Fiber Reinforced Concrete

by

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Abstract

Engineers involved in construction face various challenges. One of them being dealing with cracks in concrete. Naturally, concrete is weak in tension defining its bristle characteristics. To compensate, fiber reinforcement is used in the concrete mixes. Popular fiber types are steel, glass, polypropylene, and carbon fibers. These types of fibers are used to reinforce concrete. These fibers all increase the tensile and flexural strength of concrete. Additionally, they all have their own advantages. This paper is oriented to briefly introduce basic properties of these fibers. This includes the composition, production, advantages, applications, and restrictions of the mentioned fibers.

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History

The integration of fiber in concrete to enhance its properties dates back nearly 4500 years. Early civilizations applied sun dried straws in mud bricks to create a tougher composite with enhanced toughness. This increased resistance to fracture and enhanced the post-cracking response of the composites. Attempts have been made to curb the cracks in Portland cement ever since it was put into use as a major construction material. With time, engineers were able to overcome the major challenges with cement, its brittleness and low tensile strength. The idea of including fibers into concrete comes from the French engineer, Joseph Lambot, in the year 1947 [1]. This discovery gave birth to reinforced concrete. Tensile strength of concrete was therefore greatly improved by the use of continuous reinforcing steel bars, with the use of discontinuous steel reinforcements still being a challenge. Steel fiber reinforcement saw a slow development before the 1960s because of limited literature on the procedures of using fiber reinforcement with little application. Research on the use of glass fibers had been in progress in the UK, Russia and the USA in the early 1950s. The use of glass fibers was rolled out in Russia as early as 1950 and was facing a great challenge as the glass were prone to alkaline attacks. This led to the Portland Cement Association starting an investigation on fiber reinforcement [2].

In the 20th century the interest of fiber reinforced concrete, FRC, increased. During this period FRC developed rapidly by increasing the number of applications. The types of fiber used during this period include: steel fiber, glass fiber, carbon fibers, and polypropylene fiber. A mixture of concrete and fiber developed a composite with improved tensile and flexural strength which can be condensed and ductile.

FRC developed further in the late 1970s and 1980s. FRC was discovered to have the ability to absorb more energy when compared to traditional concrete. A great advantage of using fibers with concrete is to clear developing cracks on the walls by spreading punching forces, a crack causing force, on the cracks to avoid further cracking. However, the use of fibers poses certain challenges concerning mixing. Some fibers tend to form balls whose effectiveness happens to decrease during mixing.

Specific fibers are used for specific applications by consumers. While all the fibers discussed increase tensile and flexural strength, some have specific advantages such as corrosion resistance. Choosing the reasonable fiber depends on the consumer’s requirements. This research paper will briefly introduce steel, glass, polypropylene, and carbon FRC. Topics covered will be their compositions, production methods, advantages, applications, and restrictions.

Chapter 1 - Steel Fiber

1.1 Introduction

Steel Fiber Reinforced Concrete, or SFRC, is a composite material. It is composed of the following ingredients:

- Hydraulic cement
- Water
- Aggregates (fine and coarse)
- Small fibers (steel fibers)
- Admixtures

Proportions differ depending the required mechanical properties as they do with typical reinforced concrete. The composite must meet ASTM standards [3].

1.2 Composition

As a concrete mixture's composition varies depending on a job, so does SFRC's composition. The composition will depend on the required strength, workability, and other properties requested from the consumer. Generally, SFRC will often have a higher percentage of coarse aggregate than normal concrete mixes. Also, in typical SFRC mixtures, fly ash is added to the mixture to reduce the amount of cement used. This can reduce the amount of cement used up to 35%. Water reducing agents, such as superplasticizers, may be added to increase the workability of SFRC. **Table 1.1** shows ranges of materials used for normal weight SFRC, while **Table 1.2** shows mixtures for typical SFRC mixtures.

