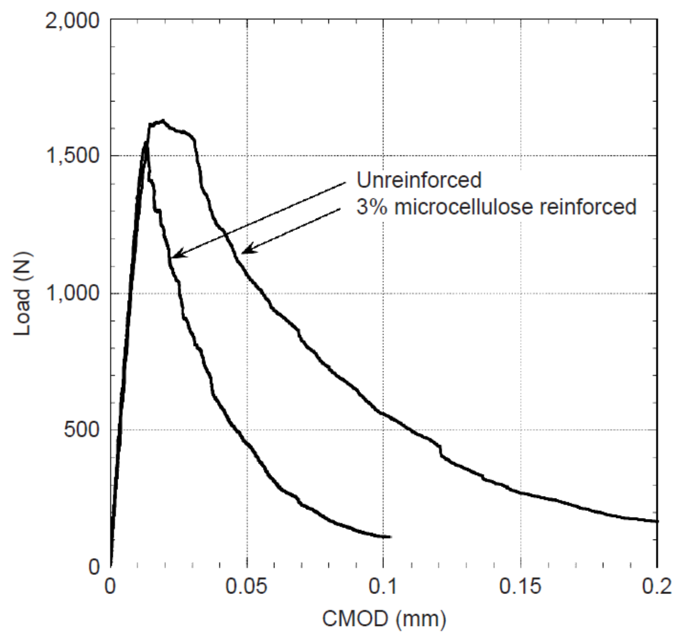


Notes: PC: plain concrete; CFRC-0.6: cellulose fiber-reinforced concrete with 0.6 kg/m3 of cellulose fiber; CFRC-0.9: cellulose fiber-reinforced concrete with 0.9 kg/m3 of cellulose fiber; CFRC-1.2: cellulose fiber-reinforced concrete with 1.2 kg/m3 of cellulose fiber; CFRC-1.2: cellulose fiber-reinforced concrete with 1.2 kg/m3 of cellulose fiber; FS: flexural strength.

Source: Buch, Rehman, and Hiller (1999) *(131)*; Ma et al. (2020) *(144)*.

Figure 4.12: (a) Compressive strength, (b) flexural strength, and (c) flexural load-displacement curve of cellulose fiber-reinforced concrete.

Cellulose fibers can increase the fracture characteristics of cementitious composites. A study reported an increase in fracture toughness based on splitting tensile strength and notch beam test *(145)*. By adding 3 wt%, cellulose microfibers increased fracture toughness by 50%. Cellulose fiber reinforcement was found effective in bridging microcracks and delaying the crack propagation, increasing the fracture toughness, shown in the load-deformation graph in Figure 4.13 *(145)*.



Source: Peters et al. (2010) *(152)*.

Figure 4.13: Load-deformation graph of unreinforced and cellulose fiber-reinforced beams.

All tested natural fiber types at all doses showed increased impact energy compared to the control concrete, according to the study. The highest increases were 137%, 104%, 74%, and 34% for a 2 wt% dose of jute, sisal, coconut, and sugarcane fiber, respectively. The internal geometry of cellulose fiber, which consists of both amorphous and crystalline regions, helps to increase the impact energy *(143)*.

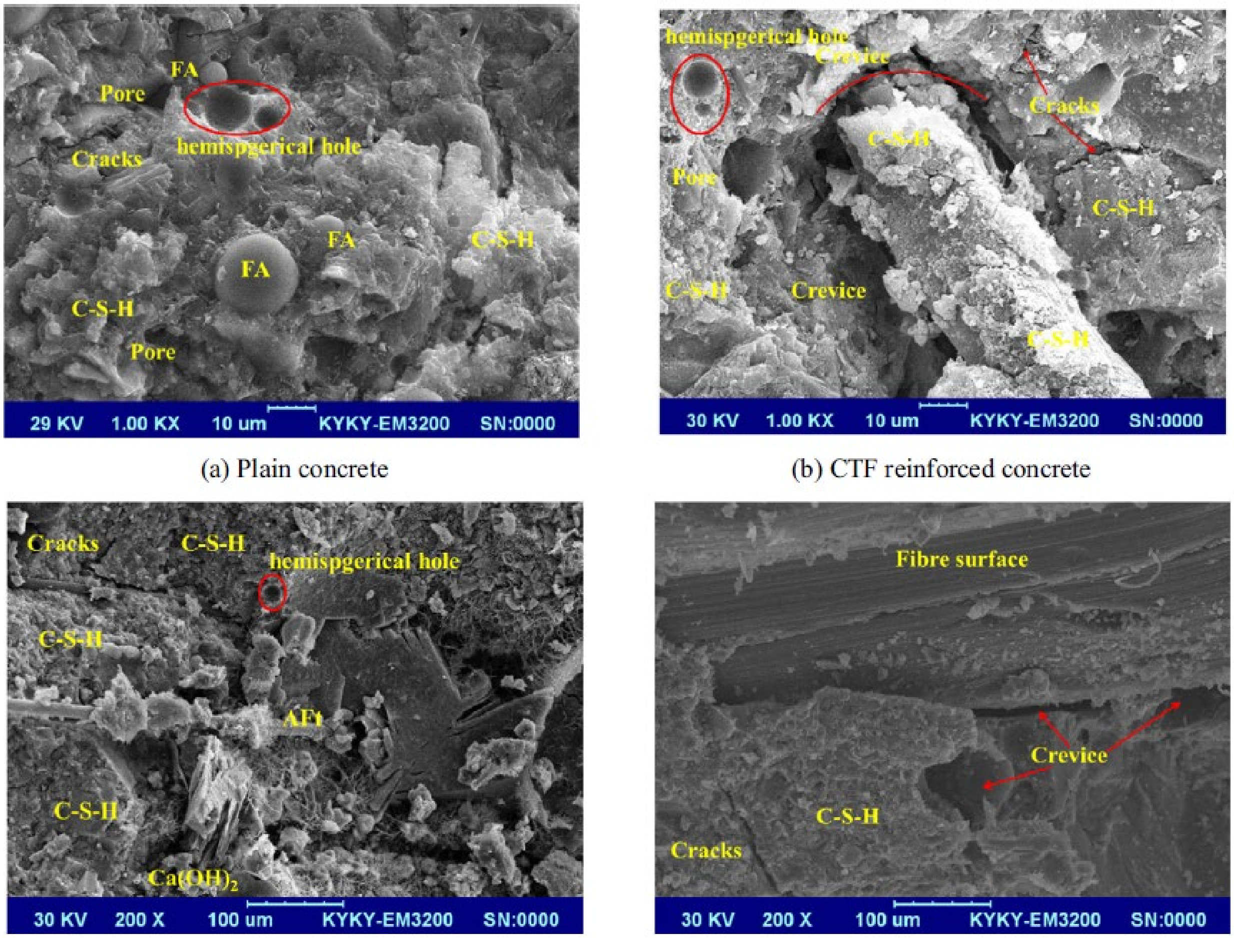
4.6.5 *Impact of Cellulose Fibers on Durability and Microstructure of Concrete*

Low water penetration and absorption are vital for the durability of concrete. Water entry into concrete can lead to deterioration from freeze-thaw actions, entry of harmful salt ions, and steel reinforcement corrosion. FRC exhibited lower water absorption than plain concrete at low doses of up to 2 wt% *(143)*. For instance, the water absorption with 0.25% sisal fiber was 45% less than the plain concrete. Incorporating higher doses (above 2 wt%) of fiber caused porous zones at the fiber-matrix interface, increasing water absorption. Coconut and sugarcane fibers had higher porosity and crystallinity than the jute and sisal fibers; hence, concrete reinforced with coconut and sugarcane fibers had 19% and 11% higher water absorptions, respectively, than the other sisal FRC at 0.25% dose. Cellulose fibers can limit the crack width due to high water absorption, provide internal curing, reduce plastic shrinkage, and assist in crystallizing hydration products *(140)*. The addition of cellulose fiber decreased the water penetration depth by 23% and the water permeability coefficient by 41%, indicating cellulose fiber's effectiveness in increasing the durability of concrete *(142)*.

The flexural strength and toughness of cellulose fiber-reinforced composites decrease upon wetting and drying cycles and affect the durability of the composites *(146)*. Cellulose fiber can be treated or cured for better durability and performance. A study used CO_2-cured cellulose fiber for better durability in cement composites. Cured cellulose fiber-reinforced board provided better flexural strength and decreased capillary porosity, and it enhanced the bonding of cellulose fiber with the cement matrix *(146)*.

The microstructural analysis using an optical and scanning electron microscope (SEM) used in a study showed that cellulose fibers were uniformly distributed, and no fiber agglomeration was noticed. C-S-H, $Ca(OH)_2$ crystals, and AFm were formed around the fibers, thus providing a constraint system with strong integrity *(142)*. Cellulose fiber had good adhesion with the cement matrix because of its small size, providing internal stability and bridging actions, which increased compressive strength (Figure 4.14).

In the SEM observations shown in Figure 4.14, a denser microstructure was visible near the porous zone near the fibers compared to the zone away from the fibers. Higher hydrates were found near the fibers, which caused pore refinement and better bonding near the fibers, and hence better mechanical performance. However, this study did not find any significant post-crack bridging performance with cellulose fibers, which was attributed to fiber mineralization *(142)*.



(a) Plain concrete

(b) CTF reinforced concrete

(c) PF reinforced concrete

(d) VS reinforced concrete

Source: Xu et al. (2020) *(142)*.

Figure 4.14: Comparison of the microstructure of cement composites with (a) control, (b) cellulose, (c) polyvinyl alcohol, and (d) polyolefin fibers.

5 RECYCLED STEEL FIBERS

5.1 Introduction

Metallic fibers may be produced from a wide range of metals, including copper from electrical wires and other sources, aluminum, brass, nickel, and chrome. However, steel fibers are the most common for concrete applications due to their high strength and durability. Steel fibers have been used as primary or secondary concrete reinforcement for over two decades *(8,147)*. Steel FRC contains discrete macroscale steel fibers, introduced into fresh concrete during production to be randomly distributed in the concrete matrix. Steel fibers offer many enhancements to concrete performance, including reduced shrinkage, enhanced mechanical properties, and fracture toughness. Variations in the geometry of steel fibers in a hybrid steel fiber system are often common to arrest crack initiation and restrict crack propagation in concrete *(148)*.

5.2 Feedstock Description: Recycled Steel

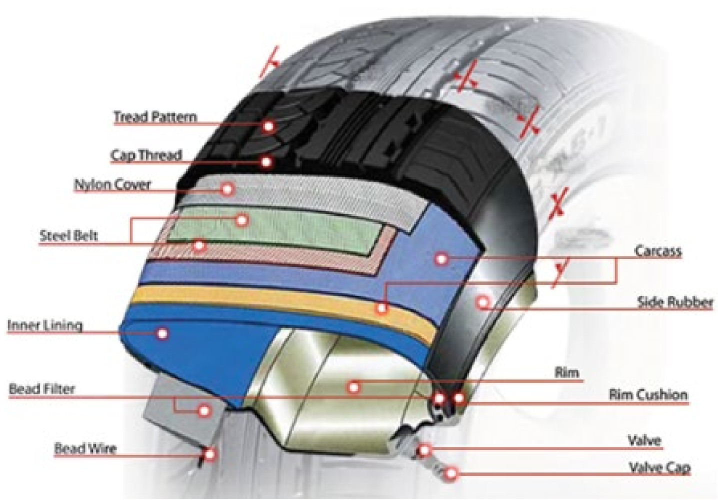
Steel products are an essential part of many aspects of everyday life due to steel's many favorable properties. Furthermore, steel is 100% recyclable, allowing for the reuse and recycling of industrial scraps and end-of-life (EOL) products *(149)*. For example, according to the survey of concrete fiber manufacturers, scrap steel from automobile manufacturing and EOL tires and brake pads are recycled to manufacture steel fibers engineered specifically for concrete. At the laboratory scale, some studies have used recycled steel fibers from tire cords extracted from unvulcanized rubber belts *(150)*, cans, and waste turbary steel fibers *(8)*, as well as lathe industry steel scrap as reinforcement in concrete *(151)*. According to EPA data, approximately 28% of ferrous metals from durable goods were recycled in 2018, which included large and small appliances, furniture, and automobile tires *(152)*. The remaining waste mostly went to landfills. This data indicates a significant unrealized opportunity for recycling steel from such sources.

Recycling steel reduces the resources and energy consumption of making primary steel *(149)*. In the case of concrete fibers, using recycled steel can lower the high cost of steel fibers from primary steel from $2.50/lb. ($5.50/kg) to $0.75/lb. ($1.70/kg), according to communications with fiber suppliers. Furthermore, recycled steel fibers have been shown to have a lower environmental impact, in terms of global warming potential (GWP), than fibers from primary steel in concrete. According to a previous study, the global warming potential (GWP) of industrial steel fibers from primary steel is approximately 1,096 kg CO_2eq, while recycled steel fibers from tires had a GWP of approximately 55 kg CO_2eq *(15)*.

Recycled steel fibers from EOL tires are the most studied for use in concrete compared to recycled steel fibers from other steel sources. The steel wires used by the tire industry have high tensile strength, 400 to 465 ksi (2800 to 3200 MPa), and high carbon content (0.70% to 0.95%) *(153)*. According to scientific literature, the retrieved recycled fibers still hold more ductility and higher tensile strength than steel fibers engineered for concrete *(8)*. The processing method involved in producing recycled steel fibers from EOL tires is described in the following discussion.

5.3 Description of Recycling, Production, and Processing Method

Each year, California faces the challenge of safely managing or diverting approximately 51 million reusable and waste tires *(154)*. EOL tires are a source of scrap steel, and several steel fiber manufacturers are working on innovative technologies to produce recycled steel fibers for concrete *(11,12)*. Figure 5.1 shows the typical structure of a radial tire. The tire mainly consists of rubber, textile fibers, and steel. Rubber makes up almost 50 wt% of the tire, and steel is 15 to 17 wt% of the whole tire *(8)*.



Source: Nankang Tyres (2012) *(155)*.

Figure 5.1: Structure of a typical radial tire.

Table 5.1 summarizes various recycling methods to retrieve scrap steel from waste tires. Mechanical (shredding, milling) processing of waste tires, followed by post-processing of the steel (sorting and screening), is the most common recycling method. A combination of mechanical and thermal processes (pyrolysis) or shredding under cryogenic conditions was also employed to produce recycled fibers with less rubber residue. The dimensions and shape of steel fibers produced may vary depending on the manufacturer’s machinery and end application *(8)*.

Table 5.1: Different Recycling Methods Adopted in Studies Published from 2000 to 2019

Reference	Year	Recycling Method	Dimensions/Shape	Sources
Zamanzadeh et al. *(156)*	2015	Cryogenic	Variable geometry and shape	Waste tires
Bjegović et al. *(157)*	2012	Mechanical recycling	Irregular shape and dimension	Waste tires
Centonze et al. *(158)*	2012	Shredding	0.24 mm dia., 31.4 mm length (average of 2000 fibers)	Waste tires
Graeff et al. *(159)*	2012	Mechanical recycling	0.2 mm dia., length of 90% of fibers ranges 3–22 mm	Used tires
Bjegović et al. *(160)*	2013	Mechanical recycling	0.18±0.029 mm dia., 9 mm length with Irregular shape	Waste tires
Centonze et al. *(161)*	2013	—	—	Waste tires
Santos & Rodrigues *(162)*	2013	—	—	Used tires
Sotoudeh & Jalal *(163)*	2013	Warm milling and machining process	—	Industrial waste
Groli et al. *(164)*	2014	Shredding	Avg. 16.5 mm Length	End-of-life tires
Aghaee et al. *(165)*	2015	—	Avg. 1.2 mm dia., 50±10 mm length	Previously used waste steel wires from reinforcement and formworks
Caggiano et al. *(166)*	2015	Shredding	Avg. 0.27 mm dia., average 12 mm length	Waste tires
Martinelli et al. *(167)*	2015	—	Avg. 0.27 mm dia., an average of 2000 fibers	Used tires
Peng et al. *(168)*	2015	—	1 mm dia., and 30–35 mm length for Hooked and crimped fibers	Waste tires
Bartolac et al. *(169)*	2016	—	Avg. 0.15 mm dia., Avg. 20 mm length with irregular shape	Waste tires
Centonze et al. *(170)*	2016	Shredding	Avg. 0.31 mm dia., average 25.5 mm length, average of 1000 fibers	End-of-life tires
Mastali & Dalvand *(171)*	2016	—	Avg. 0.25 mm dia., average 40 mm length	—
Sengul *(172)*	2016	Pyrolysis and mechanical recycling	0.3 mm dia. and 52 mm length, 0.9 mm dia. and 60 mm length, 1.37 mm dia. and 50 mm length	Scrap tires and industrial waste

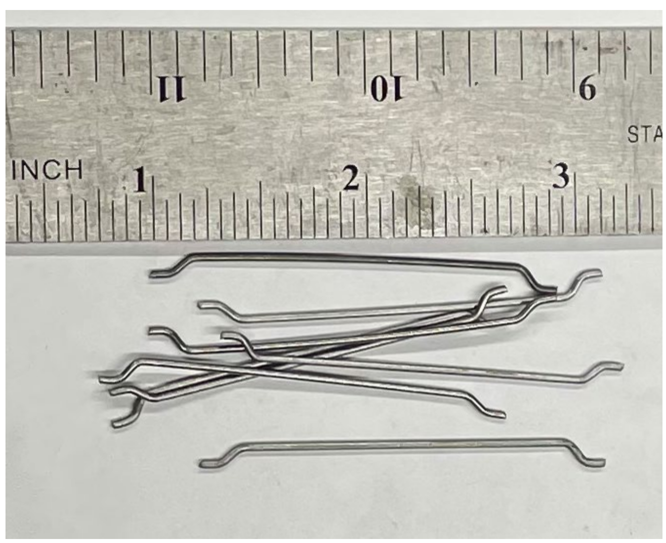
Reference	Year	Recycling Method	Dimensions/Shape	Sources
Alsaif et al. *(173)*	2017	Shredding	<0.3 mm dia., 15–45 mm length	Waste tires
Baricevic et al. *(174)*	2017	—	Avg. 0.25 mm dia., avg. 26.17 mm length	Waste tires
Atoyebi et al. *(175)*	2018	Thermal recycling	0.18 mm dia., 20 mm length	Waste tires
Dehghanpour and Yilmaz *(176)*	2018	Thermal recycling	0.26 mm dia., 25 mm length	Waste tires
Fauzan et al. *(177)*	2018	Manual cutting	Avg. 0.28 mm dia., avg. 25.4 mm length	Waste tires
Hu et al. *(178)*	2018	—	Avg. 0.22 mm dia., avg. 23 mm length	End-of-life tires
Leone et al. *(179)*	2018	Shredding	Avg. 0.25 mm dia., avg 13.94 mm length, average of 1200 fibers	Scrap tires
Mastali et al. *(180)*	2018	—	Avg. 0.15 mm dia., avg. 50 mm length, average of 156 fibers	—
Najim et al. *(181)*	2018	Shredding followed by heating	50 mm length with 50 aspect ratio	Waste tires
Sengul et al. *(182)*	2018	Mechanical recycling	Ranges from 0.18 to 2 mm dia., 41–114 mm length	Waste tires
Skarżyński and Suchorzewski *(183)*	2018	Shredding at ambient temperature	Avg. 0.25 mm dia., avg. 26.17 mm length	Waste tires
Al-Musawi et al. *(184)*	2019	—	0.2 mm dia., 21 mm length	Unvulcanized rubber belts
Bensaci et al. *(185)*	2019	—	0.18–1.25 mm dia., 0.8–55 mm length	Waste tires
Frazão et al. *(186)*	2019	Shredding	Avg. 0.22 mm dia., 23 mm length	Waste tires
Wang et al. *(187)*	2000	–	—	Used tires
Neocleous et al. *(188)*	2006	Pyrolysis, shredding	—	Used tires

Source: Liew and Akbar (2020) *(8)* .

5.4 Physical and Chemical Properties of Recycled Steel Fibers

Recycled fibers, shown in Figure 5.2(a), are inherently variable in size, shape, and surface conditions (rubber or nylon impurities) depending on the processing method compared to industrial steel fibers, shown in Figure 5.2(b), which are homogenous in size, shape, and composition.

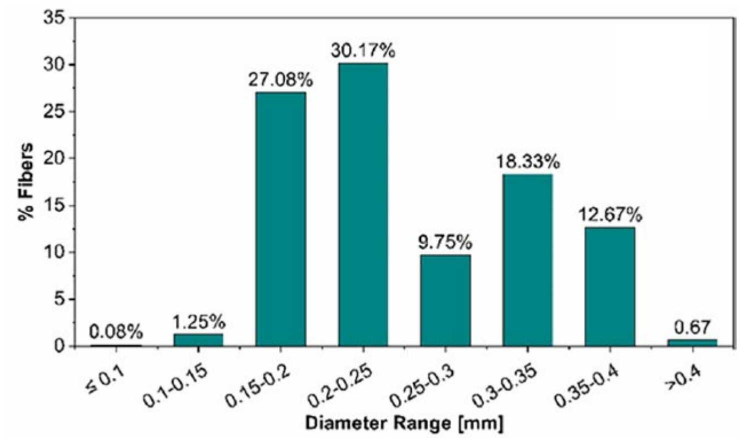
(a)



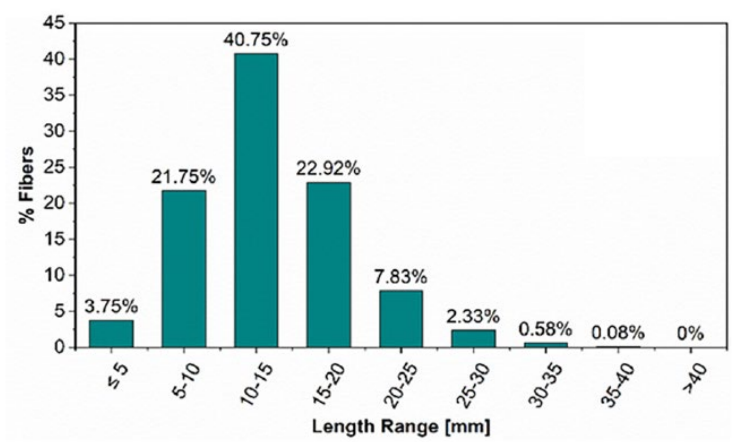
(b)

Figure 5.2: (a) Recycled steel fiber by FlexoFibers (FX 25), and (b) virgin steel fiber by Sika Fibers (Novocon HE4550).

Steel fibers from primary steel must comply with ASTM A820 for use in concrete. According to the standard, steel fibers can be straight or deformed. The five different manufacturing processes are cold-drawn wire (Type I), cut sheet (Type II), melt-extracted (Type III), mill cut (Type IV), and modified cold-drawn wire (Type V). The minimum average tensile strength requirement for steel fibers is 50,000 psi (345 MPa), with no single fiber failing below 45,000 psi (310 MPa). No specified size requirement is provided in ASTM A820, but the aspect ratio of steel fibers is typically between 20 and 100 *(189)*. As shown in Figure 5.2, recycled fibers are variable in length and diameter as opposed to the uniform geometric properties of steel fibers from primary steel. The frequency distributions of the diameter and length of a sampling of recycled steel fiber are shown in Figure 5.3(a) and Figure 5.3(b), respectively.



(a)

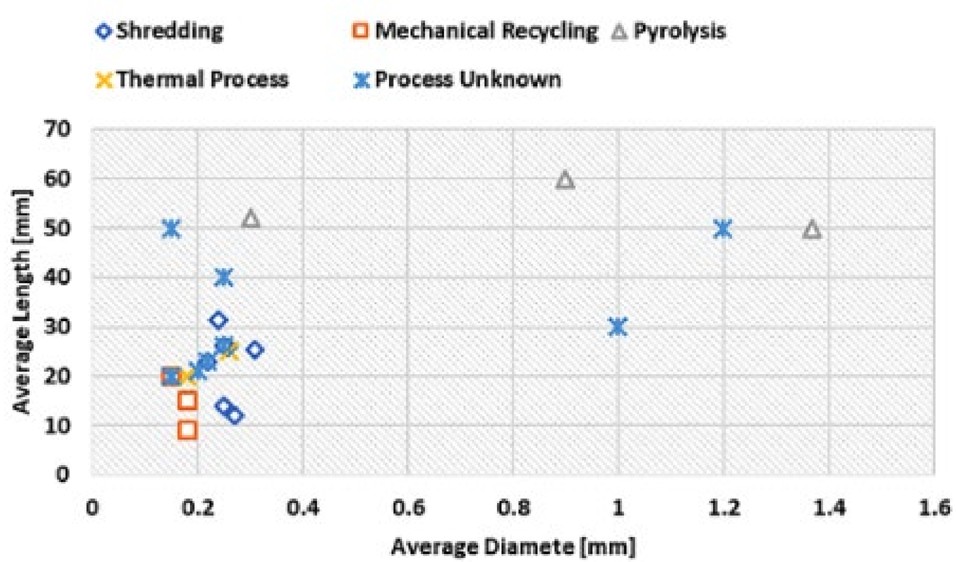


(b)

Source: Liew and Akbar (2020) *(8)*.

Figure 5.3: Frequency distribution of (a) diameter and (b) equivalent length of recycled steel fibers.

The diameter of the fiber depends on the origin of the waste tire (e.g., automobiles or heavy vehicles), whereas the length of the fiber depends on the recycling method, such as shredding, manual cutting, and mechanical recycling. Mechanical recycling includes recycling waste tires and producing steel fibers by cryogenic processing or shredding *(8)*. Shredding is the main subprocess in mechanical recycling that keeps the molecular structure of the recycled material intact *(190)*. Figure 5.4 shows the average length and diameter of recycled steel fibers from various studies *(8)*. Most fibers showed an average diameter in the range of 0.007 to 0.015 in. (0.18 to 0.38 mm), and only a few fibers showed much larger diameters of over 0.04 in. (1 mm). The average length varied from just under 0.4 in. (10 mm) to 2.4 in. (60 mm).



Source: Liew and Akbar (2020) *(8)*.

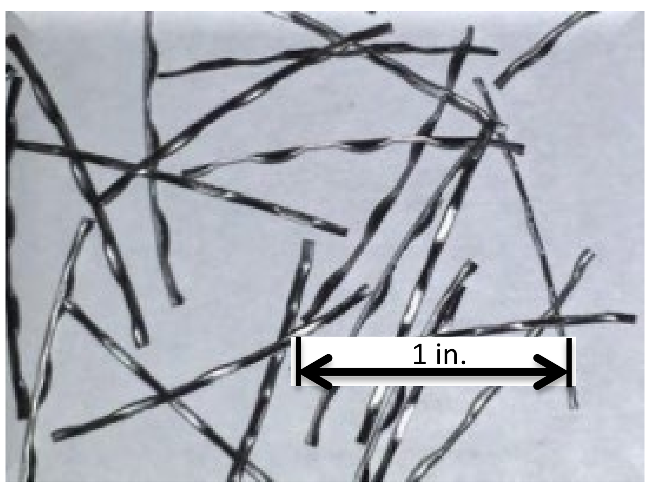
Figure 5.4: Length and diameter of recycled steel fibers by different processes.

For recycled steel fibers from the lathe industry scrap, the length was 1 to 1.5 in. (25 to 40 mm). The diameter of such fibers was 0.01 to 0.02 in. (0.3 to 0.6 mm), and the aspect ratio was 50 to 100. The modulus of elasticity and density of recycled steel fibers from industrial scrap were 29,000 ksi (2 x 10^5 MPa) and 13,000 lb./yd^3 (7,850 kg/m^3), respectively *(151)*. Industrial steel fibers are more durable compared to recycled steel fibers from post-consumed truck tires *(186)*. Recycled steel fibers are susceptible to surface corrosion; however, impurities like rubber debris present on the surface of the steel fibers have a negligible effect on the development of corrosion, as corrosion products form uniformly throughout the length of the fibers. Corrosion of steel fibers can be mitigated by keeping the water-to-cement (w/c) ratio to less than 0.5 and providing a minimum reinforcement cover of 0.1 to 0.4 in. (2 to 10 mm) *(191)*.

5.5 Identified Suppliers of Recycled Steel Fibers for Concrete Applications

5.5.1 *Recycled Steel Fibers by Concrete Fiber Solutions (Chicago, Illinois)*

According to the manufacturer, Concrete Fiber Solutions (CFS) LLC is a significant producer of recycled steel fibers and holds almost 90% of the steel fiber supply market in the United States. CFS produces recycled steel fibers from automobile and steel stamping industry scrap steel. The CFS trademark recycled steel fiber product is CFS 100-2 (Type II), Type V, and UHPC fibers (note: their UHPC fibers are not ASTM certified). The CFS-recommended fiber product for pavement-specific applications is CFS 100-2, which is shown in Figure 5.5. These fibers are 1 in. (25 mm) in length and have an aspect ratio of 43. CFS purchases scrap steel from industries and then processes the scrap steel using slitters. A slitter is a machine used to cut or slit large steel pieces into smaller sizes and is used to produce 1 in. (25 mm) pre-coiled bands of CFS 100-2 fibers from scrap steel.



Source: Concrete Fiber Solutions (2022) *(192)*.

Figure 5.5: CFS 100-2 recycled steel fibers.

CFS 100-2 recycled fibers arrest microcracks and allow for greater joint spacings for concrete slabs. Experience using CFS 100-2 with pavements involves the construction of a bridge overlay by the Missouri Department of Transportation on Interstate 64, with a fiber dosage of 190 lb./yd^3 (112.7 kg/m^3). The CFS 100-2 reinforced concrete as bridge overlay helped reduce cracks generated due to the flex of the bridge section. With a lower aspect ratio (<50), the many workability issues in general have not been reported for CFS 100-2. To avoid fiber balling issues at higher fiber dosages, a high-range water reducer (HRWR) admixture is recommended when working with CFS 100-2. In the concrete mix design, extra water demand should be considered for fibers similar to fine aggregates.

CFS 100-2 are low-carbon steel fibers that provide good corrosion resistance and long-term durability in concrete. These fibers also have sufficient bond pullout resistance. However, these fibers are not corrosion-resistant, just like rebars in concrete. However, since these are fibers and not continuous reinforcement, steel corrosion does not network throughout the cement matrix. The CFS recycled steel fibers cost $0.95/lb. ($2.1/kg) plus the delivery cost ($0.15/lb. [$0.33/kg] for flatbed transport and $0.10/lb. [$0.22/kg] for rail transport).

5.5.2 *Recycled Steel Fibers by Sika Fibers (Chattanooga, Tennessee)*

Novocon XR, the trademark product of Sika Fibers, is made from shaved wires from used brake pads and other sources of metallic scrap. Novocon XR is a Type V fiber with a length of 1.5 to 2 in. (38 to 50 mm) and an aspect ratio of 30 to 40. The average equivalent diameter of Novocon XR is 0.045 in. (1.14 mm), and the density is 7.85. Figure 5.6 shows a sample of Novocon XR recycled steel fibers. The tensile strength reported for this fiber is greater than 140,000 psi (965 MPa).

The standard recommended dosage rate for Novocon XR is 25 to 67 lb./yd^3 (15 to 40 kg/m^3). Approximately 1,500 fibers per pound of concrete can be accommodated at this dosage rate. It should be noted that adding these fibers to concrete will reduce concrete slump. Therefore, an HRWR admixture should be added to achieve the required workability. The cost of Novocon XR is $2.25/lb. ($5/kg).

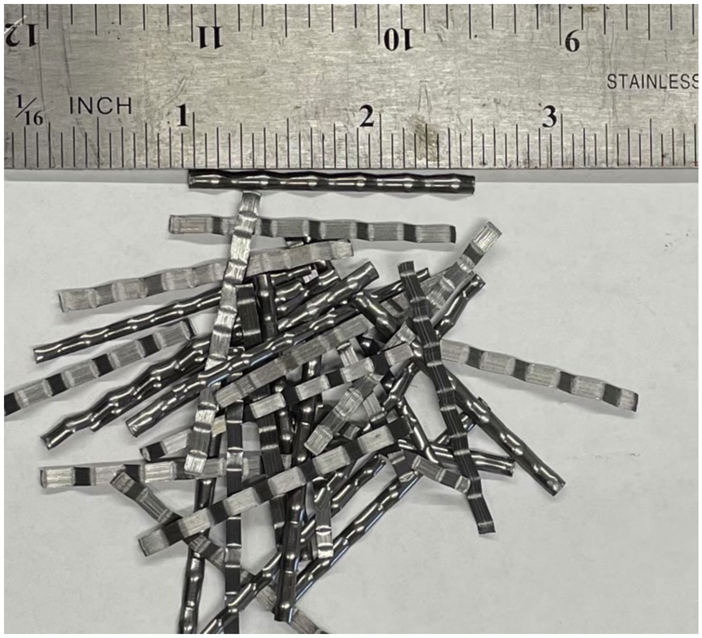
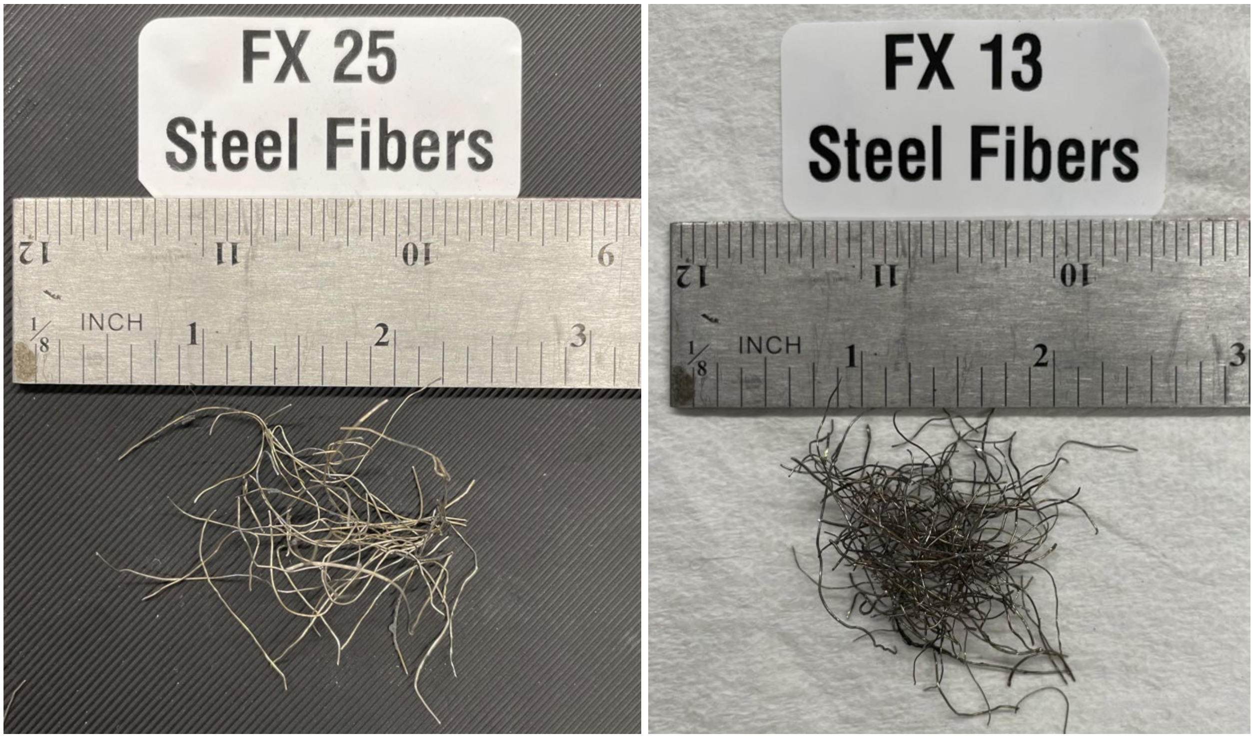


Figure 5.6: Picture of a sample of Novocon XR steel fibers from Sika Fibers.

5.5.3 *FlexoFibers (Madrid, Spain)*

FlexoFibers is a concrete fiber manufacturing company based in Madrid, Spain. It produces recycled steel fibers from waste rubber tires. Nylon present in scrap tires is burned, and then the remaining steel is sent to the foundry. FlexoFibers gets this scrap product at a low price and uses it to make FX25 and FX13 recycled fibers for steel. Both fibers have a common diameter of 0.01 in. (0.25 mm). The length of FX25 is 1 in. (25 mm) and that of FX13 is 0.5 in. (13 mm). The aspect ratio of these fibers is 120 for FX25 and 40 for FX13, with a high fiber count in concrete. These fibers do not have any particular shape, and they are not straight. They can be bent easily without breaking. FX25 is used mainly in structural concrete, and FX13 is used in ultra-high-performance (UHPC) concrete. FlexoFibers is developing an industrial plant that was 98% built when the interview for this project took place. The capacity of this plant is 2,200 US tons/year (2,000 metric tons/year). Cemex has already used FlexoFibers products in some of its projects. Figure 5.7 shows images of sample FlexoFibers recycled fiber products.



(a) (b)

Figure 5.7: Pictures of samples of FX 25(a) and FX13(b) steel fibers from FlexoFibers.

5.5.4 *COR-TUF UHPC Recycled Fibers (Manassas, Virginia)*

COR-TUF UHPC is a US-based manufacturer of UHPC. It uses recycled high-tensile steel fibers derived from waste passenger car tires. During the preparation of this report, these fibers were being manufactured in Switzerland. A new fiber manufacturing plant is being prepared in Pennsylvania, which will be completed within a year. Initially, COR-TUF faced some hurdles in separating rubber debris/nylon fibers from recycled steel fibers. But now, with innovative technologies, it can produce almost 99% pure recycled steel fibers. The manufacturing process of this fiber does not involve any thermal heating process. Instead, the fibers are produced by shredding waste tires. Next, the fibers are separated using sieves and high-pressure air.

The COR-TUF recycled fibers are Type V and are 0.2 to 1.2 in. (5 to 30 mm) long. The diameter of this fiber varies from 0.007 to 0.01 in. (0.17 to 0.23 mm). The variation in length, diameter, and shape of this fiber is high, shown in Figure 5.8, because the fibers are derived from different car tires. The tensile strength of this fiber has not been tested yet. The dosage rate in UHPC may vary from 2 vol% to 10 vol% or about 265 lb./yd^3 (157.2 kg/m^3). Any balling issues associated with the higher dosage rate of this fiber can be mitigated with water-reducing agents.

The manufacturing capacity of the COR-TUF recycled fibers will be 30,000 lb./day (13,500 kg/day) once the manufacturing plant starts operation in Pennsylvania. This fiber costs approximately \$0.75/lb. (\$1.65/kg). A summary of the properties of the identified recycled steel fibers is provided in Table 5.2.

Figure 5.8: Sample of COR-TUF UHPC recycled steel fibers.

5.5.5 *Summary of Findings from Recycled Steel Fiber Suppliers*

Table 5.2 provides a comparison of the four identified fiber suppliers: Concrete Fiber Solutions LLC, Sika Fibers, FlexoFibers, and COR-TUF UHPC. As discussed before and summarized in the table, the suppliers utilize different source materials, such as scrap steel from various industries. Fiber lengths range from 0.2 to 2 in. (5 to 50 mm), with varying aspect ratios. Fiber diameters range from 0.007 to 0.045 in. (0.17 to 1.14 mm). Specific gravities are around 7.85 to 7.86. Ultimate tensile strengths vary, with COR-TUF UHPC not providing data. Manufacturers claim advantages, including increased crack resistance, toughness, and fatigue strength. Costs per pound (per kg) vary, ranging from \$0.75 to \$2.25 (\$1.65 to \$5), excluding shipping costs.

Table 5.2: Summary of Properties of Identified Recycled Steel Fibers

Fiber Supplier/Property	Concrete Fiber Solutions LLC	Sika Fibers	FLexoFibers	COR-TUF UHPC
Source material	Scrap steel from auto industries	Shaved steel wires from used brake pads	Scrap steel from waste tires	Scrap steel from passenger car tires
Fiber length	1 in. (25 mm)	1.5-2 in. (38-50 mm)	1 in. (25 mm) and 0.5 in. (13 mm)	0.2 -1.2 in. (5-30 mm)
Aspect ratio	43	30-40	120 and 40	N/A
Fiber diameter	N/A	0.045 in. (1.14 mm)	0.01 in. (0.25 mm)	0.007-0.01 in. (0.17-0.23 mm)
Specific gravity	7.86	7.85	N/A	N/A
Ultimate tensile strength	70,000-80,000 psi (480-550 MPa)	140,000 psi (965 MPa)	360,000 psi (2500 MPa)	N/A
Advantage to concrete as per manufacturer	Arrest microcracks allow for greater joint spacing	Increase crack resistance, toughness, fatigue strength	Higher crack resistance, better distribution at a lower dosage	N/A
Cost per pound (cost per kg) excluding shipping cost	$0.95 ($2.10)	$2.25 ($5)	N/A	$0.75 ($1.65)

5.6 Performance in Concrete Based on Technical Literature

5.6.1 *Dispersion*

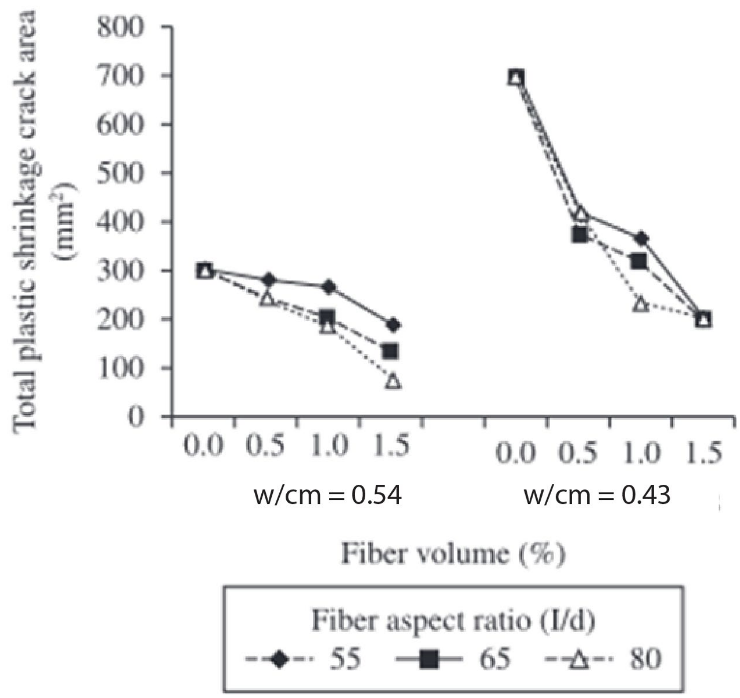
Dispersion of recycled steel fibers in concrete depends on the geometry, dosage, and type of concrete mixer used *(8)*. It was observed that steel fibers with relatively uniform geometry and a dosage rate of 0.26 vol% combined with a conventional concrete mixer for mixing could only increase the compressive strength by 12%. In comparison, a planetary concrete mixer can achieve a relatively higher level of steel fiber dispersion. The effect of this improved dispersion can be observed indirectly as the compressive strength increases by 20% of the control mix, even at a lower recycled steel fiber dosage rate of 0.23 vol% *(193)*. Another study also showed that adding superplasticizers could effectively increase the dispersion of recycled steel fibers in concrete *(184)*.

5.6.2 *Impact of Steel Fibers on the Workability of Concrete*

The extent of the effect on the workability of concrete depends on fiber dosage, size, and the concrete mixture composition *(194)*. At dosages less than 1 vol%, steel fibers have a marginal impact on fresh concrete workability. Irrespective of the origin of steel fibers (e.g., scrap industrial steel, tires), workability decreases as the fiber volume increases *(151)*. Steel fibers also increase the air content and unit weight of concrete *(195)*.

5.6.3 *Impact of Steel Fibers on Plastic and Drying Shrinkage*

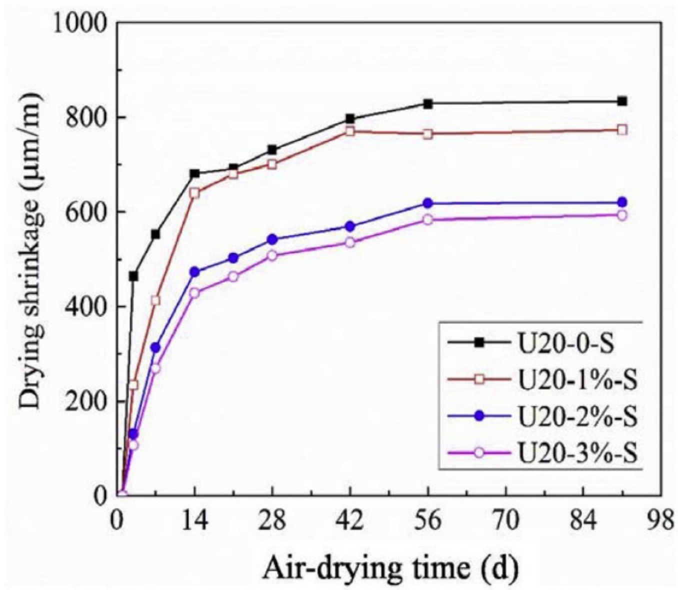
Overall, steel fibers can have a positive effect on reducing drying shrinkage in concrete. One study found an inverse relationship between plastic shrinkage crack area and the dosage of steel fibers. At 1.5 vol% dosage, steel fibers effectively reduced the total plastic shrinkage crack area significantly, shown in Figure 5.9. Also, as the aspect ratio of fibers increased, the plastic shrinkage cracking decreased *(196)*. A similar study showed that 0.1 vol% steel fibers in concrete effectively reduced plastic shrinkage crack width and area by 50% compared to non-FRC specimens. This benefit is achieved due to the improvement of the tensile strain capacity of concrete with steel fibers *(197)*.



Source: Eren and Marar (2010) *(196)*.

Figure 5.9: Effect of steel fiber volume on plastic shrinkage crack area.

According to one study, the shape and volume fraction of steel fibers in UHPC significantly affect the drying shrinkage strains. Adding 2 vol% steel fibers in concrete reduced the drying shrinkage by 25% to 36% compared to the non-FRC specimens, shown in Figure 5.10 *(198)*. If the aspect ratio of steel fibers is constant, hooked-end steel fibers perform better in reducing shrinkage strains *(198,199)*. However, steel FRC usually has a higher water demand and air content than plain concrete, which may lead to more drying shrinkage in concrete if extra water is added to increase workability *(150)*. Internal curing agents can also help reduce shrinkage in steel FRC *(8)*.



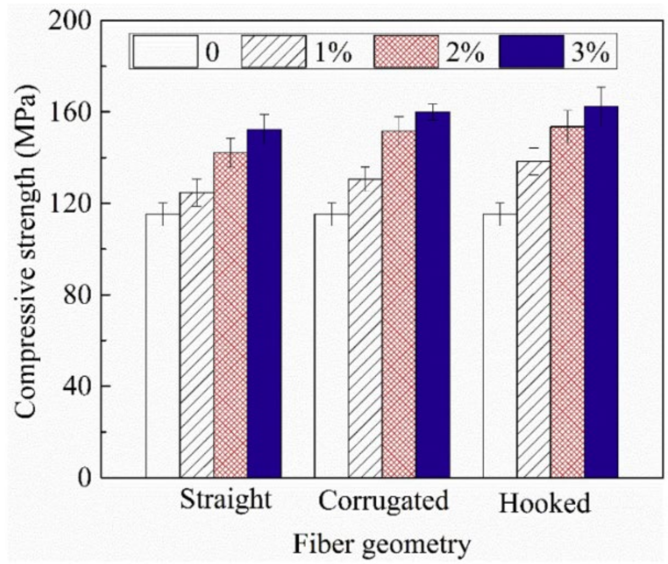
Note: Legends contain steel fiber dosage in vol%.
Source: Wu, Shi, and Khayat (2019) *(198)*.

Figure 5.10: Effect of varying steel fiber dosages on the drying shrinkage of concrete.

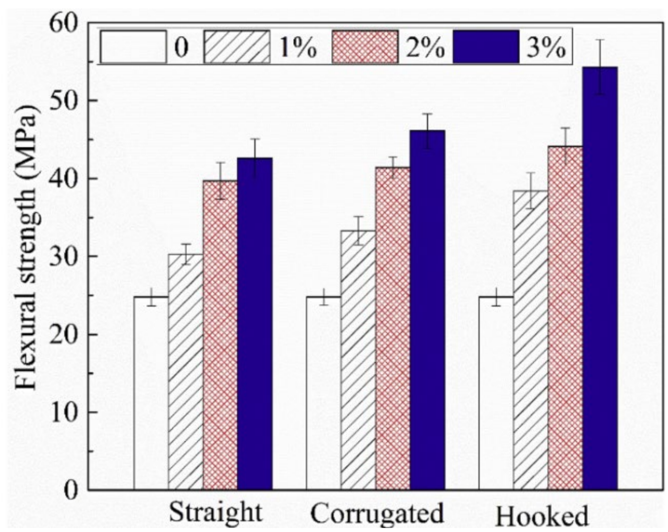
5.6.4 *Impact of Steel Fibers on Strength and Toughness of Concrete*

A high dosage (5 vol%) of recycled steel fibers increased the compressive strength of concrete by almost 59% compared to plain concrete *(163)*. For UHPC, a study showed that a 3 vol% fraction of hooked-end steel fibers could improve the compressive and flexural strength of non-FRC by more than 30% and 70%, respectively, shown in Figure 5.11 *(198)*. However, a higher dosage of steel fibers in concrete increases the water demand of the concrete, which can be detrimental to the strength gain of concrete *(8)*. Less than 0.5 vol% industrial or recycled steel fibers do not significantly increase the compressive strength of the concrete *(200)*. Previous studies indicate that if uniform dispersion of steel fibers can be ensured in the concrete, a higher than 0.5 vol% can significantly increase the compressive strength *(8,163)*.