Table 1.1 Range of proportions for normal weight fibre reinforce Concrete[4]

Property	Mortar	9.5mm Maximum aggregate size	19 mm Maximum aggregate size
Cement (kg/m^3)	415-710	355-590	300-535
w/c ratio	0.3-0.45	0.35-0.45	0.4-0.5
Fine/coarse aggregate (%)	100	45-60	45-55
Entrained air (%)	7-10	4-7	4-6
Fibre content (%) by volume			
smooth steel	1-2	0.9-1.8	0.8-1.6
deformed steel	0.5-1.0	0.4-0.9	0.3-0.8

Table 1.2 Typical steel fibre reinforce shotcrete mixes [4]

Property	Fine aggregate mixture (Kg/m^3)	9.5mm Aggregate mixture (Kg/m^3)
Cement (Kg/m^3)	446-559	445
Blended sand (<6.35mm)	1438-1679	697-880
9.5mm aggregate		700-875
Steel fibres	35-157	39-150
Accelerator	Varies	Varies
w/c ratio	0.40-0.45	0.40-0.45

There are two ingredients that have the biggest effect on the workability of SFRC. The first one is the quantity of aggregate particles. As aggregates over 5mm are increased, the workability of the mixture decreases. This can be seen in **Figure 1.1.** The second factor that effects workability of SFRC is the aspect ratio, or (*l/d*), of the fibers. As the ratio increases the workability decreases as seen in **Figure 1.2.**

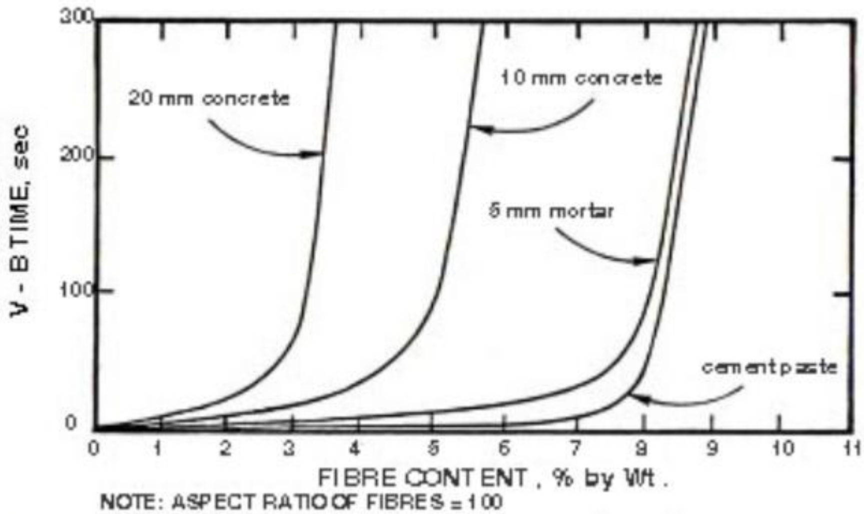

Figure 1.1 Workability versus fibre content for Matrices with different maximum aggregate sizes [4]

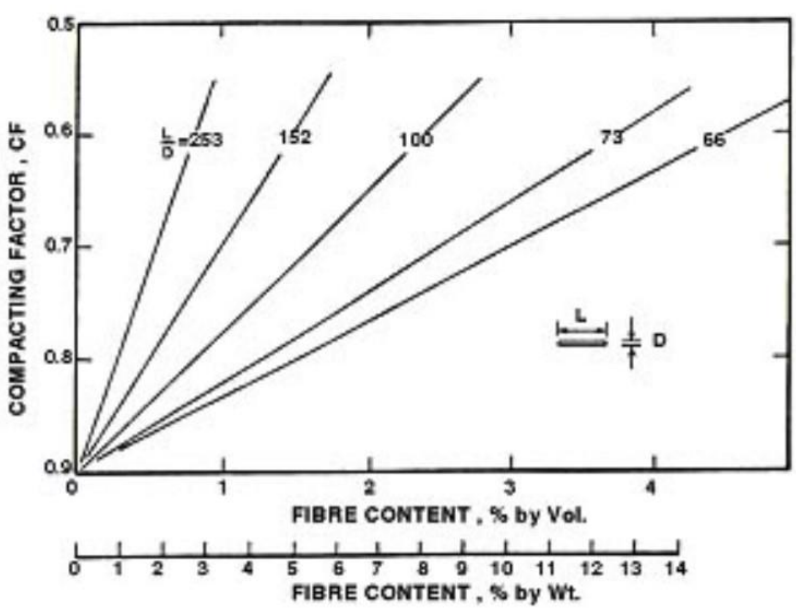

Figure 1.2 Effect of fibre aspect ratio on the workability of concrete, as measured by the compacting factor [4]

1.3 Production

1.3.1 Method

A common preparation method for SFRC is using a mix truck or revolving drum mixer. Using these mixers requires that the concrete mixture is complete before adding the fibers. The concrete mixture that is to be prepared should have a slump of 50-75 mm greater than the required slump of the SFRC. To clarify, if a SFRC with a slump of 200mm is desired, the concrete slump should be somewhere between 250-275mm. The fibers are then added to the mixer. Another way to add the fibers is to do so during the addition of the fine aggregate while preparing the concrete.