On the other hand, if proper dispersion cannot be achieved, the threshold fiber volume fraction should be 0.5% *(8)*. For pavement applications with fiber volume fractions of less than 0.5 vol%, there is usually little change in compressive or flexural strength. The benefits of steel fiber addition can be seen in post-crack strength and toughness. Steel fibers also help in the flexural fatigue performance of concrete *(201)*.



(a)



(b)

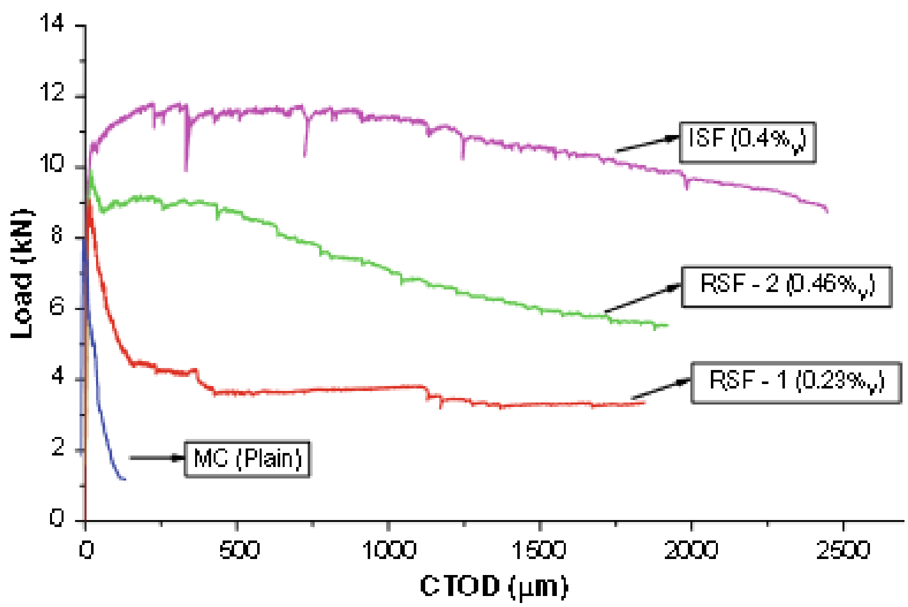
Source: Wu, Shi, and Khayat (2019) *(198)*.

Figure 5.11: Effect of steel fibers geometry and volume fraction on (a) compressive and (b) flexural strength of ultra-high-performance concrete.

Recycled steel fibers from lathe industry scrap, when added to reinforced concrete at 1.5 vol%, resulted in a 28-day compressive strength of 6,200 psi (43 MPa) and a flexural strength of 1,740 psi (12 MPa), which is almost a 10% increase in compressive strength and a 50% increase in flexural strength compared to the non-FRC control mix *(151,202)*. It should be noted that these beam specimens were also reinforced with rebars.

5.6.5 *Impact of Fibers on Residual Strength or Post-Crack Strength*

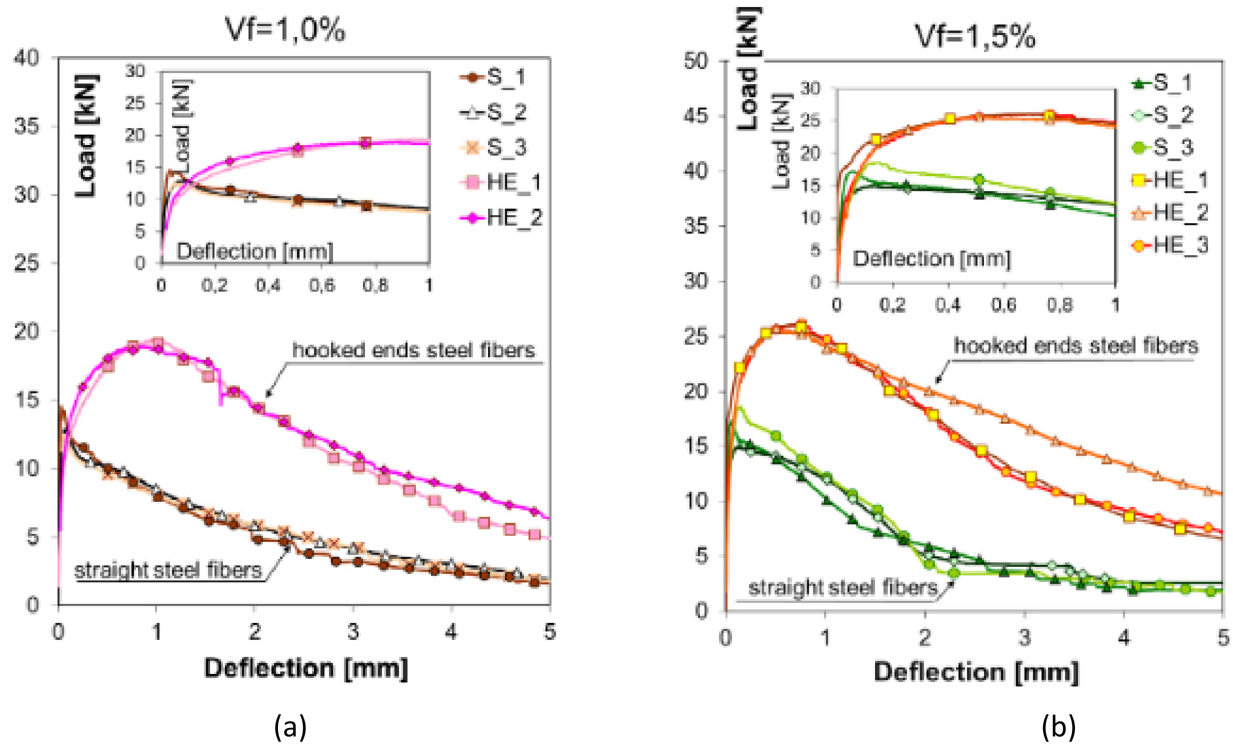
The residual strength (f_{150}) is often considered the primary performance parameter for FRC and is used as a direct input to the structural design of concrete pavements *(*209*)*. Steel fibers usually increase the residual strength of concrete *(8,193,201,203)*. A study showed that recycled steel fibers, when added at 0.46 vol%, can contribute to the post-crack performance of concrete. However, as shown in Figure 5.12, recycled fibers do not match the post-crack performance of virgin industrial steel fibers *(193)*. For example, at the 1000 µm crack tip opening displacement, the load-carrying capacity of recycled steel FRC at 0.46 vol% was almost 85% lower than that of industrial steel FRC at 0.4 vol% of fiber dosage.



Source: Aiello et al. (2009) *(193)*.

Figure 5.12: Load versus crack tip opening displacement (CTOD) for MC (plain), RSF-1,2 (recycled steel), and ISF (industrial virgin steel) fiber-reinforced concrete.

Recycled steel fibers from scrap tires can provide comparable post-crack strength to that of virgin steel fibers *(193)*. However, to achieve a significant increase in residual or post-crack strength, the addition of recycled steel fibers should be around 0.4 vol% of the mix. Better post-crack behavior can be achieved with the hybrid of hooked or textured steel fibers *(8)*. Hooked-end steel fibers have higher post-peak strength than straight-end steel fibers when applied at either 1.0 vol% (Figure 5.13a) or 1.5 vol% (Figure 5.13b) in concrete *(203)*. This is due to the higher fracture energy of hooked-end FRC than straight steel FRC, irrespective of the fiber dosage. A study reported that replacing industrial virgin steel fibers with recycled steel fibers may reduce the residual flexural strength by 70% *(180)*. This finding may be due to the fact that recycled steel fibers often have impurities on their surfaces, reducing post-crack performance in concrete *(8)*.

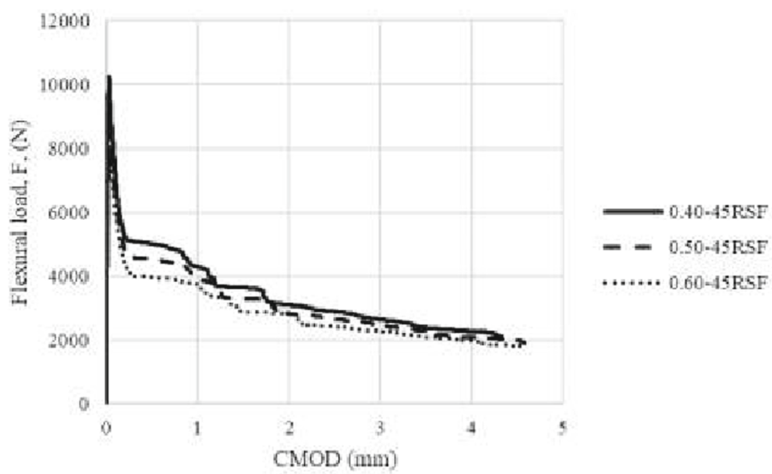


Note: S = straight; HE = hooked end.

Source: Pajak and Ponikiewski (2013) *(203)* .

Figure 5.13: Load-deflection behavior of steel fibers: (a) 1.0 vol% (b) 1.5 vol% in self-compacting concrete.

Another study on recycled steel fibers showed that the application of 75 lb./yd^3 (45 kg/m^3) recycled steel fibers—with varying w/c ratios of 0.40, 0.50, and 0.60—can contribute to the post-crack performance of FRC. The feedstock for the recycled steel fibers used in the study was EOL vehicle tires *(204)*. Figure 5.14 shows that recycled steel fibers and a lower water-cement ratio of 0.40 resulted in the highest flexural strength of 12.38 MPa. The reason behind improved post-crack performance with recycled steel fibers was attributed to the fact that the fibers transfer the stress after the first crack occurrence in the concrete matrix, thus providing better load distribution than non-FRC *(204)*.



Source: Ilki et al. (2023) *(204)*.

Figure 5.14: Load-deflection behavior of recycled steel fibers at various dosages.

Table 5.3 shows the residual strength values for different types and dosages of synthetic and steel fibers for pavement overlay applications examined in a study. A 0.19 vol% of steel fibers in concrete can result in a residual strength of 175 psi (1.21 MPa). Synthetic fibers used in the study varied in shape, geometry, and dosage rate. Results indicated that to exceed the residual strength of steel FRC at 0.19 vol% dosage, a higher dosage (0.38 vol%) of synthetic fiber is required in the concrete *(201)*.

Table 5.3: Comparison of Residual Flexural Strength of Fiber-Reinforced Concrete

Fiber Type	Age (days)	Fiber Volume (% of total concrete volume)	Fiber dosage, (lb./yd^3 [kg/m^3])	f150 value (psi [MPa])
Synthetic fiber #1	14	0.27	4.0 [2.4]	90 [0.65]
Synthetic fiber #1	28	0.38	5.8 [3.4]	155 [1.05]
Synthetic fiber #2	28	0.27	4.1 [2.5]	160 [1.10]
Synthetic fiber #2	28	0.38	5.8 [3.5]	225 [1.55]
Synthetic fiber #3	28	0.50	7.6 [4.5]	160 [1.10]
Steel fiber	28	0.19	25.1 [14.9]	175 [1.21]

Source: Roesler et al. (2019) *(201)*.

5.6.6 *Impact of Steel Fibers on Durability of Concrete*

Using steel fibers in concrete can reduce drying shrinkage issues, improve impact resistance, restrain crack propagation, and enhance the durability of concrete *(8)*. Controlling crack width with steel fibers decreases harmful chemical ingress into the concrete and thus reduces the deterioration of concrete. One study showed that steel fibers could significantly decrease the permeability of concrete at fiber dosages of 1%, 2%, and 4% by weight of the concrete mixture *(205)*. Recycled steel fibers, when used at a dosage rate of 2% to 6% by weight fraction of concrete, enhanced the freeze-thaw durability of concrete pavements by controlling and limiting the crack width even after 2 million load repetitions. Recycled steel fibers also showed resistance to continuous wetting and drying cycling, and only the fibers exposed to the surface were at risk of moisture-related deterioration *(206)*.

6 RECYCLED CARBON FIBERS

6.1 Introduction

Carbon fibers are a highly used engineered material in aerospace, automobile, energy, sporting goods, and defense industries, among other sectors. The use of carbon fibers is gaining even more popularity over other fiber materials, such as steel fibers, owing to excellent engineering properties, including low specific weight, high strength, chemical stability, and durability. As a result, carbon fiber demand is expected to reach 0.22 million tons (0.2 million metric tons) in 2023 *(207)*. The carbon fiber market was $4.7 billion in 2019 and is expected to reach $7.8 billion in 2024 *(208)*.

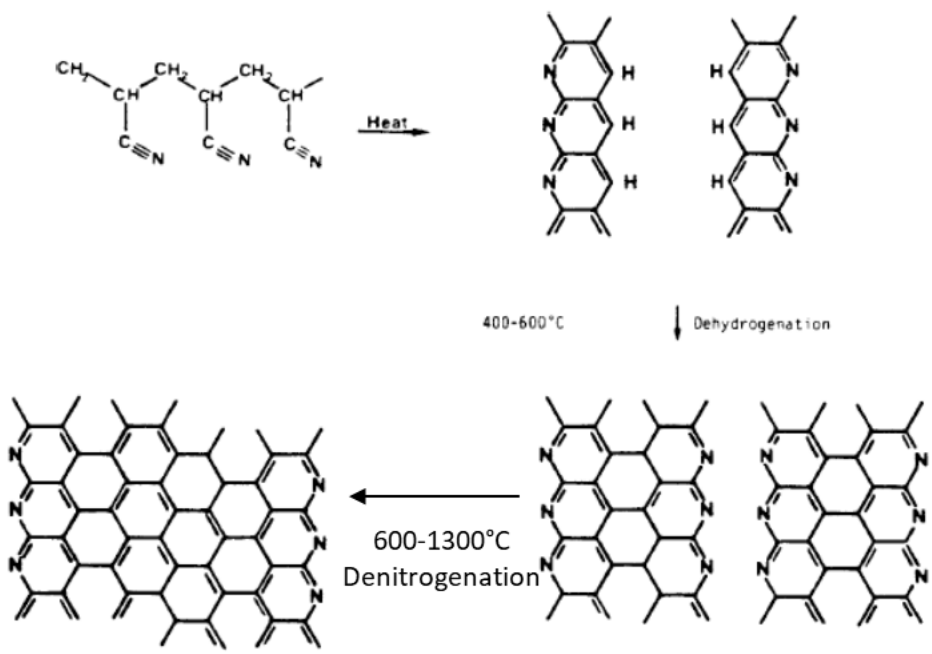
Compared to other fibers (steel, glass, and polymeric fibers), carbon fibers have some intrinsic properties that make them a good discrete reinforcement in cementitious composites. For example, carbon fibers can be used to create self-sensing smart composites. Carbon fibers are highly durable in the concrete alkaline environment, with high corrosive and fire resistance properties.

6.2 Feedstock Description: Carbon Fiber

Carbon fibers can be derived from polymer precursors. The primary feedstock for most carbon fiber productions is polyacrylonitrile (PAN), pitch, and rayon. The feedstock/precursor for carbon fiber productions is Kevlar coated with polyimide, nylon, poly(phenylene oxadiazole), poly(methyl vinyl ketone), polyacetylene, polyacetylene copolymer blends, polyarylacetylene, polybenzimidazole, polybutadiene, polyethylene, polyimide, polymerizable naphthalene derivatives, polystyrene and pitch blends, rayon, and syndiotactic 1,2-polybutadiene *(209)*. Polymers from renewable and recycled sources can be used as precursors for carbon fiber production. Lignin is the second most abundant source of polymers. Wood contains about 8% lignin by weight. Lignin is a byproduct of paper and other wood-based industries and is produced in the range of 1,000 times the total carbon fiber production *(209)*. Renewable sources like cellulose and recycled fibers like polyolefin and polyester are high-volume sources for carbon fiber production. Similarly, recycled sources like EOL carbon fiber-reinforced polymer can be used for carbon fiber retrieval. The use of recycled materials will enable the production of low-cost carbon fibers. Moreover, waste generated from carbon fiber manufacture and EOL products (e.g., CFRP composites used in aircraft) can be recycled as feedstock for carbon fibers.

6.3 Description of Recycling, Production, and Processing Method

The primary feedstock/precursor of carbon fibers is organic polymers with long chains that bind with carbon atoms. The polyacrylonitrile (PAN) method is the dominant method of carbon fiber production, accounting for 90% of all carbon fiber production *(208)*. Figure 6.1 shows the schematic of carbon fiber production from PAN. PAN is initially heated to reorganize the chemical structure, then heated from 752°F to 1112°F (400°C to 600°C) for dehydrogenation and from 1112°F to 2372°F (600°C to 1300°C) for denitrogenation to produce carbon fiber.

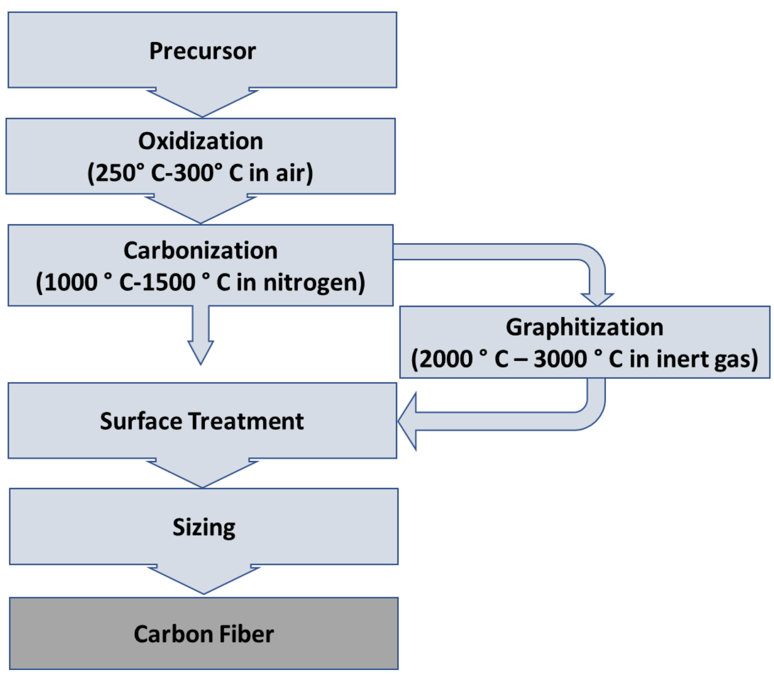


Source: Chand (2000) *(210)*.

Figure 6.1: Schematic of PAN process of carbon fiber production.

Raw materials and production processes can influence the quality of carbon fibers. In the production process, the raw material polymers are processed into long strands of fibers after undergoing some chemical and mechanical methods. The fibers are then processed into different sizes and shapes based on industry needs. The industrial production process of carbon fibers is outlined in the following discussion *(211)*, and a flow diagram of carbon fiber production is shown in Figure 6.2:

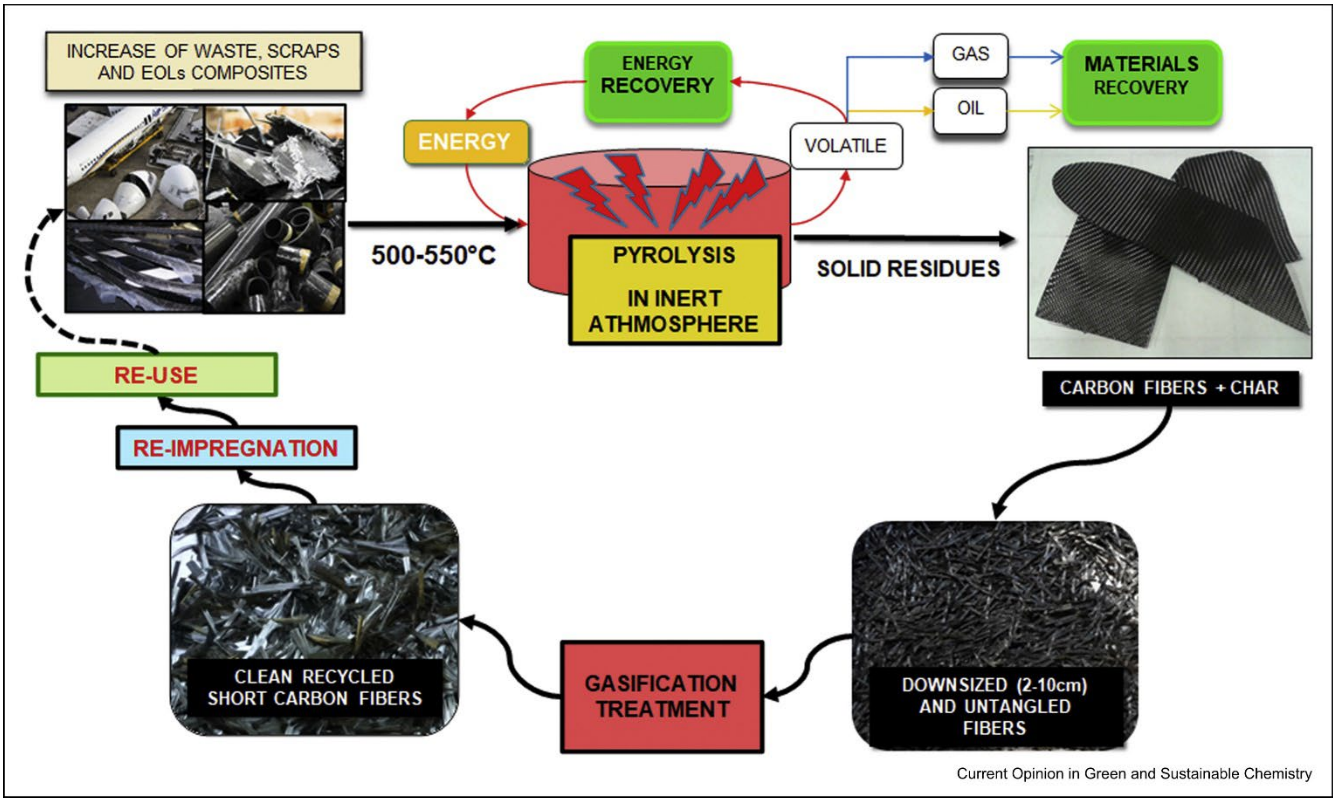
- Stabilizing: Fiber is heated in air to 392°F to 572°F (200°C to 300°C) to enable more stable bonding.
- Carbonizing: The stabilized fibers are heated to 1,832°F to 5,432°F (1,000°C to 3,000°C) at high pressure in an oxygen-free environment. This enables the expulsion of noncarbon atoms, ensuring more tightly bonded carbon crystals aligned parallel to the long axis of the fiber.
- Treating the surface: The fiber surface is oxidized to enable better bonding and roughness of the surface. The uncured carbon fibers have surfaces that do not bond very well with the composites. Adding oxygen provides better chemical bonding in composites and rough surfaces for better mechanical properties.
- Sizing: After the surface treatment, the fibers are coated to protect them from damage during winding or weaving.



Source: Teijin (n.d.) *(211)*.

Figure 6.2: Carbon fiber production process flow diagram.

Recycled carbon fibers can be produced from carbon fiber manufacturing scraps as well as from thermal and chemical processes of CFRP scraps and EOL products like planes. Figure 6.3 shows the pyrolysis process of carbon fiber materials recovery from composites. In this process, materials are heated in an inert atmosphere at temperatures of 932°F to 1022°F (500°C to 550°C), and the resulting solid residue is downsized to sizes of 0.79 to 3.94 in. (2 to 10 cm), which, after gasification treatment, produces clean recycled short carbon fibers.



Source: Giorgini et al. (2020) *(212)*.

Figure 6.3: Recovery of carbon fibers from composite waste using pyrolysis and gasification process.