Figure 1.3 Revolving drum mixer

Figure 1.4 Mixing truck

1.3.2 Complications

One of the issues with producing SFRC is to add enough fibers to the concrete to attain the required mechanical properties while preserving adequate workability. The performance of SFRC is enhanced as the aspect ratio is increased, but as discussed in section 1.2 an increase aspect ratio decreases workability.

Another issue with the production of SFRC is the tendency of the fibers to clump into balls. This can be caused by several factors, including but not limited to:

- Fibers are already clumped when received

- Fibers are rapidly added to mixture
- Too much is added

To prevent complications the fibers should be added free of clumps. This can be achieved by passing them through a screen. The preparation should be done with care and professionalism to minimize complications and maximize the mechanical properties of SFRC.

1.4 Advantages

Concrete usually has a high compressive strength but steel fibers can be used to enhance post-cracking ductility, energy absorption, tensile strength, and flexural strength. Tensile strength could be increased up to 133% with the addition of steel fibers. This would be the optimal increase if the fibers are aligned in the direction of the tensile stress. This is difficult to obtain since most likely fibers will be aligned randomly. **Figure 1.5** shows a more achievable tensile stress strength increase. The increases to the flexural strength of the concrete are also noticeable when steel fibers are used. The flexural strength is also modified with changing aspect ratios, (l/d), and weight percent of fibers, W. **Figure 1.6** show the relationship between steel fibers with flexural strength.

It can be seen that the increase in flexural strength is far greater than the increase in tensile strength gains. It should also be noted that increases in compressive strength can be achieved with the addition of SFRC, but it is not significant as it ranges from 0-25%.

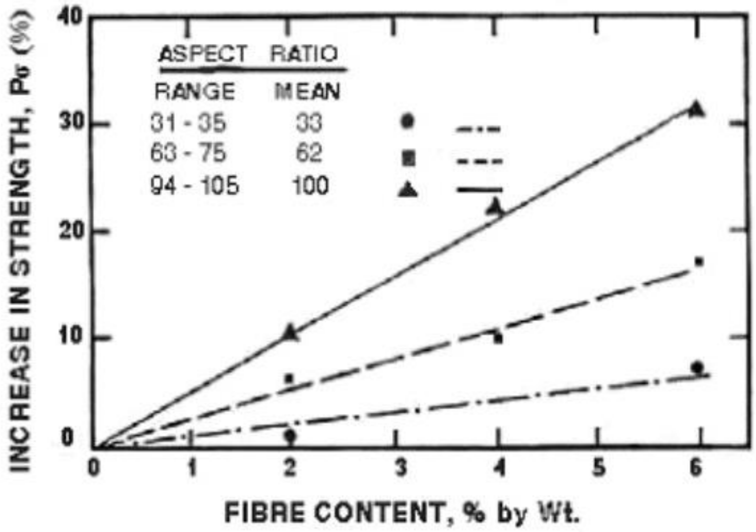

Figure 1.5 Influence of fibre content on tensile strength [4]

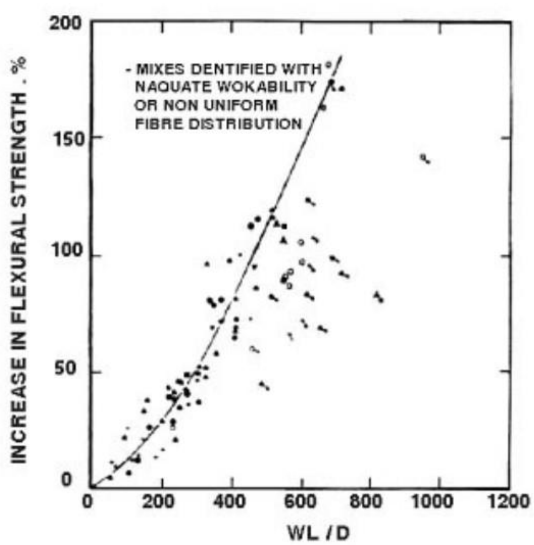

Figure 1.6 Effect of Wl/d on flexural strength of concrete [4]

1.5 Applications

SFRC has many applications including industrial floors, roads, railways, runways, tunnel linings and many more to mention. A perfect example of steel reinforced fibers application is in the making of steel reinforced floors. This plays an important role in absorbing destructive waves or energy when underlying structures are subjected to seismic forces. Additionally, steel fibers have been used regularly as a supplement to reinforced concrete in water construction such as in the surface slabs of the dam in Longshua, China, whereby the structure has withstood many seismic loads including earthquakes. The longest SFRC slab used was 75m long with no visible cracks after earthquakes hits [5]. Traditional reinforced concrete of the dam slabs after the earthquake can be seen in **Figure 1.7.**

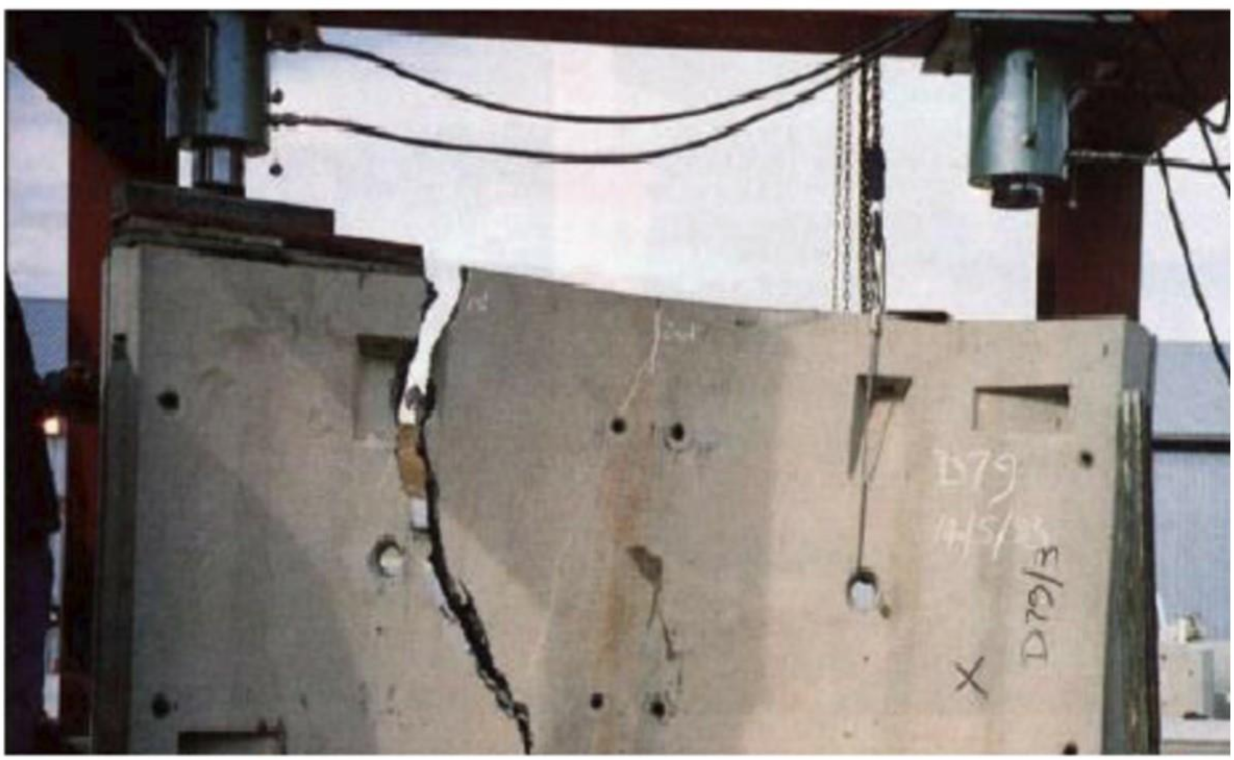

Figure 1.7 Longshua dam RC slab after earthquake [5]

1.6 Restrictions

Although the use of steel fibers in concrete reinforcement is beneficial in preventing wall cracking as well as increasing the strength and durability of concrete, the functionality of fiber is limited in areas prone to corrosiveness. This is especially seen in the fibers that are at the surface of the concrete [6]. To reduce corrosiveness of steel; iron, chromium, nickel or any other alloy materials are added to create stainless steel, which is resistible to corrosion [7]. It should also be noted that in structural members where flexural or tensile loads occur, the reinforcing steel must be capable of supporting the total tensile load.