6.4 Physical and Chemical Properties of Carbon Fibers

Carbon fibers have excellent engineering properties that enable their application in high-value and high-performance engineering products. Carbon fibers are usually 0.00023 in. to 0.79 in. (6 to 20 µm) in diameter and can vary in length *(213)*. The fiber lengths used in concrete in different studies range from 0.006 in. (150 µm) to as long as 1.97 in. (50 mm) *(207,214,215)*. They are light in weight compared to steel fibers, and unlike steel, glass, and polymeric fibers, carbon fibers are resistant to corrosion, acid, and alkali attacks. The favorable properties of carbon fibers for concrete use are the following *(210,213,216)*:

- Low specific weight, which is important for lightweight requirements
- High tensile strength of 5.8 to 725 ksi (40 to 5000 MPa) and modulus of 1,015 to 58,015 ksi (7 to 400 GPa)
- Low creep rate and fatigue
- Low thermal expansion and conductivity
- High electrical conductivity - enables smart sensing
- Chemical inertness and high durability
- Resistance to organic solvents, acids, and alkali attacks
- Noncorrosive property of carbon fibers
- Good fire-resistant capacity

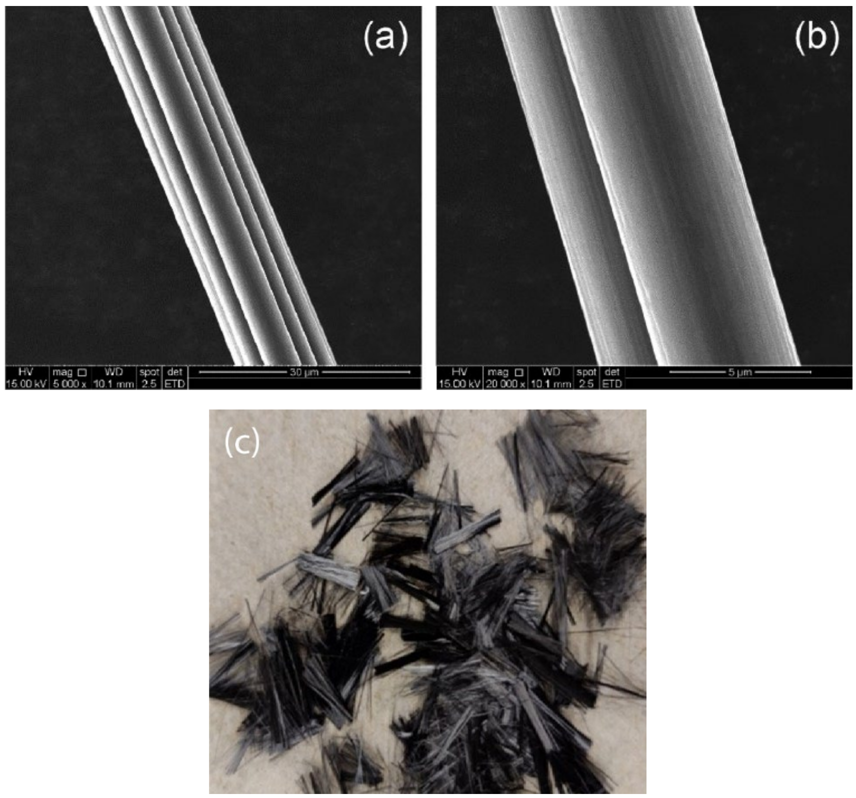
These properties make carbon fiber a strong candidate over metal and other fiber types for many engineering applications. A comparison of carbon fibers with other kinds of fibers is shown in Table 6.1.

Table 6.1: Comparison of Different Types of Fibers in Terms of Mechanical Properties and Weight

Type of Fiber	Tensile Strength (Ksi) [MPa]	Young's Modulus (Ksi) [GPa]	Ultimate Elongation (%)	Specific Gravity
Acrylic	31-61 [210-420]	305 [2.1]	25-45	1.1
Asbestos	81-142 [560-980]	12183-20305 [84-140]	0.6	3.2
Carbon	261-377 [1800-2600]	33359-55114 [230-380]	05	1.9
Glass	152-558 {1050-3850]	10153 [70]	1.5-3.5	2.5
Nylon	112-122 [770-840]	609 [4.2]	16-20	1.1
Polyester	107-127 [735-875]	1218 [8.4]	11-13	1.4
Polyethylene	102 [700]	20-61 [0.14-0.42]	10	0.9
Polypropylene	81-112 [560-770]	508 [3.5]	25	0.9
Rayon	60.9-91.4 [420-630]	1015 [7]	10-25	1.5
Rock Wool	71.1-111.7 [490-770]	10153-17249 [70-119]	0.6	2.7
Steel	40.6-400.6 [280-2800]	29443 [203]	0.5-3.5	7.8

Source: Yurtseven (2004) *(217)*.

Another feature of carbon fibers is their electrical conductivity, which can be used in smart infrastructure applications, such as self-sensing material. One study demonstrated that electrical resistivity is strongly correlated with cyclic compression loading, which may enable structural health monitoring nondestructively by sensing the change in the internal stress-strain of the structure *(218)*. Figure 6.4 shows the SEM images of carbon fiber strands with multiple filaments.



Source: de Souza et al. (2020) *(207)*.

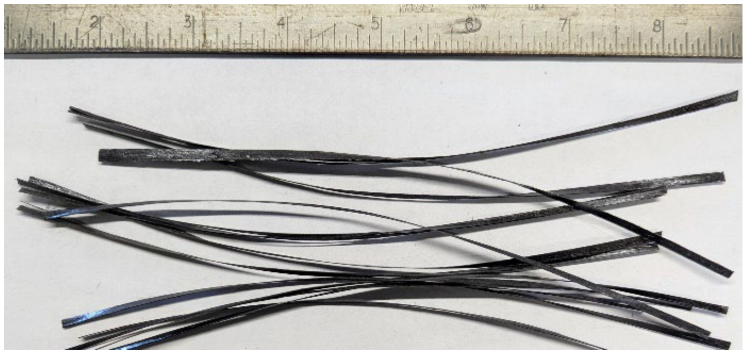
Figure 6.4: (a, b) SEM image of carbon fiber at different magnitudes and (c) image of chopped carbon fibers.

6.5 Identified Suppliers of Carbon Fibers for Concrete Applications

Table 6.2 shows the suppliers of carbon fibers in the United States. C4Labs is a startup company that produces recycled carbon fibers from Toray Industries' excess carbon fiber production. It can customize the size of carbon fibers for concrete and other applications. Figure 6.5 shows the as-received and chopped carbon fibers produced by C4Labs.

Table 6.2: Suppliers of Carbon Fibers in the United States

<table>
<tr><th>Company Name</th><th>Location</th><th>Source Material</th><th>Product Description</th></tr>
<tr><td>C4Labs</td><td>Tacoma, Washington</td><td>Carbon fibers from Toray Industries</td><td>Recycled carbon fibers</td></tr>
<tr><td>US Composites Inc.</td><td>West Palm Beach, Florida</td><td>—</td><td rowspan="10">Virgin carbon fibers</td></tr>
<tr><td>Fiber Glast</td><td>Brookville, Ohio</td><td>—</td></tr>
<tr><td>Gurit USA Inc.</td><td>Bristol, Rhode Island</td><td>—</td></tr>
<tr><td>Toray Carbon Fibers America</td><td>Decatur, Alabama</td><td>—</td></tr>
<tr><td>Protech Composites</td><td>Vancouver, Washington</td><td>—</td></tr>
<tr><td>Coposite One LLC</td><td>Miami Gardens, Florida</td><td>—</td></tr>
<tr><td>Zoltec Corporation</td><td>Bridgeton, Missouri</td><td>—</td></tr>
<tr><td>M9 USA</td><td>Woodinville, Washington</td><td>—</td></tr>
<tr><td>Rock West Composites</td><td>West Jordan, Utah</td><td>—</td></tr>
<tr><td>ACP Composites</td><td>Livermore, California</td><td>—</td></tr>
<tr><td>Mitsubishi Rayon Carbon Fiber & Composites, Inc.</td><td>Irvine, California</td><td>—</td><td>Carbon fiber, composites</td></tr>
<tr><td>Teijin Carbon America Inc.</td><td>Rockwood, Tennessee</td><td>—</td><td>Chopped and milled carbon fibers</td></tr>
</table>



(a)

(b)

Figure 6.5: (a) Carbon fibers as received from C4Labs and (b) carbon fibers after chopping to a smaller size.

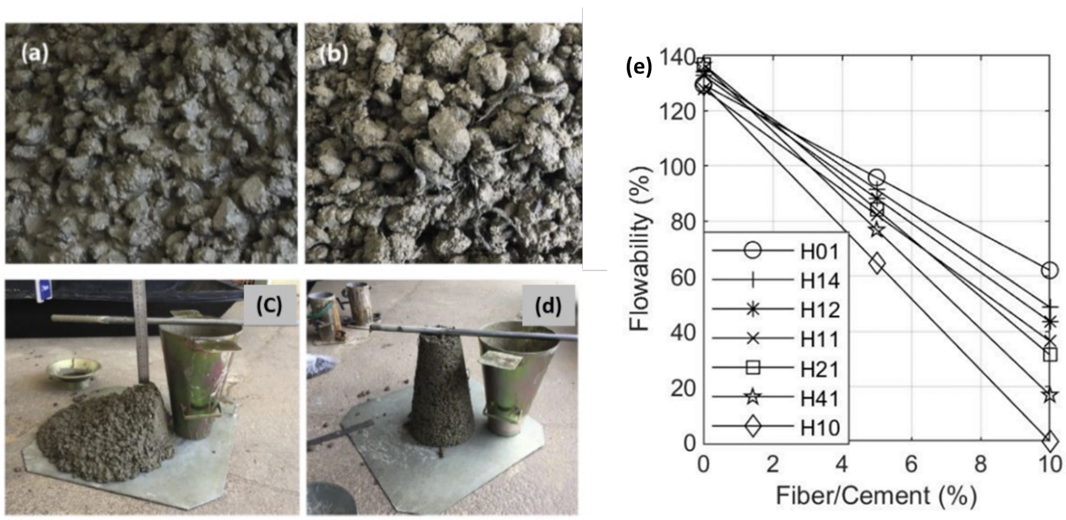
6.6 Performance in Concrete Based on Technical Literature

6.6.1 *Dispersion*

Good dispersion of carbon fibers is essential for the desired performance of fibers in reinforced composites. Optimization of the mixing process can enable better dispersion of the fibers. It was shown that adding fibers before the cement is added is better than adding fibers after the cement *(219)*. The doses of carbon fibers used in cementitious composites range from 0.1 to 10 wt%, with 2 wt% the most common dose found in the literature *(207,213,215,220)*.

6.6.2 *Impact of Carbon Fibers on the Workability of Concrete*

One study showed that carbon fibers reduce the flowability of mortar compared to the control mix without any fibers *(215)*. The workability is dependent on fiber characteristics (fiber size and doses). Milled fibers processed in an in-house milling system by commercial carbon fiber suppliers with a smaller length than the chopped fibers showed better workability compared to the chopped fibers at a dose of 2 wt%. The study concluded that workability can be improved by changing the fiber size distribution. Increasing the fiber doses has a linear inverse relationship with workability (Figure 6.6). The higher the doses of carbon fiber, the less flowability or workability is achieved. Another study used 2 wt% carbon fiber of cement in concrete and noticed a remarkable decrease in workability measured by the inverted cone slump test *(221)*. The carbon fiber concrete sample had a zero-slump value compared with the 6 in. (155 mm) slump of plain concrete. However, using chemical admixture can improve the workability of the concrete with carbon fiber to produce a more workable concrete. Carbon fibers were also found to decrease the segregation of self-consolidating concrete by reducing the fluidity of concrete .

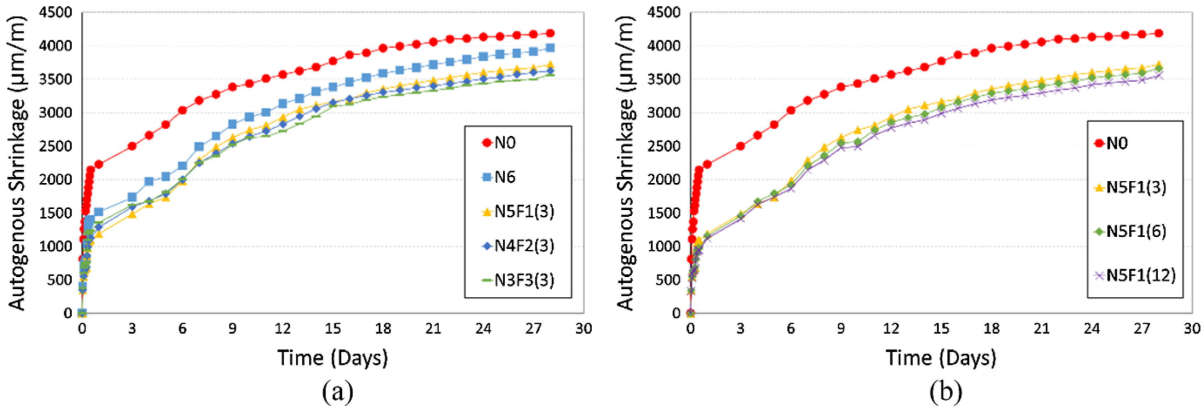


Source: de Souza et al. (2020) *(207)*; Abdellatef et al. (2022) *(215)*.

Figure 6.6: Influence of carbon fiber volume on the flowability of cementitious composites (a) fresh plain concrete and (b) fresh carbon fiber-reinforced concrete (c) slump test on plain concrete, (d) slump test on carbon fiber-reinforced concrete, and (e) flowability of fresh cementitious composites with carbon fiber different carbon fiber doses.

6.6.3 *Impact of Fibers on Plastic and Drying Shrinkage*

The incorporation of carbon fiber reduces the autogenous shrinkage of cementitious composites. A study examined the effect of carbon nanotubes (CNT) and carbon fibers on the autogenous shrinkage performance of mortar systems *(222)*. It reported a decrease in autogenous shrinkage with the inclusion of carbon fibers. Figure 6.7 shows that increasing the doses and sizes of carbon fibers reduces the shrinkage of cement paste.



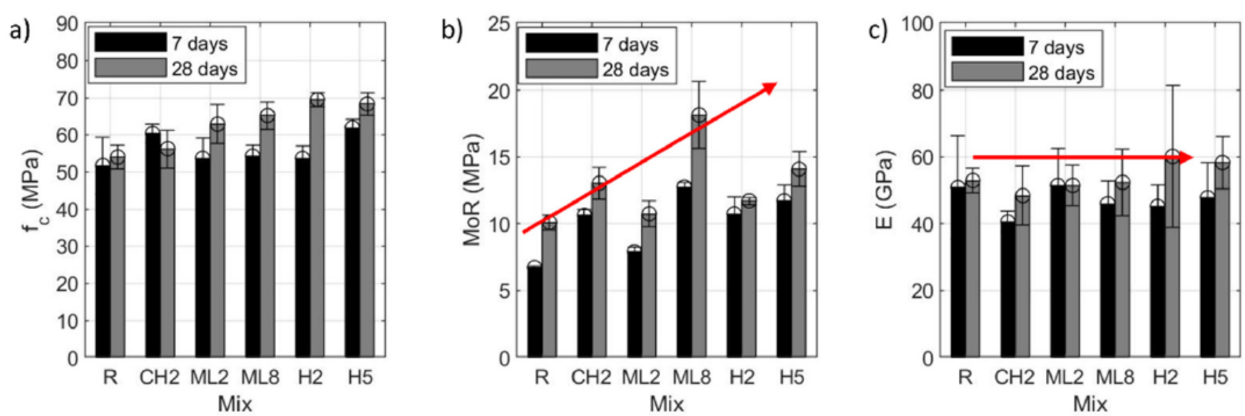
Notes: N0: Plain mortar; N6: Cement paste with 0.6 wt% CNT of cement mass; N5F1(3): Cement paste with 0.5 wt% CNT and 0.1 wt% 3mm carbon fiber of cement mass; N4F4(3): Cement paste with 0.4 wt% CNT and 0.2 wt% 3mm carbon fiber of cement mass; N3F3(3): Cement paste with 0.3 wt% CNT and 0.3 wt% 3mm carbon fiber of cement mass; N5F1(6): Cement paste with 0.5 wt% CNT and 0.1 wt% 6mm carbon fiber of cement mass; N5F1(12): Cement paste with 0.3 wt% CNT and 0.1 wt% 12mm carbon fiber of cement mass.

Figure 6.7: Effect of carbon fibers and carbon nanotube on the autogenous shrinkage of cement paste: (a) various doses of CF and CNT and (b) fiber sizes.

6.6.4 *Impact of Carbon Fibers on Strength and Toughness of Concrete*

Most studies reported a positive effect of carbon fiber addition on the mechanical properties of FRC. One study reported a 15% improvement in compressive strength with 2% waste carbon fiber *(207)*. Improved bond resistance and reduction in crack propagation were attributed to the improvement in compressive strength. Carbon fibers could increase the compressive strength of cementitious composites depending on the fiber size distribution and fiber volumes *(215)*. Under compression, a loading crack initiates at the matrix interface, and materials fail under multiple cracks. Fiber size distribution has a significant influence on the compressive strength of cementitious composites. Long fibers help to reduce crack propagation rather than the initiation of the cracks. On the other hand, short fibers contribute more to delaying crack initiation. Milled carbon fibers with shorter lengths at 2 wt% and 8 wt% fiber doses significantly improved the compressive strength, while chopped fibers with higher lengths could not produce a significant influence on compressive strength. However, hybrid fibers of two different sizes produced 25% and 11% higher compressive strength compared to the individually sized chopped and milled fibers. A good fiber size distribution by using hybridization of different micro-sized fibers improved the packing density and hence demonstrated better compressive strength.

Fiber parameters are important factors that may affect the performance of fiber-reinforced cementitious materials. The mixing process of cementitious composites can change the fiber length based on the strength and initial length of the fibers. One study investigated the effect of different commercial fibers with varying properties and lengths due to the mixing process on the tensile properties of carbon FRC *(213)*. The difference in fiber properties produced significantly different composites (Figure 6.8). Carbon fiber can improve the tensile strength four times, and strain capacity can be improved up to 90 times, allowing a ductile failure mode compared to plain concrete *(213)*. Larger diameter and strain capacity fibers may yield better performance despite having less strength and modulus because they prevent fiber breakage during mixing and under loading conditions *(213)*. In one study, a 21% improvement was reported in tensile strength with 2% carbon fibers, which was statistically significant at a 95% confidence level. Carbon fibers, due to their excellent properties, improve the transition zones and reduce crack formation and propagation, contributing to the better tensile strength of the concrete. However, another study did not find any significant influence with 2%, 3%, and 4% carbon fiber by weight of cement on the compressive strength of mortar specimens *(214)*.

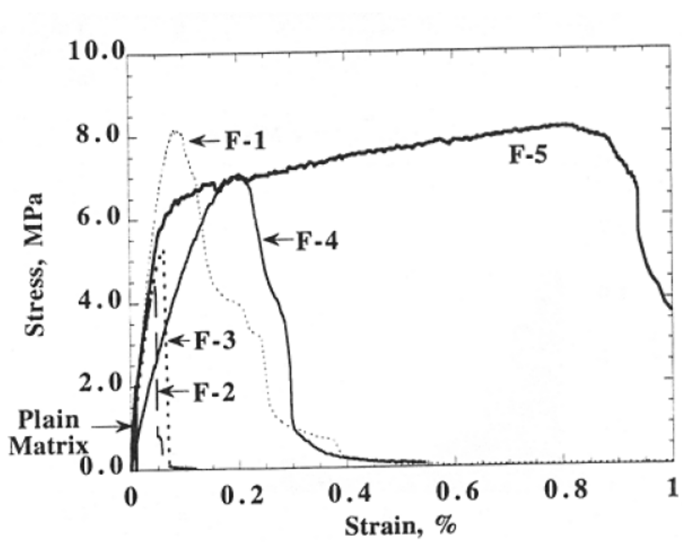


Notes: R: Control mix, CH2: 2 wt% chopped fiber mix, ML2: 2 wt% milled fiber mix, ML8: 8 wt% milled fiber mix, H2: 2 wt% hybrid fiber mix, H5: 5 wt% hybrid fiber mix.

Source: Abdellatef et al. (2022) *(215)*.

Figure 6.8: Effect of carbon fibers on cementitious composites (a) compressive strength, (b) flexural strength, and (c) modulus of elasticity.

The inclusion of carbon fibers, in general, improves the MOR and fracture toughness (Figure 6.9). The longer fiber size group and higher dose of fibers performed better in terms of fracture flexural strength and fracture toughness. However, carbon fiber could not produce any significant effect on elastic modulus *(207,215)*. A study reported up to a 129% improvement in flexural strength in cement mortar with 4% microfiber *(214)*. For maximum performance in terms of flexural strength and fracture energy, the optimum fiber size should be close to the critical length of the fiber, which is the length at which the fiber will go through both pullout and debonding.



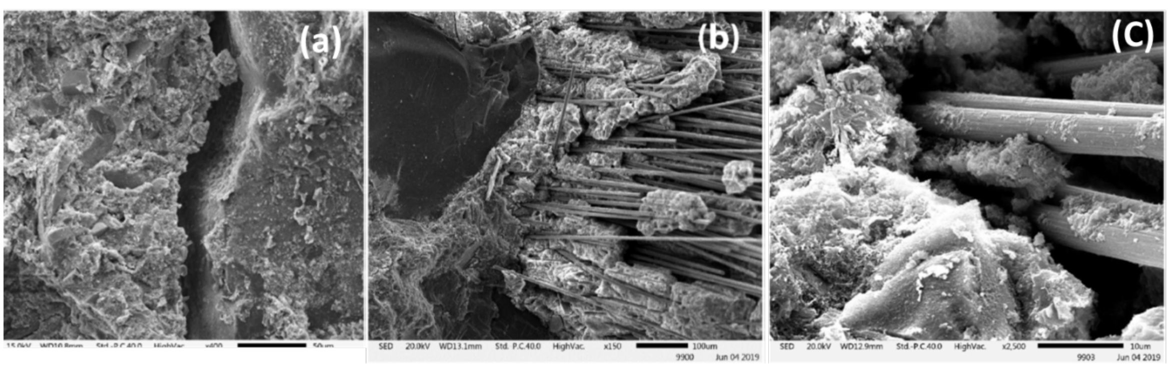
Notes: F-1 through F-5 are commercially available carbon fibers with varying properties (length, diameter, modulus) and yielded significantly different composite behaviors.

Source: Li and Obla (1994) *(213)*.

Figure 6.9: Stress-strain curve from uniaxial tension test with different carbon fibers.

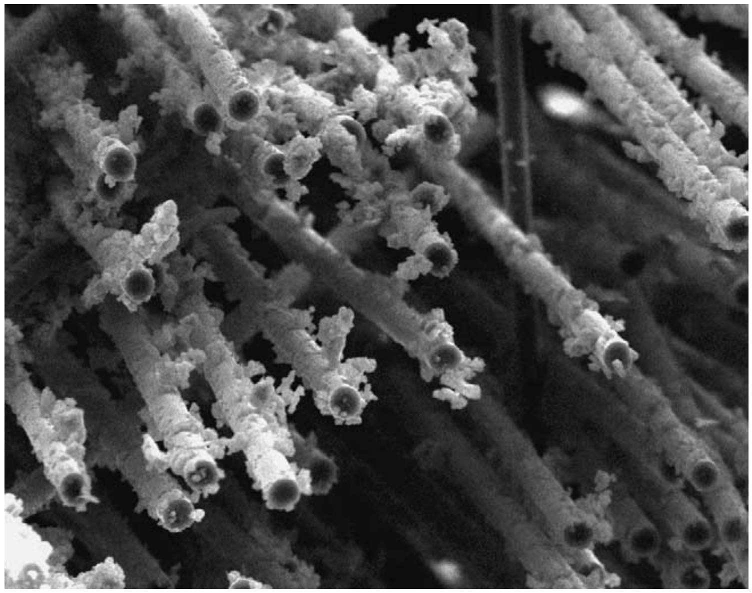
The composite behavior of the fiber matrix mainly depends on the interfacial characteristics. Interfacial bonds are hence important to effectively use the high strength of the fibers in the composites. Higher bond strength leads to higher strength and ductility *(223)*. Interfacial bonding largely depends on fiber properties (diameter, surface morphology, and functional groups). A study used two carbon fibers of varying diameters *(223)*. Cement composites containing smaller diameter fibers (10 µm) produced a bond strength of 72.5 psi (0.5 MPa), which was improved by 50% to 100% by densifying the matrix with a lower w/c ratio and using silica fume. For the larger diameter fiber (46 µm), the improvement in bond strength was between 370% and 670% with the inclusion of silica fume. Carbon fibers with surface grooves allow the cement matrix to penetrate the groove to provide mechanical interlock and increase the bond strength. However, due to the micro size of the groove, cement products sometimes could not enter the groove. In that case, ultrafine materials like silica fume make the interface denser and increase the interfacial bond strength.

Scanning electron microscope (SEM) micrographs (Figure 6.10) of plain and carbon fiber concrete show that carbon fibers are present in the reinforced specimens and bridge across cracks *(207)*. Carbon fibers not only bridge across cracks but can also reduce the number of cracks. Carbon fiber improves the matrix-aggregate interfacial zone and prevents the formation of large cracks in the interface, contributing to the concrete's mechanical strength *(207)*. In addition, carbon fibers show good compatibility with cement composites. An SEM image (Figure 6.11) of pulled-out fibers from the cement matrix shows good penetration of the matrix into the carbon fibers and the formation of hydrates on the fiber surface, which suggests good interface bonding with the cement matrix *(216)*.



Source: de Souza et al. (2020) *(207)*.

Figure 6.10: SEM shows the microstructure of concrete specimens after compression test for (a) plain concrete and (b) 2% carbon fiber.



Source: Badanoiu and Homgren (2003) *(216)*.