Chapter 2 - Glass Fiber

2.1 Introduction

Glass FRC is popular in architectural buildings where design creativity is desired. GFRS has a low density with a high strength to weight ratio. That makes it ideal for design panels that are required to be thin but still strong. GFRC is versatile in nature and has various applications.

2.2 Composition

Just as steel fibers are mixed with different alloys to achieve desired properties, glass fibers are composed with numerous chemical compositions to achieve required properties [8]. The most popular oxides are seen in **Table 2.1** below.

Table 2.1 Approximate chemical compositions of some glass fibers (wt.%) [8]

Composition	E glass	C glass	S glass
SiO_2	55.2	65.0	65.0
Al_2O_3	8.0	4.0	25.0
CaO	18.7	14.0	-
MgO	4.6	3.0	10.0
Na_2O	0.3	8.5	0.3
K_2O	0.2	-	-
B_2O_3	7.3	5.0	-

Where:

- E glass= Electrical Glass
    - This type of glass has good electrical insulation

- It is the least common glass type
- C glass= Corrosion Glass
    - This type of glass has a high resistance to chemical corrosion
- S glass= High Silica Glass
    - This type of glass can withstand high temperatures

2.3 Production

The glass fibers are formed into numerous form. The most popular forms are shown in **Figure 2.1**. The process includes melting all the raw material at first, then depending on what form is required the procedure differs. For the commonly used continuous yarn form, the melted glass is poured into platinum bushings producing fine strands. They are then electronically spun onto a drum [8].

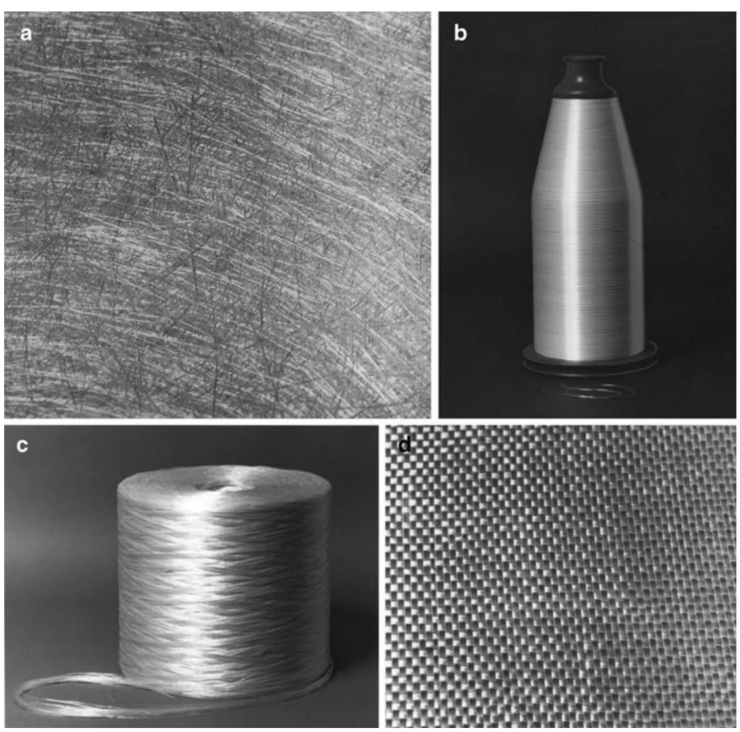

Figure 2.1 Glass fiber in a variety of forms (a) chopped strand, (b) continuous yarn, (c) roving, (d) fabric [8]

Proportions of the actual FRC mix depends on some variables. Glass FRC is prone to shrinkage. With that in mind, the water to cement ratio should be minimized. **Table 2.2** shows an example of a typical mix with its proportions.

Table 2.2 Typical Mix Formulations [9]

Materials	Weight (kg)
Cement	50
Sand	50
Polymer	5
Water	13
Glass Fibre	5.5

2.4 Advantages

As stated, density of glass fiber is low and the strength is high. This makes the strength to weight ratio of glass fibers is very high. We can also look at different chemical compositions that gives advantages that are desired. This includes high temperature resistivity, electrical insulation, or other qualities described in Section 2.2.

Glass FRC increases flexural strength drastically. This can be seen in the stress vs strain curve shown in **Figure 2.2** The test specimens include the 3 grades of Glass FRC as specified by The International Glassfiber Reinforced Concrete Association (IGFRCA) [9].

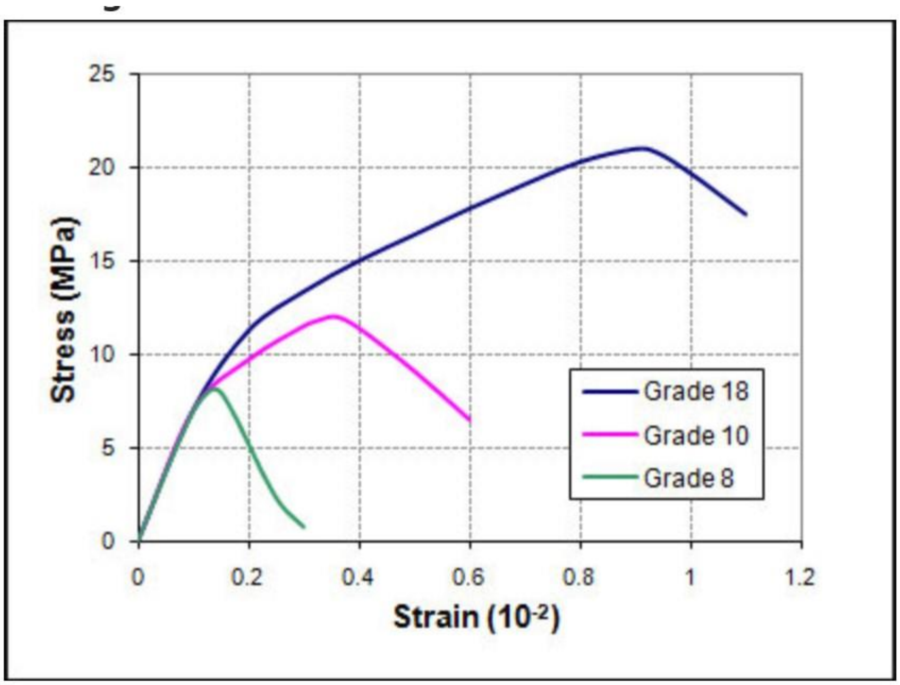

Figure 2.2 Flexural Strength Classification [9]

2.5 Applications

Because of Glass Fiber Reinforcement Concrete's versatile nature, it can be used for architectural purposes for making decorative panels. Glass FRC can be used for panels that are thin and light. This is because of its high strength to weight ratio. Its versatility provides countless flexibility in design and offers a multitude of color finishes, textures, and patterns. Glass Fiber Reinforcement Concrete panels that have a surface mass of 20kg/m and a thickness of 10 mm can attain a sound reduction that is close to 30dB [10]. This has made it more suitable for construction of music studios and sound proofing houses. Glass Fiber Reinforcement Concrete is used for interior construction in the making of kitchen tops, industrial, and commercial tops. This is because it is scratch resistant and stain resistant. Glass Fiber Reinforcement Concrete can also be used to line the walls of the sewer since it is resistant to acid, water, lime, and salt. Therefore, ensuring the sewers stay in a good condition for a longer time. Masonry walls can be retrofitted with glass fiber mesh to strengthen it since the walls usually have low resistance to environmental conditions. Historic restoration is made easier and possible using Glass Fiber Reinforcement Concrete because it can be made to look like a replica of many building designs.

2.6 Restrictions

A lot of time and planning is needed for the use of Glass Fiber Reinforcement Concrete before construction. This is because it needs to be made precast. This might not be convenient.

Chapter 3 - Polypropylene Fiber

3.1 Introduction

Polypropylene Fiber Reinforcement Concrete was first used in the year 1965 as a concrete admixture during the construction of a building for the USA engineer's corps. The fiber has since undergone a lot of development and is currently used as a short-fabricated material that produces Fiber Reinforced Concrete.

Polypropylene FRC is great in preventing and minimizing the spreading of cracks in concrete. The fibers come in various forms, depending on the consumer's requirements. The usage of polypropylene fibers to reinforce concrete shows compressive, flexural, and tensile strength increases.