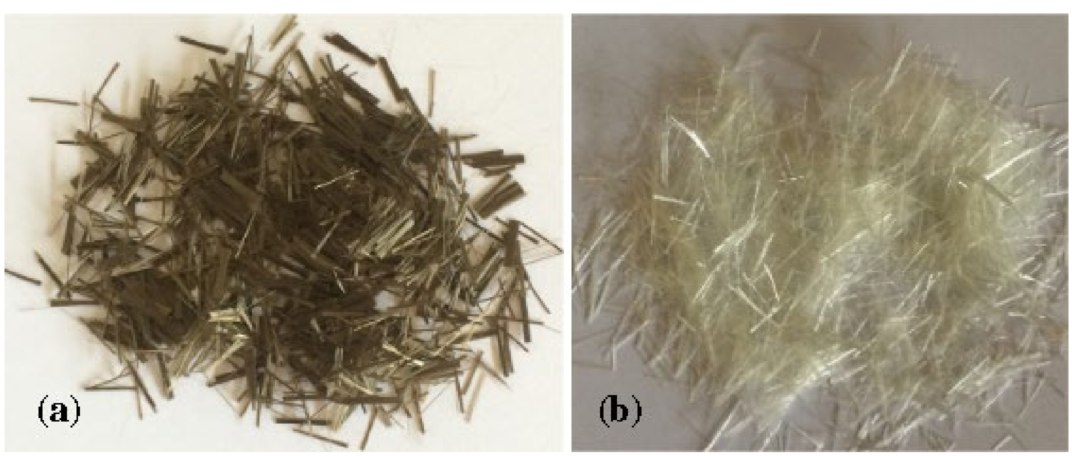
Figure 6.11: Fiber pulled out from mortar shows the presence of hydrates on fibers.

7 GLASS FIBERS

7.1 Introduction

Glass fibers are included in this review because they are made from naturally occurring rocks or minerals. The parent mineral (a mix of silica, alumina, boron, iron, potassium, magnesium, and sodium oxides) is melted and extruded into filament while being coated with the appropriate sizing material for bonding with the matrix of the end application *(17,19)*. Glass fibers were first introduced in cement concrete composites as reinforcement in 1931 *(16)*. Since then, they have been considered fiber reinforcement in concrete for their properties, such as low specific weight and negligible water absorption *(4)*. The annual consumption of glass fibers exceeds 5 million metric tons globally *(224)*. Industries such as construction, aerospace, automotive, and energy produce substantial waste glass as byproducts or waste products that can be reused as glass fiber-reinforced composites *(16)*. Glass fiber-reinforced polymers, due to their excellent mechanical properties and low cost, find their use in 90% of all composite products *(225,226)*.

Depending on the parent material composition, glass fibers can be classified as silica glass (SG) fibers and basalt glass (BG) fibers *(17)*. The main difference between these two glass fibers is primarily in their chemical composition *(19)*. Silica glass fibers are generally manufactured with alkali-resistant properties, meeting the ASTM C1666 (2015) standard. Figure 7.1 shows an example image of the two types of glass fibers: basalt glass and silica glass.



Source: Kizilkanat et al. (2015) *(18)*.

Figure 7.1: (a) Basalt fibers and (b) silica fibers.

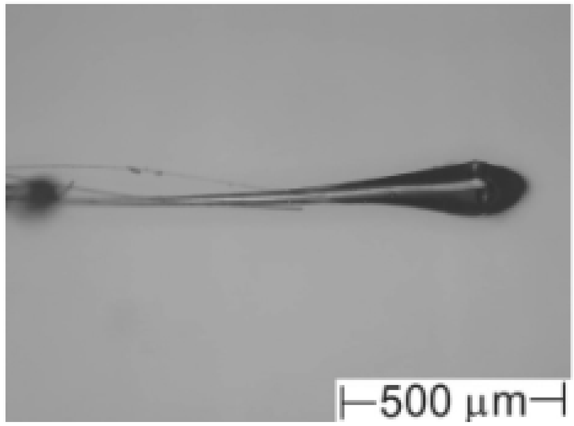
7.2 Feedstock Description: Glass

7.2.1 *Silica Glass Fibers*

Typically, inorganic glass is made from an amorphous silicon-oxygen network *(227)*. The first type of glass fiber used in cement concrete was made from electrical grade glass, known as E-glass, and was prone to degradation in alkali environments *(17)*. Due to this limitation of these SG fibers, alkali-resistant (AR) SG glass fibers were developed. The glass composition of alkali-resistant glass fibers is approximately 16% zirconium oxide *(227)*. The wind energy sector is a great source of feedstock for SG fibers and is expected to produce approximately 6.6 million US tons (6 million tonnes) of glass fiber-reinforced polymer over the coming decade *(226)*. Assuming a 50% yield of glass fibers from the source polymer, 6.6 million US tons can produce up to 400 million yd^3 (305 million m^3) of glass fiber-reinforced concrete at a dosage rate of 15 lb./yd^3 (9 kg/m^3). The dosage rate was based on the standard glass fiber dosage suggested by major glass fiber manufacturers for concrete bridge decks. Wind turbine rotor blades are a major source of SG fibers *(226)*. Mechanical grinding is adopted as a successful recycling method for glass fibers, which involves shredding, milling, and grinding of the composite to produce SG fibers of a size smaller than the original scrap material *(228)*. In one study, a novel zig-zag air separator method was developed to produce SG fibers with mechanical properties similar to virgin composite fibers *(226,228)*.

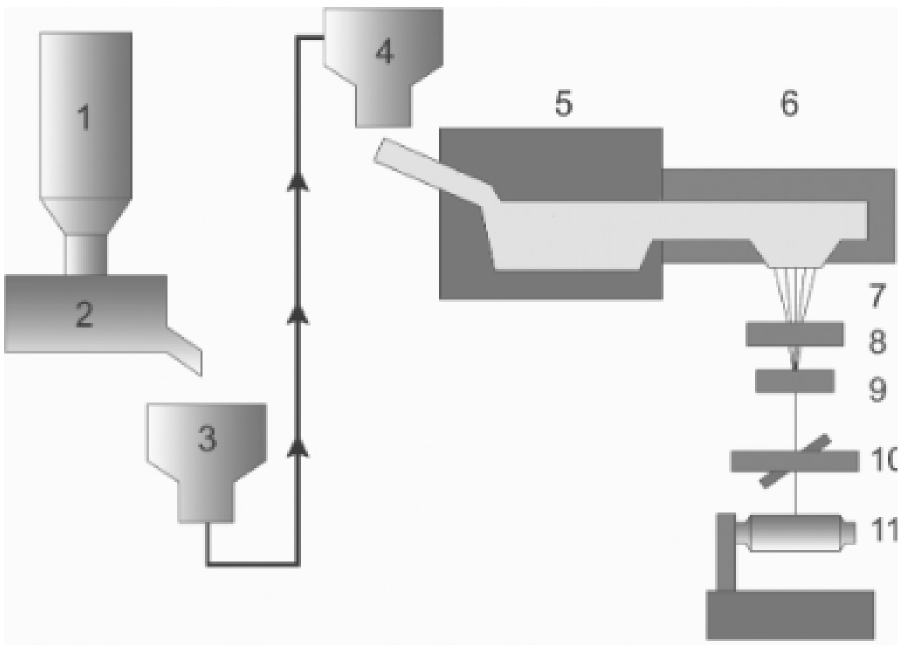
7.2.2 *Basalt Glass Fibers*

Basalt fibers are produced directly from crushed basalt stone. It is an igneous rock and is found in most countries around the world. Since it is an igneous rock, it originates in a molten state and thus is amorphous in nature *(229)*. A melt-blowing technology is often adopted to melt the basalt stone, and then an air blast is used to produce glassy amorphous basalt fibers. This method is known as the Junkers method *(19,230)*, and basalt fibers produced using this method are shown in Figure 7.2. Continuous BG fibers are produced using the spinneret method, shown in Figure 7.3.



Source: Deák and Czigány (2009) *(19)* ; Vas et al. (2007) *(230)*.

Figure 7.2: Short basalt fibers produced by Junkers method.



Notes: A simplified scheme of a basalt fiberization processing line: (1) crushed stone silo; (2) loading station; (3) transport system; (4) batch charging station; (5) initial melt zone; (6) secondary heat zone with precise temperature control; (7) filament forming bushings; (8) sizing applicator; (9) strand formation station; (10) fiber tensioning station; (11) automated winding station.

Source: Deák and Czigány (2009) *(19)*.

Figure 7.3: Spinneret method to produce continuous basalt fibers.

7.3 Physical and Chemical Properties of Glass Fibers

7.3.1 *Silica Glass Fibers*

Silica glass fibers have a specific gravity of 2.6 to 2.7 and negligible water absorption. The length of SG fibers varies from 0.24 to 0.80 in. (6 to 18 mm), and the diameter is approximately 0.0008 in. (0.02 mm). The tensile strength of SG fibers is reported to be 500 ksi (3400 MPa), and the modulus of elasticity is between 11,000 and 11,600 ksi (77 and 80 GPa) *(16,18,231)*. The chemical composition of a typical glass fiber comprises SiO_2 (60%), CaO (20%), and Al_2O_3 (12%). In addition to these three oxides, there are trace elements of iron, potassium, magnesium, and sodium in SG fibers *(19)*. ASTM C1666 specifies the physical and chemical requirements for alkali-resistant glass fibers, shown in Table 7.1.

Table 7.1: Test Requirements for Alkali-Resistant Glass Fiber

Property	*Specification Value*	*Method of Test*
Zirconia content (ZrO_2)	16% min	X-ray fluorescence
Density	2.68 ± 0.3 g/cm^3 [1.67.0 ± 19 lb./ft^3]	ASTM D3800
Tensile strength	1.0-1.7 GPa [145 x 10^3 – 246 x 10^3 psi]	ASTM D2256, ISO 3341, JISR 3420
Range of filament diameters	8-30 µm [31 x 10^{-5} – 118 x 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 ^oC [176 ± 2 ^oF] ≥250 MPa [36,250 psi] for water-dispersible strands ≥350 MPa [50,750 psi] for integral strands	EN 14649

Source: ASTM C1666.

7.3.2 *Basalt Glass Fibers*

Basalt glass fibers have a specific gravity of 2.8. They have a length of 0.5 in. (12 mm) and a diameter of 0.0007 to 0.0008 in. (0.013 to 0.02 mm). The modulus of elasticity of basalt fibers is reported to be 13,000 ksi (89 GPa), and tensile strength is 600 to 670 ksi (4100 to 4800 MPa) *(18)*. The percentage elongation of BG fibers is 3.15%, which is 0.60% higher than SG fibers *(*21*)*. The chemical composition of BG fibers consists of SiO_2 (40% to 50%), Al_2O_3 (14% to 17%), Fe_2O_3 (10% to 11%), CaO (8% to 9%), and less than 10% each of potassium, magnesium, sodium, and titanium *(19)*.

7.4 Identified Suppliers of Glass Fibers for Concrete Applications

7.4.1 *Silica Glass Fibers by Owens Corning (Toledo, Ohio)*

Owens Corning has been manufacturing glass fibers for more than 50 years. It produces 30 to 40 fiber products for concrete. However, it recommends Anti-CRAK HP 67/36 for concrete pavement slabs-on-ground and overlay applications. Figure 7.4 shows a representative sample of this SG fiber by Owens Corning. HP 67/36 is made from alkali-resistant silica glass with 17% zirconium. The glass used to produce HP 67/36 is sourced from virgin material, and recycled glass is rejected for this purpose due to the presence of contaminants. The silica sand used to produce this fiber is mined in China, and the main production operation unit is based in China. A silane-based binder or glue is used to hold the glass filaments together. Since this is an alkali-resistant glass fiber, zirconium passivates the alkali reaction. However, some deformation can be seen on the surface when exposed to an alkaline environment inside the concrete. The HP 67/36 has a length of 1.5 in. (36 mm) and an aspect ratio of 67. The modulus of elasticity of this fiber is 10 x 10^6 psi (72 GPa), and the tensile strength is 145 ksi (1000 MPa). The specific gravity of this fiber is 2.68, which is typical for SG fibers, and moisture absorption is less than 0.50%. To avoid degradation of the SG fibers while concrete mixing, HP 67/36 should be added toward the end of the mixing process. This SG fiber does not generate any clumping or balling issues while mixing and does not impact the workability of fresh concrete when added at recommended dosages. For bridge decks, the recommended dosage of HP 67/36 fiber is 15 lb./yd^3 (9 kg/m^3). This fiber is used at the macroscale and helps mitigate plastic and drying shrinkage cracking, improving fatigue and impact resistance and durability. The cost of HP 67/36 fiber, when it reaches the ready-mix concrete suppliers, is approximately $3 to $4/lb. ($7 to $8/kg).

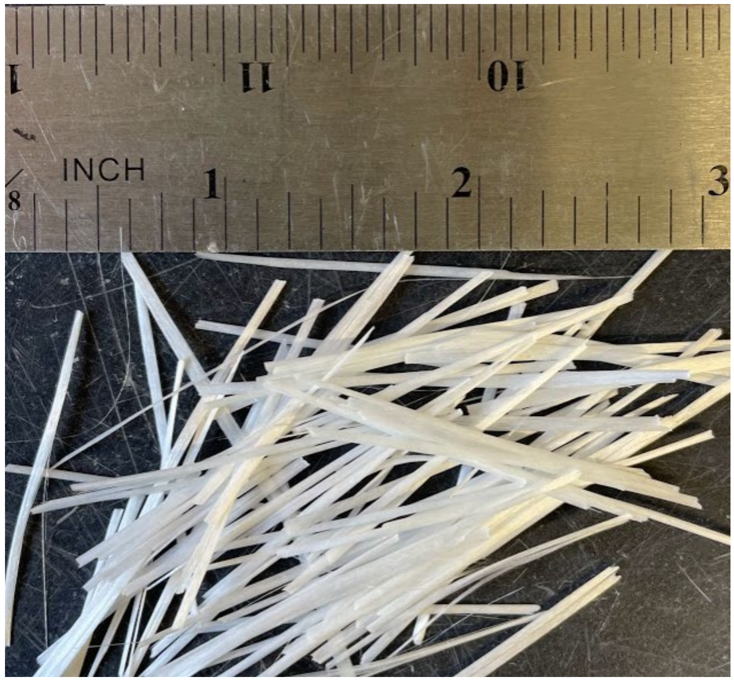


Figure 7.4: A picture of a sample of Anti-CRAK HP 67/36 silica glass fibers.

7.4.2 *Basalt Glass Fibers by Mafic (Shelby, North Carolina)*

Mafic produces basalt chopped fibers as chopped basalt filaments for concrete applications. The feedstock for this fiber is natural basalt rock, and a silane-based binder is used as the sizing ingredient. Mafic BG fibers vary in length from 0.1 to 4.0 in. (3 to 96 mm) and have a diameter of 0.35 to 0.75 mils (9 to 19 µm). The specific gravity of Mafic basalt fibers is 2.63.

7.4.3 *Basalt Glass Fibers by Technobasalt (Kyiv, Ukraine)*

Technobasalt produces basalt fibers in the form of crumbly monofilaments or complex basalt fibers glued together. Technobasalt BG fibers vary in length from 0.1 to 4.0 in. (5 to 100 mm) and have a monofilament diameter of 0.35 to 0.75 mils (9 to 16 µm). An example image of this BG fiber is shown in Figure 7.5. The specific gravity of Technobasalt basalt fibers is 2.8 to 3. The modulus of elasticity of this fiber is 11,500 to 16,000 ksi (79 to 110 GPa), and the tensile strength is 160 to 200 ksi (1100 to 1400 MPa) *(232)*.

Source: Technobasalt (n.d.) *(232)*.

Figure 7.5: Basalt fibers by Technobasalt.

7.4.4 *Summary of Findings from Glass and Basalt Fiber Suppliers*

A summary of the identified glass fiber suppliers and the properties of their fiber products is provided in Table 7.2. The table presents gathered information from three identified fiber suppliers: Owens Corning, Mafic, and Technobasalt. These suppliers use silica sand and basalt rock as their source materials. Fiber lengths vary from 0.1 to 4.0 in. (3 to 100 mm), while the aspect ratio is provided only for Owens Corning as 67. Fiber diameters range from 0.35 to 0.75 mils (9 to 19 µm). Specific gravity ranges from 2.63 to 2.8. Ultimate tensile strength varies from 145 ksi to 160 to 200 ksi (1000 to 1400 MPa). Owens Corning claims its fibers mitigate plastic and drying shrinkage cracking. Cost information is unavailable for Mafic and Technobasalt.

Table 7.2: Summary of Properties of Identified Glass Fibers in This Study

Fiber Supplier/Property	Owens Corning	Mafic	Technobasalt
Source material	Silica sand	Basalt rock	Basalt rock
Fiber length	1.5 in. (36 mm)	0.1-4.0 in. (3-96 mm)	0.1-4.0 in. (5-100 mm)
Aspect ratio	67	—	—
Fiber diameter	—	0.35-0.75 mils (9-19 µm)	0.35-0.7 mils (9-16 µm)
Specific gravity	2.68	2.63	2.8-3
Ultimate tensile strength	145 ksi (1000 MPa)	—	160-200 ksi (1100-1400 MPa)
Advantage to concrete per manufacturer	Mitigates plastic and drying shrinkage cracking	—	—
Cost per pound (cost per kg) excluding shipping cost	\$3-\$4 (\$6.5-\$8.5)	—	—

7.4.5 *Other Basalt and Glass Fiber Manufacturers*

There were several other glass fiber manufacturers identified. A list of these manufacturers is provided in Table 7.3. These suppliers will be contacted during the next phase of the project as they are mostly located outside of California, and some are located outside the United States and may not support the US market.

Table 7.3: Other Glass Fiber Manufacturers

Manufacturer Name	Product Name	Location	Website
Basanite Industries	BasaMix	Pompano Beach, Florida	basaniteindustries.com/basamixtrade.html
Basalt Fibers Green Reinforcement	Chopped fibers in concrete	T'bilisi, Georgia	basalt-fibers.com/chopped-fibers-in-concrete/
Basalt Reinforced Composites	Basalt composite fiber mix	Boca Raton, Florida	basaltreinforcedcomposites.com/products/
Kamenny Vek Advanced Basalt Fiber	Basalt chopped strands	Dubna, Moscow region, Russia	basfiber.com/products/chopped-strands

7.5 Performance in Concrete Based on Technical Literature

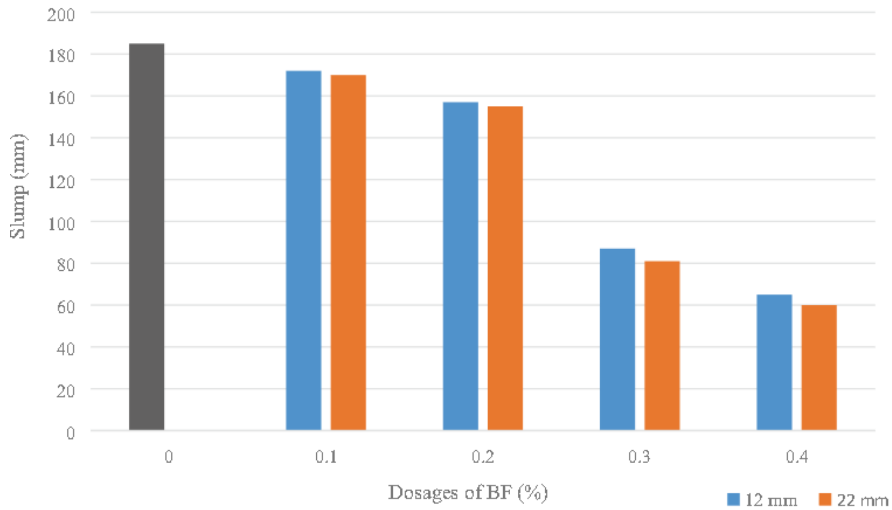
7.5.1 *Dispersion*

Silica glass fibers have been found to reduce the workability of fresh concrete due to their uneven dispersion into the concrete matrix when using conventional drum mixers. This uneven dispersion necessitates additional mixing or an increased w/c ratio *(227)*. However, additional mixing is not recommended to avoid damaging the fibers. To aid in the dispersion process and enhance resistance to mixture segregation, lubricating agents such as polyethylene oxide or carbonyl methyl cellulose can be added *(233)*.

7.5.2 *Impact of Fibers on the Workability of Concrete*

A study examined the behavior of SG chopped fibers in concrete. The findings indicated that the workability of concrete decreased as the volume of SG fibers increased. Adding 0.20 wt% of SG fibers, relative to the total cementitious material in the mix, led to zero-slump concrete. This reduction in workability was attributed to the binding nature of the reinforcement provided by the SG chopped fibers *(234)*. Another study suggested using a polycarboxylate-based water reducer to achieve the desired workability when incorporating SG fibers into concrete *(18)*.

Basalt glass (BG) fibers, when used at dosages higher than 0.2 vol% and longer than 1 in. (25 mm), were found to reduce the workability of concrete significantly, shown in Figure 7.6 *(235)*. However, other research has shown that BG fibers with a shorter length of 0.47 in. (12 mm) exhibited lower workability compared to BG fibers with a length of 0.86 in. (22 mm) *(236)*. This phenomenon was attributed to the higher fiber count in the concrete mix with shorter fibers, which reduces workability. Another study also reported that adding BG fibers, in general, reduced the workability of concrete due to forming an internal network structure. However, this reduction is less compared to the reduction in workability from PP fibers, and 0.5 vol% BG fibers resulted in a slump value of 2.56 in. (65 mm), whereas a similar load of PP fibers resulted in a slump value of 2.32 in. (59 mm) *(236)*.

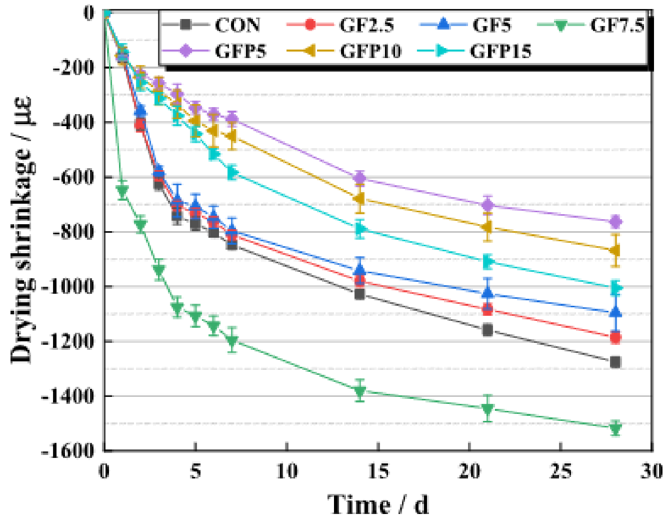


Source: Bheel (2021) *(235)*.

Figure 7.6: Effect of basalt fiber dosage and length (12 mm, 22 mm) on the concrete slump.

7.5.3 *Impact of Fibers on Plastic and Drying Shrinkage*

Silica glass (SG) fibers with a very high aspect ratio (1250) can effectively reduce plastic shrinkage cracking when applied at a dosage rate of less than 0.3 vol% in concrete. In one study, SG fibers incorporated into concrete at this dosage resulted in a 43% reduction in plastic shrinkage crack width and a 59% reduction in total plastic shrinkage crack area *(197)*. Another study reported a 30-day drying shrinkage strain of approximately 1,500 με with an SG fiber dosage of 0.75 vol% as a sand replacement in cement mortar *(237)*. Figure 7.7 shows that as the SG fiber ("GF" in the figure) dosage increases, the drying shrinkage strain also increases. The reason for higher drying shrinkage strain at a higher SG fiber volume was attributed to the increased chances of porosity of the mortar. This increased porosity results from inadequate or improper compaction of the concrete due to the formation of a dense skeleton structure when higher fiber volume dosages are used.



Source: Chen et al. (2021) *(237)*.

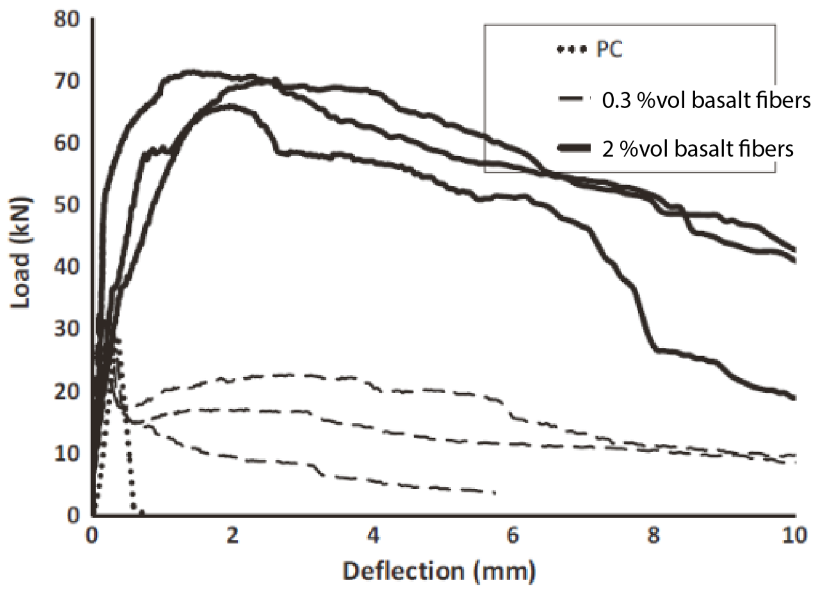
Figure 7.7: Effect of SG fibers (GF-Glass fibers; GFP-Glass fiber powder) on drying shrinkage of mortar.

Chopped BG fibers, in the form of filaments or strands, have the ability to reduce plastic shrinkage cracking in concrete *(17)*.The findings of one study suggested that the effective dosage for controlling plastic shrinkage cracking is 0.2 to 0.4 vol% of glass fibers with an aspect ratio greater than 200 *(238)*.

7.5.4 *Impact of Fibers on Strength and Toughness*

Silica glass fibers possess a high modulus of elasticity, ranging from 11,000 to 11,600 ksi (77 to 80 GPa), which aids in establishing strong connections with concrete *(239)*. Glass fibers have desirable physical and mechanical properties, which lead to increased compressive, split tensile, and flexural strength in concrete *(18)*.

A study applied 3 vol% of basalt glass (BG) fibers in concrete and observed no significant increase in modulus of elasticity or compressive strength properties. However, the split tensile strength exhibited a significant increase of 16% to 36% when BG fibers were incorporated into cement concrete with supplementary cementitious materials like silica fume or metakaolin *(240)*. On the other hand, another study found that the addition of micro basalt fibers at the low dose of 1 to 2 lb./yd³ (2 to 4 kg/m³) reduced compressive strength up to 18% but significantly enhanced flexural fracture energy up to 125% *(241)*. A different study demonstrated that incorporating chopped bundles of basalt filament microfibers could increase the pre-cracking flexural and compressive strength in concrete *(242)*, shown in Figure 7.8.

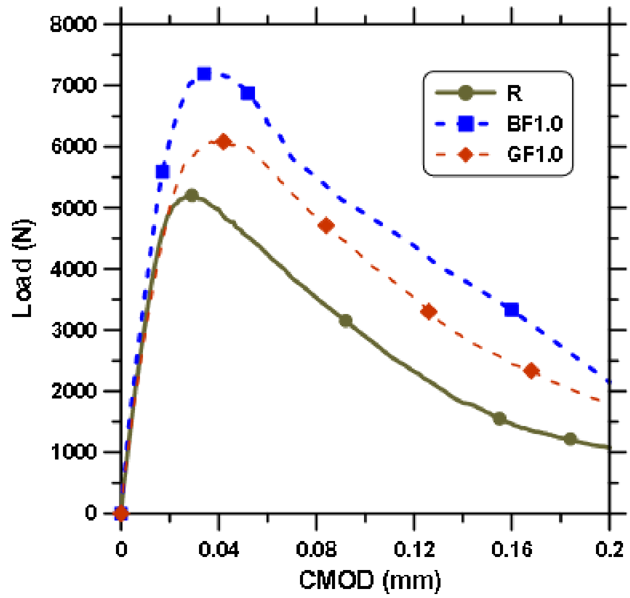


Source: Branston et al. (2016) *(242)*.

Figure 7.8: Load-deflection comparison plots for plain concrete and BG fiber-reinforced concrete.

7.5.5 *Impact of Fibers on Residual Strength or Post-Crack Strength*

A study investigated the effects of alkali-resistant macro-silica glass (SG) fibers on the post-crack flexural strength of concrete. It found that incorporating SG fibers at a dosage rate of 0.2 vol% to 0.6 vol% helped increase flexural strength by 59%. Additionally, it was observed that the residual strength was higher for smaller crack mouth openings, which was attributed to the high elastic modulus and strong bond properties between SG fibers and the concrete matrix *(243)*. However, another study reported that BG fibers have a higher crack mouth opening resistance compared to SG fibers, shown in Figure 7.9. This difference was attributed to the higher modulus of elasticity of BG fibers compared to SG fibers *(18)*.



Source. Kizilkanat et al. (2015) *(18)*.

Figure 7.9: Load-crack mouth opening displacement for SG and BG fibers.

7.5.6 *Impact of Fibers on Durability of Concrete*

Silica glass (SG) fiber-reinforced concrete exhibits an increasing resistance against chloride ion penetration with an increase in fiber volume fraction of up to 1.5% *(16)*. This improvement is attributed to the development of a denser concrete matrix when using SG fibers. Compared to polypropylene (PP) fiber-reinforced concrete, SG fiber-reinforced concrete demonstrates lower water absorption at a fiber volume fraction of 1.35% *(16)*. However, SG fiber-reinforced polymer rebars have shown durability issues when subjected to accelerated aging techniques, as they are susceptible to high-temperature exposure and aggressive chemical environments *(17)*. High-temperature exposure and aggressive chemical environments showed that SG fibers are susceptible to such extreme conditions. One study mentioned that such extreme events are not representative of the in-situ exposure conditions for SG fiber-reinforced concrete, and alkali deterioration of SG fibers may be avoided using resin impregnation *(17,244)*.

Basalt glass fibers have good resistance to salt, water, and corrosion *(235)*. A study reported that the application of BG fibers in concrete results in higher paste porosity *(236)*. The durability of BG fibers hugely decreases in an alkali environment, and as a result, zirconium coating is recommended in several studies *(245,246)*.

8 RECYCLED FIBERS FROM WINDMILL BLADES AND AUTOMOBILE AND PLANE MANUFACTURING

8.1 Introduction

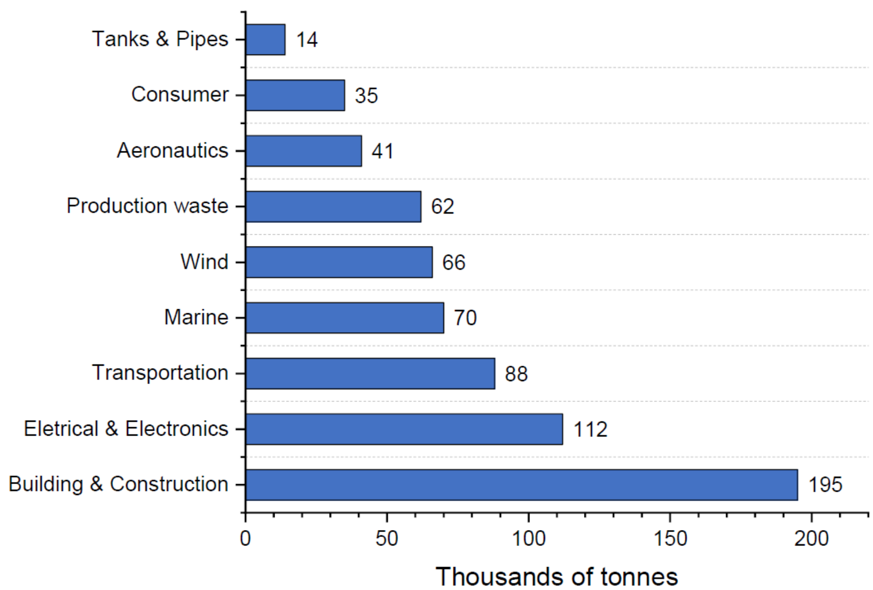
The manufacturing sector has increasingly used fiber-reinforced polymer composites over the last few decades, and growth is increasing gradually. The major sectors that use fiber-reinforced composites are renewable energy, aerospace, automobile, and defense. As the composite industry continues to grow, the question of recycling and reuse applications of composite scrap and end-of-life (EOL) products will emerge. Disposal of EOL products such as retired wind turbine blades and airplanes that use composites like glass fiber-reinforced polymer (GFRP) and carbon fiber-reinforced polymer (CFRP) in a significant portion of the structure will become a waste management, environmental, and social challenge.

On the other hand, GFRP composites contain a thermoset polymer matrix that is difficult to remold into different shapes and reuse in other applications. Thus, recycling of these composites faces technological and economic barriers and is limited in industrial operations. However, as waste disposal and environmental policies impose stricter rules demanding a proper recovery of engineered materials, quality recyclates with a feasible application become necessary.

8.2 Feedstock Description: Composite Fibers

With the increasing demand and production of composites, the feedstock of recycled fiber options is also growing. According to a 2013 study in Europe and the United States, annual CFRP scrap generation was about 3,000 tons, and 6,000 to 8,000 commercial planes will reach the end of life by 2030 *(247)*. CFRP accounts for more than 50% of the weight of both the latest Boeing B787 and Airbus A350 (283 tons) aircraft structures *(248)*. A study estimated that about half a million tons (0.45 million metric tons) of CFRP waste will be generated globally by 2050, and 145,000 tons (131,542 metric tons) will be in the United States. The composite production industry also leaves a considerable amount of scrap during the production process *(249)*. For instance, in the aerospace industry, composite production scraps are 30% to 50% of the weight of the material *(250)*.

Similarly, the increase in GFRP waste will also be inevitable due to the increase in end-of-life products such as wind turbines. By 2030, about 100,000 tons (90,718 metric tons) of wind turbine blades will reach the end of their life and enter the waste stream. Figure 8.1 shows the composite waste expected to be generated in 2025 by different sectors, indicating that the building and construction industry will produce the highest amount of waste, followed by the electrical, electronics, and transportation industries *(251)*. Currently, most of the composite waste is landfilled, which is an environmental issue. Recycling and reusing this composite waste is preferable from an environmental perspective.



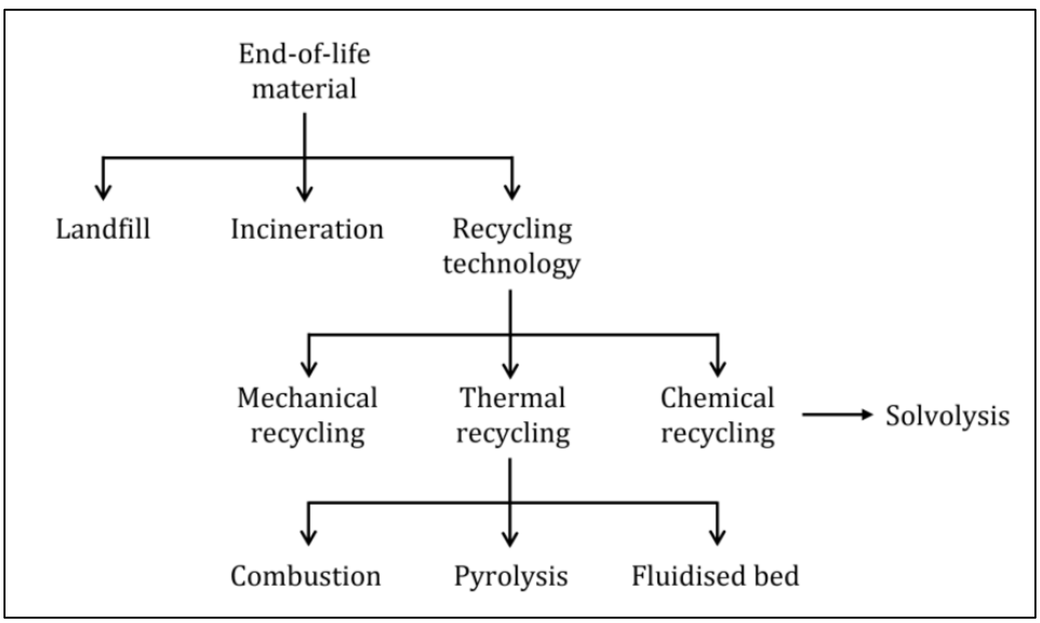
Source: Gonçalves et al. (2022) *(251)*.

Figure 8.1: Composite carbon composite waste by sector estimated for 2025.

In summary, there is a potential supply of feedstock from composite waste streams or manufacturing scraps for producing recycled composite fibers for a concrete application. Moreover, industry-scale mechanical recycling of composites is 10-fold less energy-intensive compared to the production of virgin fibers. The carbon footprint of mechanical recycling is also lower than other waste disposal options (i.e., landfilling and incineration) *(252)*.

8.3 Description of Recycling, Production, and Processing Method

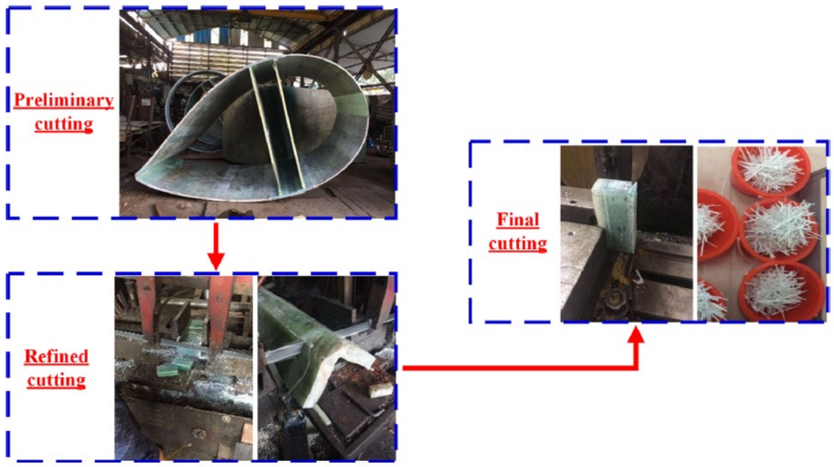
In recent years, researchers have studied the recycling of CFRP and GFRP into fibers and their potential use in cementitious composites. The recycling methods can be mechanical, solvolysis, pyrolysis, or hybrid. Figure 8.2 shows different recycling technologies available for composite waste. The mechanical process involves cutting, milling, and shredding the composites. The chemical process decomposes the composite to recover fibers. The pyrolysis process involves the heating of composites from 450°C to 1000°C, depending on the composition of the composites *(253)*. Most composites are thermosets that are difficult to remold using heat curing. The thermal and chemical processes of thermoset composites are energy-extensive and, hence, have a consequential effect on the environment. However, in thermal and chemical processes, fiber can be separated from the resins. Mechanical processing of scrap/end-of-life FRP composite products can downsize the scrap composites and shred them into suitable sizes for concrete use.



Source: Gonçalves, Martinho, and Oliveira (2022) *(251)*.

Figure 8.2: Different recycling processes of composite waste.

A study used mechanical processes to produce fibers of different sizes from wind turbine blades *(263)*. The process involved cutting the wind turbine blades into 3.94 by 7.87 in. (100 by 200 mm) GFRP laminate pieces at a recycling plant, which were then milled using a hammer mill to shred and subsequently sieved into different fiber sizes. Another study also used a mechanical process where the wind turbine blade was downsized to 39.37 to 78.74 in. (1 to 2 m) and stripped into macro fibers using a saw cut, resulting in a 3.54 in (90 mm) length and 0.12 in (3 mm) wide fibers *(263)*. The mechanical process of the recycled GFRP fiber production described above is shown in Figure 8.3.

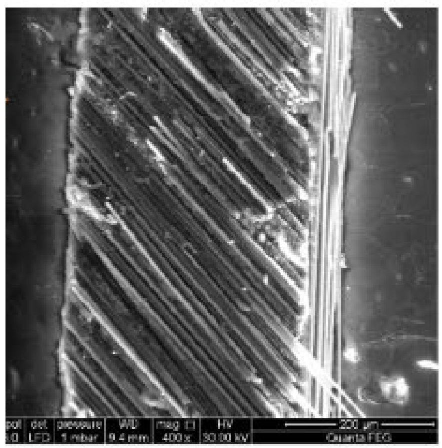


Source: Fu et al. (2021) *(254)*.

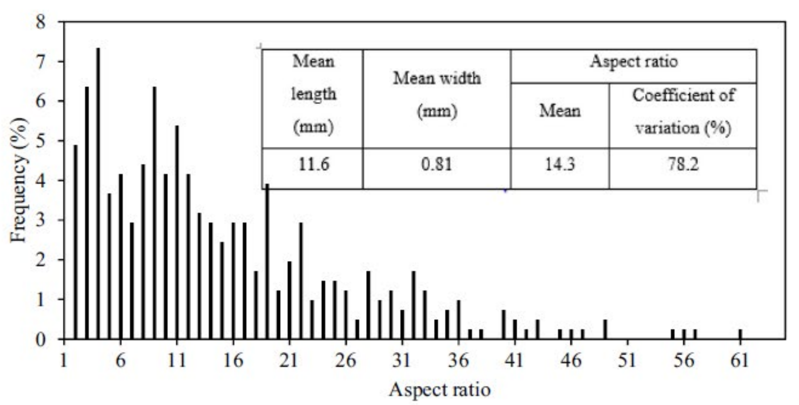
Figure 8.3: Mechanical processing of wind turbine blade into GFRP fibers.

A similar mechanical process can be applied to CFRP scrap to downsize it into suitable sizes to use in cementitious composites. One study used scrap carbon fiber composite materials from the aerospace industry to produce recycled carbon fiber composites of different sizes and used in pervious concrete as discrete reinforcement. As-received pieces of different sizes and shapes were first cut into smaller sizes of 0.20 by 0.40 in (35 mm by 70 mm), then hammer milled, and subsequently screened several times and grouped into different size groups. The fibers that passed the #10 sieve and were retained on the #20 sieve were used in the study *(264)*. Figure 8.4(a) shows the received scrap from the aerospace industry and the final products after mechanical processing, along with size distribution of the processed fibers. The SEM micrograph in Figure 8.4(b) shows that the fibers are embedded in the matrix after mechanical processing, and the composite nature was maintained. Figure 8.4(c) shows that mechanical recycling of CFRP fibers produces fibers that vary in size over a wide range. This variability in fiber size is one of the major differences between recycled fibers and virgin fibers, which are typically produced in uniform sizes.

(a)



(b)



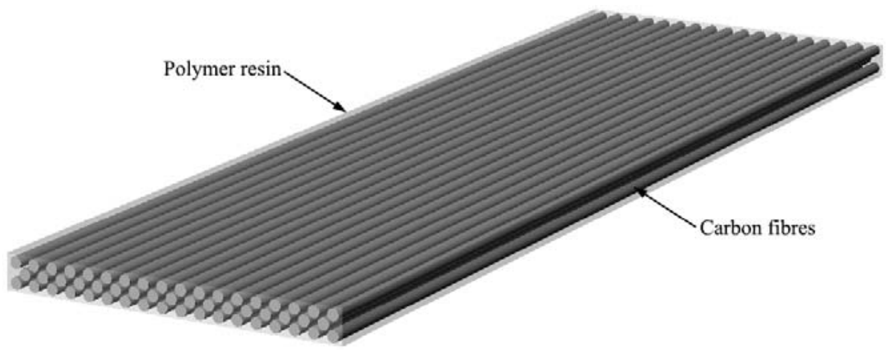
(c)

Source: Nassiri et al. (2021) *(255)*.

Figure 8.4: (a) Processing of cured carbon fiber composite materials scrap into suitable sizes for concrete use and size distribution of the composite fibers, (b) SEM image of one recycled fiber, and (c) size distribution of recycled fibers.

8.4 Physical and Chemical Properties of Composite Fibers

Fiber-reinforced polymers consist of fibers that reinforce a resin matrix. Fibers are the main structural element providing the strength and stiffness of the composites, whether resin holds the fibers together and serves as the matrix. Figure 8.5 shows a typical composite with carbon fibers embedded in the resin matrix. The composite behavior of the FRP largely depends on the structural materials, predominantly carbon and glass fibers. CFRP and GFRP have high strength and modulus, high deformation capacity, high fatigue resistance, and low thermal expansion, and they are lightweight (have a high strength-to-weight ratio).



Source: Liu, Zwingmann, and Schlaich (2015) *(256)*.

Figure 8.5: Typical structure of carbon fiber-reinforced polymer.

In contrast to the most commonly used fibers in the construction sector, composites are corrosion-resistant. The properties of FRPs are highly directional. They usually have high strength along the fiber direction and low strength perpendicular to the fibers *(256)*. The properties of the FRP depend on the fiber parameters (fiber diameter, lengths, strength, and the types and properties of the resin). Production processes can also influence the FRP properties *(257)*.

As previously mentioned, the composite behavior largely depends on the fiber properties. The high strength properties of the composites are derived from the fiber strength. Carbon fiber has higher tensile strength and elastic modulus compared to steel fibers (Table 8.1) *(256)*.

Table 8.1 Properties of Carbon Fiber Compared with Steel Fibers

Material Type	Fiber Properties	Density (lb./ft^3)[kg/m^3]	Tensile Strength (Ksi) [GPa]	Elastic Modulus (Ksi) [GPa]	Breaking Length (mi.) [km]
Carbon Fiber	Standard	110 (1760)	512 [3.53]	33359 [230]	127 [205]
	High Strength	114 (1820)	1024 [7.06]	42641 [294]	246 [396]
	High Modulus	117 (1870)	500 [3.45]	63962 [441]	117 [188]
Steel Fiber	S355	490 (7850)	73 [0.50]	30458 [210]	4 [6]
	Wire	490 (7850)	257 [1.77]	30458 [210]	14 [23]

The other component of the composites is the resin matrix. Different types of resins have been used in composites, shown in Table 8.2. The tensile strengths of the resins are 10.15 to 16.68 ksi (0.07 to 0.115 GPa), and the elastic modulus is 348 to 551 ksi (2.4 to 3.8 GPa). Generally, resins are divided into two types: thermoplastics and thermosets. Thermoplastics can be reshaped because of the linear and branch-like molecular structure, which is less restrained. In contrast, thermosets with crosslinked molecular structures are more restrained from reshaping *(256)*. Common types of resin used in composites are epoxy, vinyl ester, and polyester.

Table 8.2: Properties of Commonly Used Resins

Type	Name	Density (lb./ft^3) [kg/m^3]	Tensile Strength (ksi) [GPa]	Elastic Modulus ksi [GPa]
Thermoplastic	Polyethersulfone	86 [1370]	12 [0.084]	348 [2.4]
	Polyethereher ketone	82 [1310]	10 [0.070]	551 [3.8)]
	Polyetherimide	79 [1270]	15 [0.105]	435 [3.0]
Thermoset	Orthophthalic polyester	84 [1350]	10 [0.070]	464 [3.2]
	Vinylester	78 [1250]	11 [0.075]	479 [3.3]
	Epoxy	78 [1250]	17 [0.115]	435 [3.0]

Source: Liu, Zwingmann, and Schlaich (2015) *(256)*.

The properties of the CFRP and GFRP are presented in Table 8.3 and Table 8.4: , respectively. Carbon fibers are anisotropic, while glass fibers are isotropic. GFRP has a higher density compared to CFRP. The elastic modulus of CFRP is higher than the GFRP.

Table 8.3: Typical Properties of CFRP Composites

Property	Carbon Fiber			
	Polyacrylic Nitril Carbon		Pitch Carbon	
	High Strength	High Modulus	Ordinary	High Modulus
Density (lb./ft^3) [g/cm^3]	106-112 [1.7-1.8]	112-125 [1.8-2.0]	100-106 [1.6-1.7]	119-131 [1.9-2.1]
Tensile Strength, (ksi) [MPa]	497 [3430]	355-569 [2450-3920]	111-142 [764-980]	426-497 [2940-3430]
Young's Modulus, (ksi) [GPa]	28,427-34,084 [196-235]	49,748-92,389 [343-637]	5,366-5,656 [37-39]	56,856- 113,710 [392-784]
Elongation (%)	1.3-1.8	0.4-0.8	2.1-2.5	0.4-1.5
Coefficient of Thermal Expansion (10^{-6}/°C)	-0.6 up to -0.2	-1.2 up to -0.1	-0.6 up to -0.2	-1.2 up to -0.1

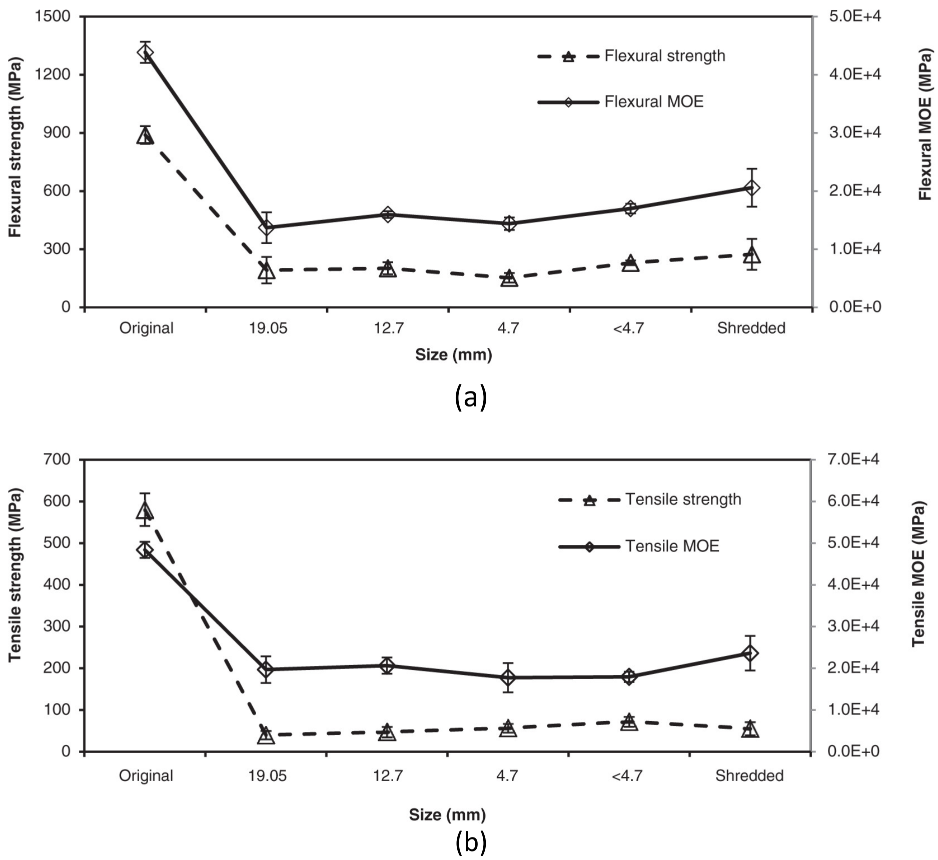
Source: Shakir Abbood (2021) *(258)*.

Table 8.4: Typical Properties of GFRP Composites

Trade Name	Density (lb./ft^3) [g/cm^3]	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Extension to Break (%)	Coefficient of Thermal Expansion (10^{-6}/°C)
E-glass	156 [2.5]	500 (3450)	10501 (72.4)	2.4	5.0
S-glass	156 [2.5]	664 (4580)	12401 (85.5)	3.3	2.9
C-glass	156 [2.5]	479 (3300)	10008 (69)	2.3	n/a
AR-glass	142 [2.27]	261-508 (1800-3500)	10153-11023 (70-76)	2.0-3.0	n/a

Source: Shakir Abbood (2021) *(258)*.

Properties of recycled fibers/shreds from composites may degrade due to the mechanical process. A study used the mechanical recycling process of post-industrial CFRP scrap and compared the mechanical properties with originally received samples. The results of the study in terms of flexural and tensile strength of the panels are shown in Figure 8.6. The findings showed a reduction in the mechanical performances of the recycled CFRP compared with the virgin composites *(259)*. However, improving the process with low mechanical energy input will produce composite fibers with comparable properties to recycled fibers *(252)*.



Source: Li and Englund (2017) *(259)*.

Figure 8.6: Mechanical properties of the CFRP panel with different sizes of shredded rCFRP: (a) flexural properties and (b) tensile properties.

8.5 Identified Suppliers of Composite Fibers for Concrete Applications

Table 8.5 shows the suppliers of fiberglass composites in the United States. Currently, one industrial-scale supplier for composite fiber producers, particularly for concrete use, has been identified. Recon Fiberglass LLC, based in Iowa, produces recycled composite fibers in the pilot phase and plans to set up a full-scale plant facility in 2023. Recon manufactures fibers ranging from 0.25 to 6 in. (6.35 to 152.4 mm) in length. Resolite FRP Composites in Moscow, Tennessee, specializes in fiberglass-reinforced plastic, producing FRP panels for various applications such as roofs, decks, and ventilators. JPS Composite Materials in Anderson, South Carolina, focuses on a range of materials, including fiberglass, quartz, para-aramid, and specialty composite reinforcement fabrics. Fibergrate Composite Structures, Inc. in Dallas, Texas, specializes in fiberglass-reinforced plastic, while Atkins and Pearce in Covington, Kentucky, produce fiberglass and textile fiber. Molded FiberGlass Companies in Ashtabula, Ohio, primarily manufacture fiberglass products.

Table 8.5: List of Suppliers of Fiberglass Composites

Company Name	Location	Manufactured Product
Recon Fiberglass LLC	Iowa	Full-scale plant will go into operation in 2023 (will produce fiber from 0.25 in. [6.35 mm] to 6 in. [152.4 mm] long)
Resolite FRP Composites	Moscow, Tennessee	Fiberglass-reinforced plastic FRP panels for roofs, decks, and ventilators
JPS Composite Materials	Anderson, South Carolina	Fiberglass, quartz, para-aramid, and specialty composite reinforcement fabrics
Fibergrate Composite Structures, Inc.	Dallas, Texas	Fiberglass-reinforced plastic
Atkins and Pearce	Covington, Kentucky	Fiberglass, textile fiber
Molded FiberGlass Companies	Ashtabula, Ohio	Fiberglass

8.6 Performance in Concrete Based on Technical Literature

8.6.1 *Impact of Fibers on Workability*

The incorporation of FRP influences the workability of fresh concrete. The reduction of workability largely depends on the size and volume of FRC fibers. All reviewed studies found a decrease in workability with FRC fiber inclusions. One study reported a more than 50% reduction in the slump value of concrete with the inclusion of 1.5% macro fibers from recycled GFRP (rGFRP). Another study reported a decrease in flow diameter measured from a miniature slump test for mortar mixes. The highest reduction in flow diameter was 18% at 5 vol% rGFRP fibers *(260)*. The larger size and the larger number of doses resulted in a larger decrease in workability. However, the study reported workable mixes with rGFRP and no issues of balling or clumping. Another study used rGFRP needles in concrete and did not notice any significant effect on workability or segregation with rGFRP needles *(261)*. One study used recycled CFRP (rCFRP) in pervious concrete and reported a uniform mix with up to 3 vol% fiber doses *(261)*. With higher doses of 4 and 5 vol% fiber doses, rCFRP fibers were clustered, which caused the dispersion issue. Another study reported good dispersion of up to 4% of CFRP fibers *(262)*. However, a different study mentioned a lower dose of 0.25% suggested for workable concrete with rCFRP. Another study reviewed the use of both rCFRP and rGFRP fibers and mentioned that rGFRP fibers have a more detrimental effect on the workability of fresh concrete, which is attributed to the higher water demand for rGFRP fibers *(263)*. This study also found the effect of higher doses of rGFRP on viscosity and concluded that the difference in workability with rGFRP and rCFRP is not quite significant, and fiber volume is a more consequential factor compared to the fiber sizes *(263)*.

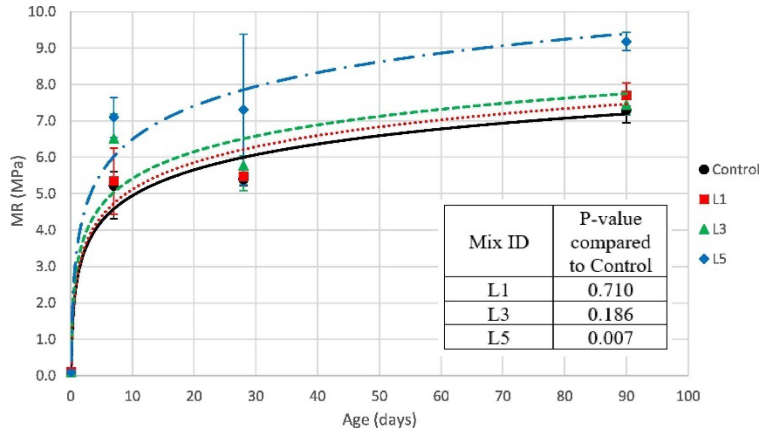
8.6.2 *Impact of Fibers on Strength and Toughness*

GFRP poses a high strength-to-weight ratio. Again, recycled needle-like fibers can act as discrete reinforcement to improve the cracking vulnerability of brittle concrete. One advantage is that the recycled GFRP fiber or filler usually reduces the overall weight when replacing aggregates. Several studies reported a reduction of hardened density ranging from 0.8% to 12% with different replacement levels of aggregates with both rGFRP powders (5% to 50%) and fibers (1% to 3%) *(261)*.

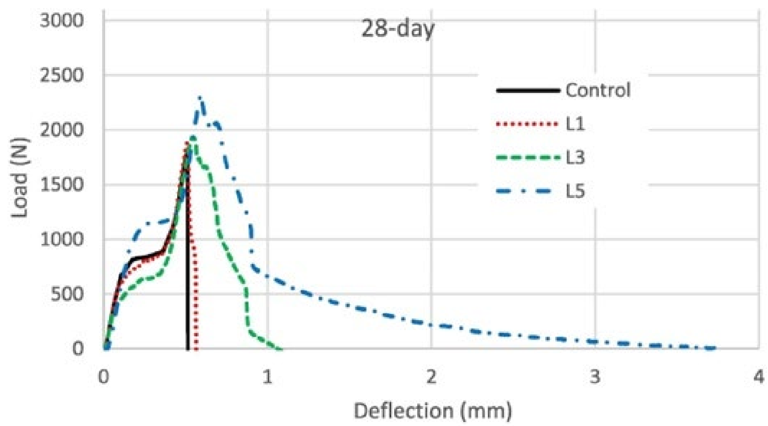
Compressive and flexural strength were also evaluated for rGFRP-reinforced cementitious systems. One study reported 12.1% and 16.4% increases in compressive strength with 4% and 8% rGFRP addition, respectively, due to the filler effect, which resulted in a more continuous particle size distribution and better particle packing in the mortar mix *(264)*. Another study looked at the strength characteristics of concrete replacing coarse aggregate with 5 wt% and 10 wt% rGFRP fibers recycled from different sources and reported decreased compressive strength and MOR with increasing fiber content *(265)*. In contrast, a different study reported a maximum 40% increase in the compressive strength of self-compacting concrete governed by the rGFRP fiber contents *(266)*. Another study reported a 1.5% reduction and no change in compressive strength for 5 vol% and 10 vol% plain rGFRP needles, respectively, whereas a 7.2% increase and 4.6% reduction in compressive strength was found for 5 vol% and 10 vol% grooved needles *(267)*. A study found a 9% and 66.4% decrease in 28 days of compressive strength for 3 vol% and 5 vol% rGFRP fiber, respectively, while a 6.4% increase was found for 1 vol% fiber doses *(268)*.

Most of the above studies used rGFRP as a filler in replacement of sand, while few studies focused on the contribution of rGFRP to MOR and toughness when used as fibers to bridge cracks. A study reported a 16% increase in flexural strength with 1 wt% rGFRP fibers in the mortar *(269)*. Another study found a 59.5% increase with 1.25 vol% recycled GFRP in self-compacting concrete *(266)*. A study reported up to a 36% increase in flexural strength with 5 vol% rGFRP fibers, which was attributed to the bridging action and stress transfer across small cracks *(268)*. However, a different study reported an 11% and 9% decrease in flexural strength for 5 vol% and 10 vol% plain needle GFRP, respectively, which was attributed to the transverse orientation of the embedded glass fibers in the needle. Another study found a 30% increase in MOR and a 230 times improvement in toughness in concrete with 1.5 vol% rGFRP fibers *(254)*. A study also found improvement in flexural strength (up to 15%) without any adverse effect on compressive strength with recycled GFRP fiber with a dose between 1 vol% and 1.75 vol% *(269)*.

A study reported 69% and 64% increases in flexural strength with 4 vol% rCFRP fibers at 7 days and 28 days, respectively *(261)*. The split tensile strength increase was between 57% and 84% in 28 days with the incorporation of fibers. Figure 8.7 shows improvement in flexural strength with increasing rGFRP content at all tested ages of the cementitious composites. In addition, the toughness of the samples, indicated as the area under the load-deflection curve, increased with fiber volumes at 28 days. Another study reported a strong increase of 143% in flexural strength with CFRP fibers and a change in fracture mode to semi-ductile *(262)*. It concluded that the improvement largely depends on matrix type and fiber volume ratio, shown in Figure 8.8.



(a)

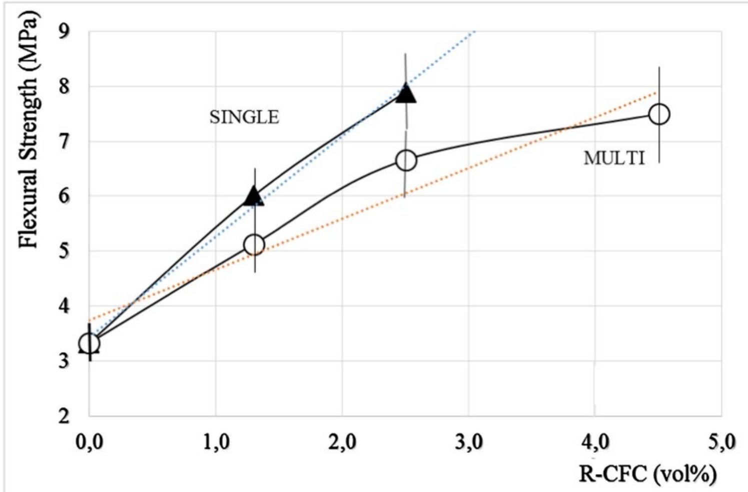


(b)

Note: L1: 1 vol% fibers, L3: 3 vol% fiber, and L5: 5 vol% fiber.

Source: Rodin et al. (2018) *(261)*.

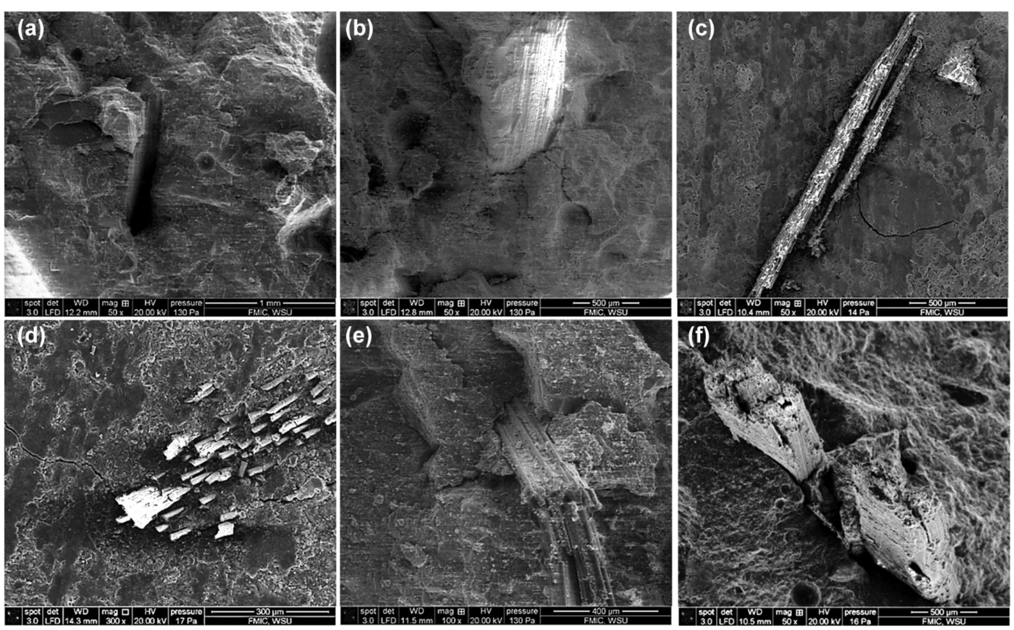
Figure 8.7: (a) Flexural strength with GFRP fibers and (b) load-deflection graphs with GFRP fibers.



Note: "Single" means single layer and "Multi" means more CF layers impregnated CFRP composites.
Source: Saccani et al. (2019) *(262)*.

Figure 8.8: Flexural strength with CFRP fiber-reinforced concrete.

SEM images of rGFRP-reinforced cement composites indicate the good compatibility of rGFRP fibers in the matrix with good interfacial integration (Figure 8.9). The failure modes of GFRP cement composites were both fiber pullout and fracture.

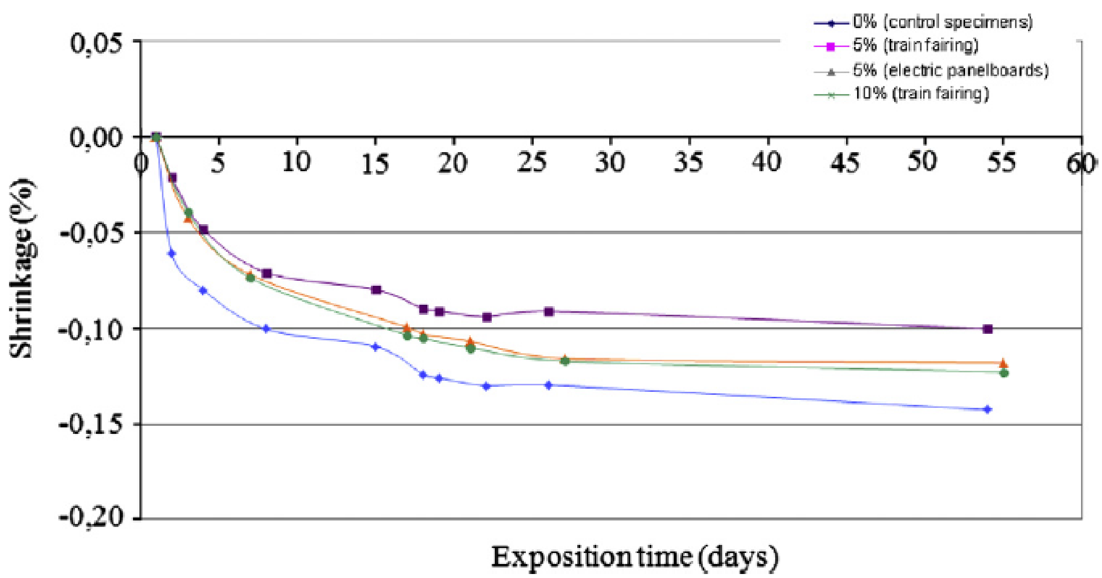


Source: Haider et al. (2021) *(260)*.

Figure 8.9: SEM micrograph of the crushed samples shows the rGFRP fiber bridging cracks and good interfacial bonding with matrix and both pullout and fracture type failures.

8.6.3 *Impact of Fibers on Durability of Concrete*

GFRP and CFRP fibers can play a positive role in shrinkage control. A study found that drying shrinkage reduces by incorporating rGFRP *(265)*. The study did not report any cracks due to shrinkage. The variability in strain with different waste streams of rGFRP was attributed to the differences in water absorption. The same study also investigated the effect of rGFRP addition on alkali-silica reactivity (ASR). Adding rGFRP up to 20 wt% did not cause any detrimental effects or expansion compared to the control concrete.



Source: Garcia, Vegas, and Cacho (2014) *(265)*.

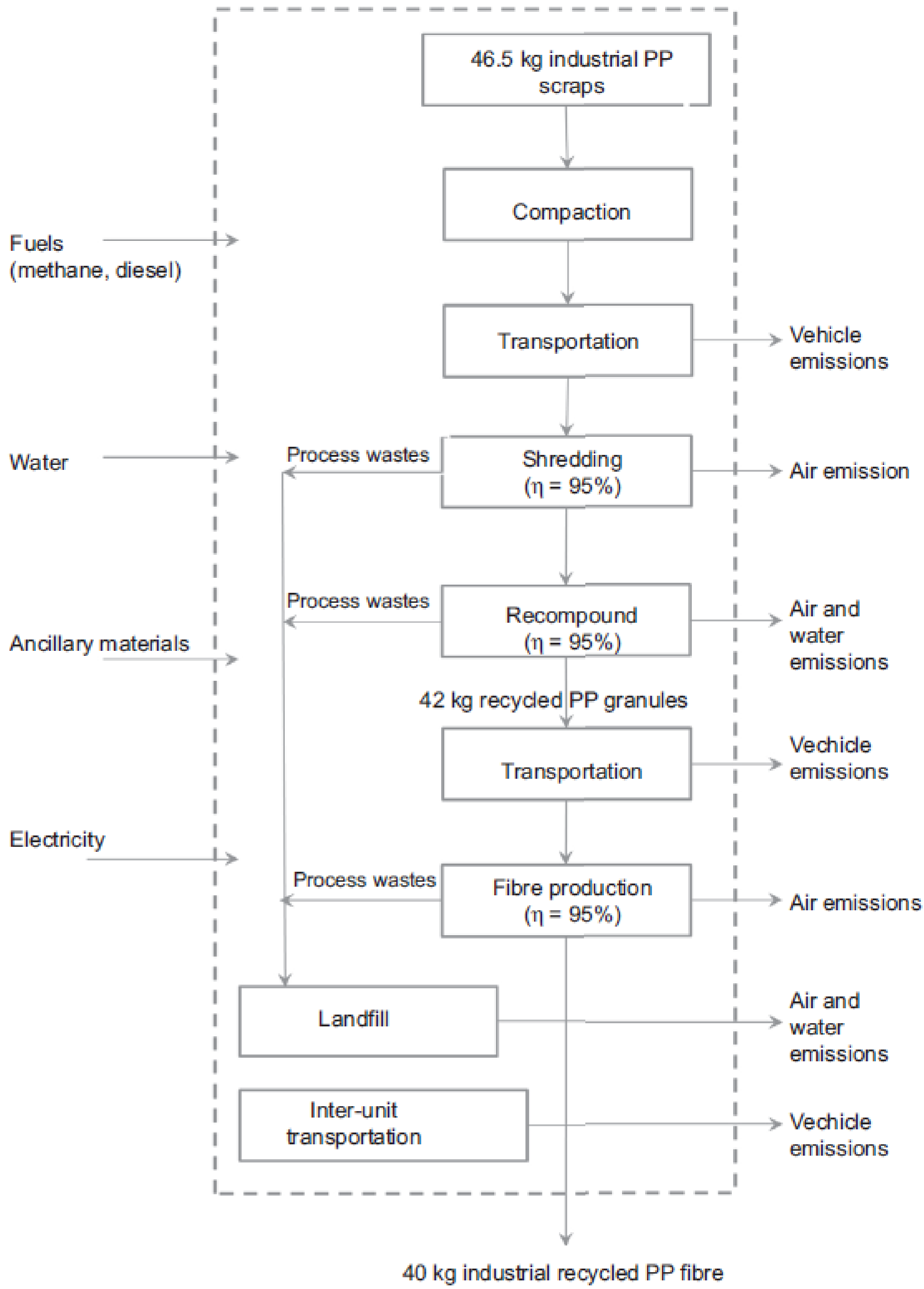
Figure 8.10: Drying shrinkage performance of rGFRP-cement composites with different sources and doses (wt%).

9 ENVIRONMENTAL IMPACTS OF RECYCLING PROCESSES

This chapter covers the environmental impacts of recycled fibers discussed earlier. For all the studied recycled fibers, the scope of environmental assessment was cradle-to-gate (production of recycled fibers). This chapter aims to survey the literature to gather any available information on the environmental impacts of recycled fiber production based on the life cycle assessment (LCA). A full LCA for concrete reinforced with recycled fibers and concrete with virgin fibers as the benchmark is warranted in future study phases.

9.1 Environmental Impact of Recycled Polymeric Fibers

Recycled plastics converted into aggregates *(270–272)* or fibers *(113,273)* for use in concrete applications have shown some environmental and economic benefits *(274)*. However, very few studies have specifically looked at the environmental impacts of recycled plastic/polymeric fibers. One study performed an LCA of virgin and industrial recycled PP fibers. Processes considered to produce industrial PP fibers recycling were shown in a system diagram (Figure 9.1). It was determined that the cradle-to-gate GWP per kg of virgin fibers was 4 kg CO_2eq (4,000 kg CO_2 eq./tonne fiber), and the GWP of industrial recycled PP fibers that were produced by mechanically processing industrial plastic waste was 2 kg CO_2eq (2,000 kg CO_2eq/tonne fiber) (i.e., the recycled fibers had 50% lower production GWP compared to virgin PP fibers).



Source. Tuladhar and Yin (2018) *(273)*.

Figure 9.1: System diagram to produce 40 kg of recycled PP fibers.

9.2 Environmental Impact of Cellulosic Fibers

An LCA study was conducted to assess the environmental impacts of cellulose staple fibers (275). The goal of the study was to determine the environmental impacts of viscose (produced from eucalyptus wood), modal (made from integrated pulp), and tencel (made from eucalyptus and beech pulp) and compare them with the production impacts of PET, PP, and cotton. The declared unit of the study was one metric ton (tonne) of staple fibers, and the scope of the study was from cradle-to-gate. The life cycle inventory (LCI) data were obtained from the ecoinvent database (V 1.3). The Centrum voor Milieukunde Leiden (CML) (Institute of Environmental Sciences) baseline method was selected for life cycle environmental impact assessment (LCIA).

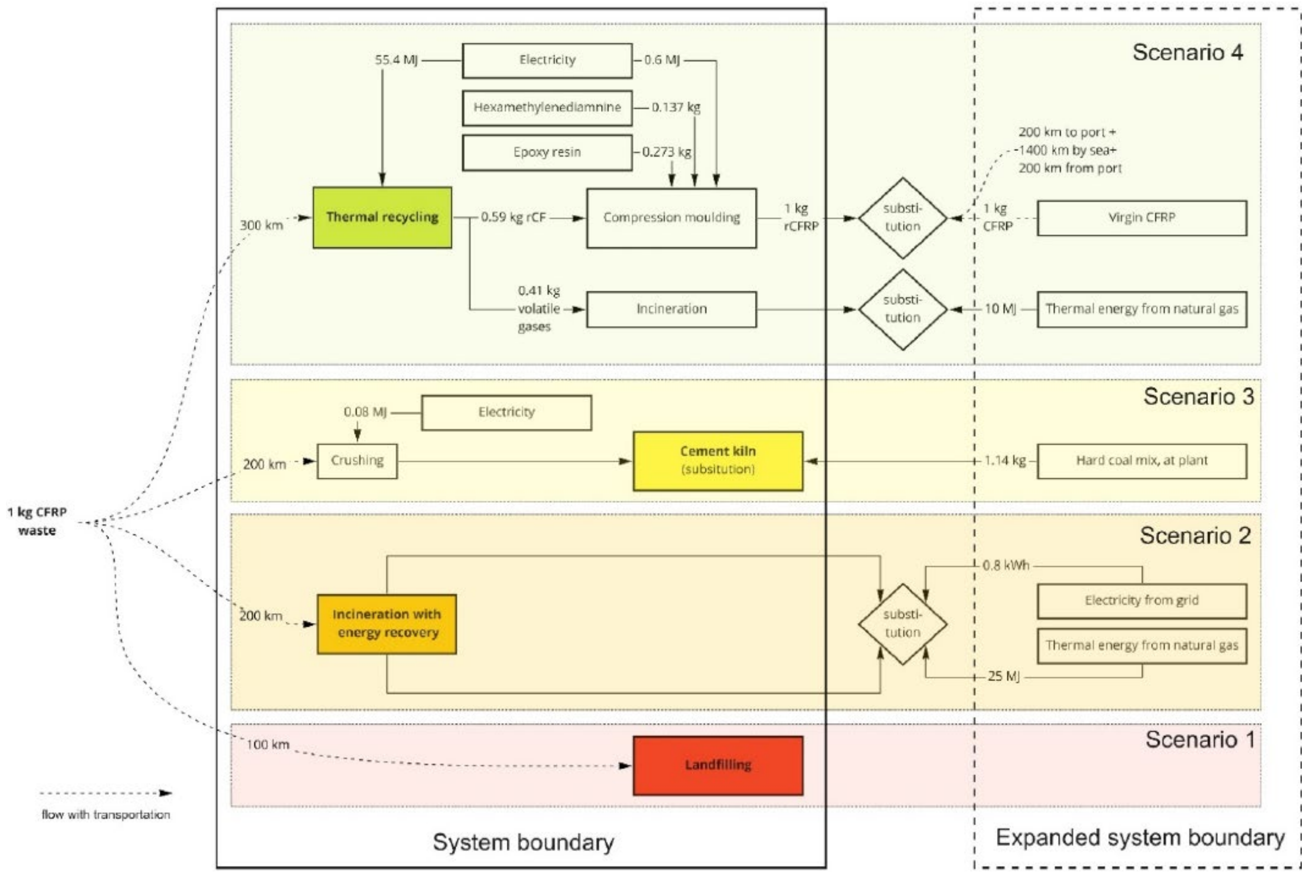
From the comparative LCA analysis, it was concluded that all the cellulose fibers had lower GWP than the PET. The modal had the lowest GWP (30 kg CO_2eq/tonne of fibers), followed by tencel (50 kg CO_2 eq./tonne fiber), while the PET had a reported GWP of 4,100 kg CO_2eq/tonne of fibers. Viscose produced in Austria had a negative GWP (-250 kg CO_2eq/tonne of fibers), indicating that it sequesters more carbon into the product than it emits. It should be noted that sequestration by plant-based materials is considered in the European Institute of Environmental Science (CML) system *(276)* but not in the US TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) *(277)* system of calculating GWP. In contrast, the viscose produced in Asia had a reported GWP of 3,800 kg CO_2eq/tonne of fibers. The discrepancies in the GWP values for the viscose might be due to the uncertainty originating from the mixed sources of market pulp. The study concluded that based on the midpoint results obtained, all the studied cellulose fibers except the viscose (Asia) had lower environmental impacts compared with PET, PP, and cotton *(275)*. Similarly, the environmental benefits of viscose (Austria) and modal were primarily attributed to the low fossil energy requirements in pulp and fiber production. In addition, viscose (Austria) and modal also had lower process emissions (e.g., SO_2 and NO_x) and lower human toxicity, photochemical oxidant formation, acidification, and eutrophication impacts.

9.3 Environmental Impact of Recycled Metallic Fibers

According to one study, steel fibers extracted from waste tires could be reused in concrete to avoid such a resource being landfilled *(8)*. Another study showed that the GWP for steel fibers, taken from *ecoinvent* 2.0, is 0.5 kg CO_2eq per quantity of fibers *(278)*. The unit for the quantity of recycled steel fiber was not reported. Another study used the proprietary data obtained for recycled steel fibers and OpenLCA 1.7 to calculate the GWP of recycled steel fibers and obtained 54.74 kg CO_2eq for 1 tonne of recycled steel fibers *(279)*. Because the study was conducted in Europe, the Institute of Environmental Sciences of Leiden University (CML) characterization factors were used to calculate the environmental impacts. However, GWP might remain unaffected since both CML and the US EPA's TRACI method demonstrate similar outcomes in their computations for the material *(280)*. Another study performed an LCA of recycled steel fibers using industry-provided information and reported the GWP to be 0.0695 kg CO_2eq per kg of fibers produced (69.5 kg CO_2eq/tonne of fibers) *(14)*. This cradle-to-gate analysis of recycled steel fibers included waste tire processing such as shredding, freezing, hammer milling to reduce the size, recycled steel fibers separating, drying, and transportation activities. Based on the manufacturer's information, the GWP of 1 tonne of industrial steel fibers (from primary steel) is approximately 1,096 kg CO_2eq, and for 1 tonne of recycled steel fibers (from tires) is approximately 55 kg CO_2eq *(15)*.

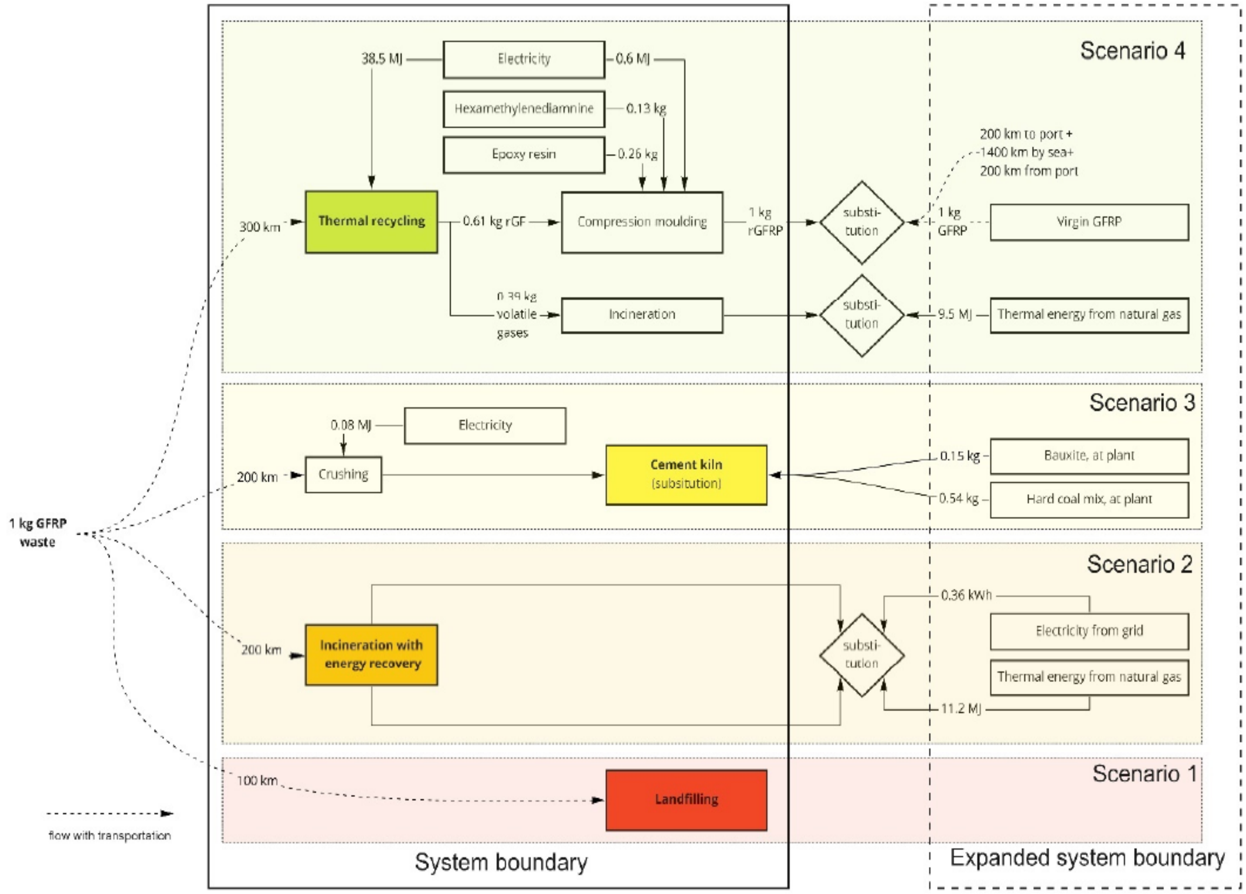
9.4 Environmental Impacts of Carbon or Glass-Reinforced Polymer Composite

A study conducted a detailed LCA study for a system in which the glass/carbon fiber content of waste CFRP and GFRP was retrieved by a thermal process and then recycled into rCFRP and rGFRP composites by applying a fresh epoxy resin using a compression molding process *(281)*. The functional unit of the study was 1 kg of the respective wastes, and the gate-to-grave approach was adopted for the assessment (waste generation, transportation to the treatment facility, and waste treatment). Figure 9.2 represents the system diagram for the management of 1 kg of waste CFRP along with the system boundary, while Figure 9.3 represents the system diagram for the management of 1 kg of waste GFRP along with the system boundary. The LCA was modeled using *GaBi* software (V 9.0.0.42).



Source: Gopalraj et al. (2021) *(281)*.

Figure 9.2: System diagram for 1 kg of CFRP waste management.



Source: Gopalraj et al. (2021) *(281)*.

Figure 9.3: System diagram for 1 kg of GFRP waste management.

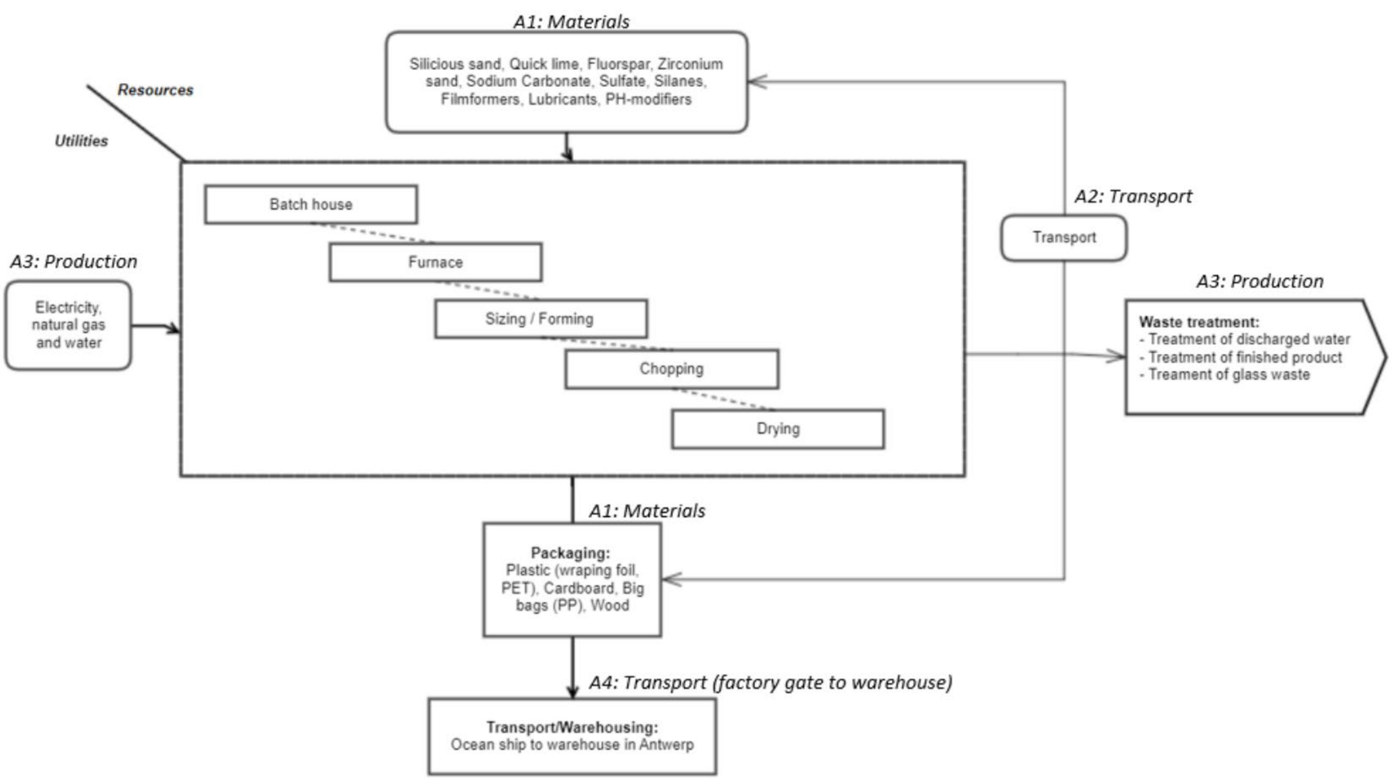
The study showed that recycling 1 kg of CFRP wastes used 15.4 kWh of electricity and produced 0.59 kg of recycled CFs. On the other hand, recycling 1 kg of GFRP waste used less electricity than CFRP wastes (10.7 kWh) and produced more recycled GFs (0.61 kg). The conclusion was that the overall carbon footprint of producing 1 kg of rCFRP was 5.68 kg CO_2eq (5680 kg CO_2eq/tonne of fibers), and for 1 kg of rGFRP composites was 4.62 kg CO_2eq (4620 kg CO_2eq/tonne of fibers).

Another study focused on comparing the recycling of waste carbon fiber composites versus landfilling and incineration *(282*). The functional unit of the study was 1 kg of waste CFRP. The ecoinvent 2.1 software was used to gather LCI for different processes. The study concluded that the thermal recycling scenario could avoid approximately 5.4 kg CO_2eq emissions (5400 kg CO_2eq/tonne of fibers).

A study evaluated the energy and environmental impacts of CF recycling by a fluidized bed process and reused it to manufacture CFRP material *(283)*. The functional unit of the study was 1 kg of generic CFRP panel measuring 300 mm by 190 mm, and a gate-to-gate approach was adopted. The study concluded that rCFRP components with identical mechanical properties to those produced from virgin CF could reduce GWP by 33% to 51%.

9.5 Environmental Impact of Glass Fibers

An environmental product declaration has been published by Owens Corning for the cradle-to-gate environmental impact of alkali-resistant glass fibers *(284)*. The functional unit considered in the EPD was 2.2 lb. (1 kg) of Cem-FIL AR-glass fibers. The base raw materials present in these fibers were silicious sand (60% to 70%), sodium carbonate (20% to 30%), zirconium sand (20% to 30%), and quick lime (5% to 10%). The system boundary considered for this study was cradle-to-gate. The process diagram is shown in Figure 9.4.



Source: Owens Corning (2021) *(284)*.

Figure 9.4: Process diagram to produce 1 kg Cem-FIL AR-glass fibers by Owens Corning.

The results of the environmental impacts of the glass fiber produced by Owens Corning are shown in Table 9.1. Using the CML method, the cradle-to-gate total GWP impact to produce 2.2 lb. (1 kg) of this glass fiber was reported to be 2.85 kg CO_2eq (3.01 kg CO_2eq from fossil use). The other two significant environmental impacts due to the production of these fibers were the abiotic depletion of fossil resources and water depletion potential.

Table 9.1: Results of Environmental Life Cycle Analysis Using CML Method for Owens Corning Alkali-Resistant Glass Fibers

Environmental Impact	Unit	A1	A2	A3	A4 (transport to Antwerp)	Total (incl. transport to Antwerp)
GWP-total	kg CO_2 eq.	1.16	0.05	1.64	0.24	3.10
GWP-fossil	kg CO_2eq.	1.31E+00	5.39E-02	1.65E+00	2.43E-01	3.26E+00
GWP-biogenic	kg CO_2eq.	-1.50E-01	2.41E-05	-4.39E-03	2.45E-04	-1.54E-01
GWP-luluc	kg CO_2 eq.	8.37E-04	1.87E-05	1.08E-04	1.28E-04	1.09E-03
ODP	kg CFC-11 eq.	8.11E-08	1.21E-08	1.15E-07	4.76E-08	2.55E-07
AP	mol H+ eq.	1.01E-02	5.39E-04	4.09E-03	6.15E-03	2.09E-02
EP-freshwater	kg P eq.	1.15E-04	8.30E-07	1.76E-05	4.07E-06	1.37E-04
EP-marine	kg N eq.	1.48E-03	1.43E-04	8.60E-04	1.21E-03	3.69E-03
EP-terrestrial	mol N eq.	2.47E-02	1.59E-03	9.08E-03	1.36E-02	4.90E-02
POCP	kg NMVOC eq.	4.82E-03	4.39E-04	2.80E-03	3.57E-03	1.16E-02
ADP-minerals and metals	kg Sb eq.	6.65E-06	1.22E-07	3.34E-07	5.34E-08	7.16E-06
ADP-fossil	MJ, net calorific value	1.72E+01	8.22E-01	2.12E+01	3.46E+00	4.26E+01
WDP	m^3 world eq. deprived	1.12E+00	6.51E-03	6.75E-02	2.84E-02	1.23E+00

Source: Owens Corning (2021) *(284)*.

10 SUMMARY AND RECOMMENDATIONS

10.1 Summary of Findings

The technical literature for fibers, their types and subclasses, and their general expected performance in concrete was summarized in this report. Suppliers of recycled fibers and fibers from natural and renewable sources were identified and interviewed for this study. Information about feedstock, the recycling process, geometric properties, dosage in concrete, technical data, and the cost was gathered from the supplier.

For recycled polymeric fibers, the following manufacturers were identified:

- Euclid Chemical (Micro)
- Barchip Inc. (Macro)
- Forta Concrete Fibers (Micro and Macro)
- GCP (Micro and Macro)

For cellulose fibers, products at large scale are available from the following manufacturers:

- International Paper
- CreaFill Fibers Corporation
- Solomon Colors Inc.
- J. Rettenmaier USA LP
- FibreZone India

For recycled steel fibers, products at large scale are available from the following manufacturers:

- Concrete Fiber Solutions
- Sika Fibers
- FlexoFibers
- COR-TUF UHPC

The following manufacturer produces fibers for concrete from recycled windmill blades:

- Recon Fiberglass LLC

Glass and basalt fibers are available for concrete from the following manufacturers:

- Owens Corning
- Mafic
- Technobasalt

Technical literature was reviewed and summarized on the performance of fiber type on workability, mechanical properties, and durability of concrete. Identified fibers are in the material categories of polymeric, steel, carbon, carbon fiber, cellulose fibers, glass fiber composites, glass, and basalt fibers. A summary of the findings based on the technical literature review of fiber-reinforced concrete is provided in Table 10.1. These findings were determined based on research on virgin fibers, with the recycled fibers expected to cause similar effects on the target properties. It is seen that polymeric microfibers, polymeric macrofibers, cellulose fibers, steel fibers, carbon fibers, CFRP/GFRP fibers, and glass/basalt fibers all reduce concrete workability and reduce plastic shrinkage at varied levels. Steel, carbon, CFRP/GFRP, and glass/basalt fibers increase compressive strength to some extent. Moreover, steel, carbon, CFRP/GFRP, and glass/basalt fibers, along with cellulose fibers, enhance tensile/flexural strength. Additionally, polymeric macrofibers, cellulose fibers, steel fibers, carbon fibers, and CFRP/GFRP fibers contribute to increased post-peak strength and toughness in concrete. Since the technical performance has been gathered for virgin fibers, laboratory testing is required to confirm the level of performance enhancement achieved in concrete from recycled fibers compared to virgin fibers.

Table 10.1: Summary of the Impact of Fibers on Essential Properties of Concrete

Fiber Type/ Property of Concrete	Polymeric Microfiber	Polymeric Macrofiber	Cellulose Fiber	Steel Fiber	Carbon Fiber	CFRP/ GFRP Fiber	Glass/ Basalt Fiber
Reduce workability	Y	Y	Y		Y	Y	Y
Reduce plastic shrinkage	Y	Some	Y		Y	Y	Some
Increase compressive strength	N	N	N	Y	Y	Some	Y
Increase tensile/flexural strength	N	Some	Y	Y	Y	Y	Y
Increase post-peak strength and toughness	N	Y	Y		Y	Y	Y

A literature review was also performed to determine the availability of eLCAs for recycled fibers since the recycling process, such as washing, thermal, mechanical, or chemical treatments, will have environmental burdens such as water use, chemical use, particulate matter, and energy consumption. For example, glass and basalt fibers require high temperatures of approximately 2550°F to 2900°F (1400°C to 1600°C) for melting and forming into fiber shapes *(19)*. Therefore, when evaluating recycled fibers, their merits, and their drawbacks in terms of technical performance within the concrete, along with considerations of cost and environmental impacts, should be taken into account.

Although limited, a few studies were found that reported the cradle-to-gate environmental impacts for each recycled fiber category. A summary of the GWP in terms of kg CO_2eq per kg of recycled fibers is shown in Table 10.2 based on the limited published literature for recycled fibers. According to the table, recycled polymeric fibers have a GWP of 2.00 kg CO2eq per kg of recycled fiber, while recycled steel fibers have a significantly lower GWP of 0.07. Cellulose fibers have the lowest GWP at 0.03, while rCFRP and rGFRP fibers have GWPs of 5.68 and 4.62, respectively. Glass fibers fall in the middle with a GWP of 2.85 kg CO2eq per kg of fiber.

A full LCA taking into account the specifics of the recycling process and, most importantly, the expected changes in the dimensions of the concrete pavement to achieve the same design life or the expected life for the same design as a conventional concrete pavement will be required to properly assess and determine the GWP of the recycled fibers compared to the baseline virgin fibers. The end of life of fiber-reinforced concrete will also need to be determined. EOL concerns, such as whether the rFRC can be recycled or reused similarly to conventional concrete, should also be considered.

Table 10.2: Global Warming Potential (GWP) of Recycled Fibers Gathered from the Literature

Fiber Type	Cradle-to-Gate GWP (kg CO_2eq per kg of recycled fiber)	Reference
Recycled polymeric fibers	2.00	Yin et al. *(113)*
Recycled steel fibers	0.07	Soltanzadeh et al. *(14)*
Cellulose fibers	0.03	Shen et al. (2010) *(275)*
rCFRP fibers	5.68	Gopalraj et al. (2021) *(281)*
rGFRP fibers	4.62	Gopalraj et al. (2021) *(281)*
Glass fibers	2.85	Owens Corning EPD *(284)*

10.2 Recommendations

The identified recycled fiber products from the listed suppliers in Section 10.1 are recommended for laboratory testing in Phase II of the project. More recycled fibers and fibers from natural resources may be identified during the project and included in the laboratory testing phase. Virgin fibers will also be included in testing for baseline comparison. The scope of testing in Phase II includes characterization of the full mechanical properties of rFRC samples, including flexural testing per ASTM C1609 and free drying shrinkage. In later phases of the project, the benefits of the fibers to the durability of concrete in terms of freeze-thaw cycling and other attributes will be characterized. In the future phases, the project will focus on the incorporation of the observed enhancements in mechanical properties and drying shrinkage into pavement design.

Consideration of rFRC into pavement design will also include an eLCA to determine the full benefits of recycled fibers to concrete pavements by considering the full life cycle (cradle-to-grave) of the pavement. This is because simply comparing cradle-to-gate impacts of virgin fibers versus recycled fibers may be misleading as they might have different performances. Furthermore, one may require an excessive amount of recycled fibers to achieve the same concrete performance, thereby resulting in high GWP instead of savings. Thus, understanding the implications of fiber quantity and performance on the overall environmental impact is essential for making informed decisions during the pavement design process. Furthermore, an eLCA is required to address the possibility of using renewable sources, like cellulose fibers, as an alternative to polymeric fibers for controlling plastic shrinkage in concrete, and glass and basalt fibers over polymeric fibers in enhancing post-peak crack-control and load-bearing capacity of the concrete.

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