3.2 Composition

Polypropylene is from the polyolefin family of chemicals [11]. These chemicals have the properties that allow them to resist corrosion, rust, water absorption, and are flame resistant. Properties of popularly used polypropylene fibers have the properties shown in **Table 3.1** where a denier is a unit of fineness equaling to the fineness of a 9000 m fiber weighing 1 gram [11]. Most applications require 3 pounds of fiber per cubic yard of concrete. This makes up 0.2% of the FRC by volume. Other components are the same as traditional concrete which include cement, water and aggregate.

Table 3.1 Polypropylene properties [11]

Fiber diameter	88-10,000 denier
Density	56 lb/ft^3
Specific gravity	0.91
Young's modulus of elasticity	500,000-700,000 psi
Tensile strength	70,000-110,000 psi
Elongation at break	10-15 %

3.3 Production

When manufactures produce polypropylene fibers, they are usually bundled up in thick straw-looking structures. After being mixed in with the concrete mix, the coarse and fine aggregates

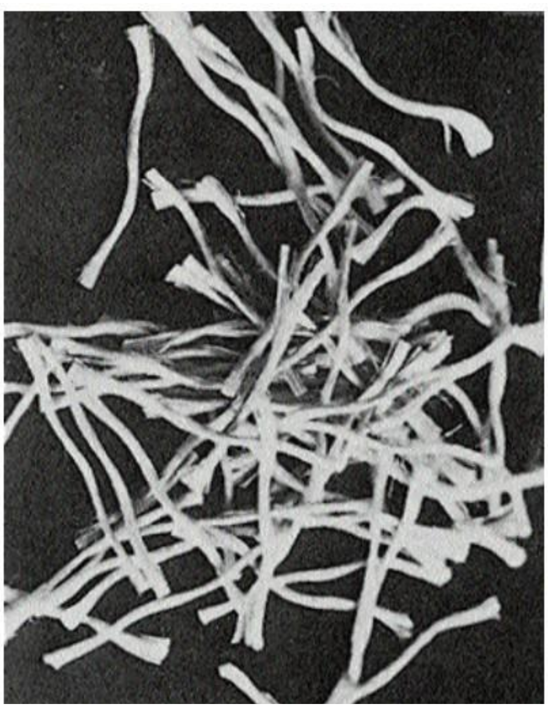

Figure 3.1 Polypropylene fibers before mixing [11]

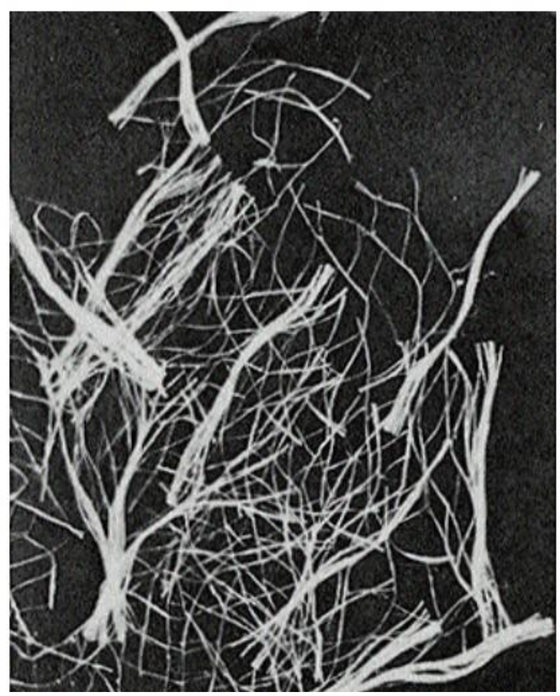

Figure 3.2 Polypropylene fibers after mixing [11]

beak them up into individual web-like fibers. **Figure 3.1 and Figure 3.2** show the comparison of the fibers before and after mixing.

Fiber length also must be adequate when mixing the concrete. Generally, longer fibers have higher pullout strength than shorter fibers. Longer fibers adhere better to the mixture, resulting in the greater pullout strength. A problem arises in using longer strands because longer fibers are distributed less evenly than shorter ones. To maintain balance between uniform distribution and pullout strength, a combination of long and short fibers are used. Longer fibers dominate the mixture when more course aggregates are used and vice versa. Fiber lengths are usually 0.5-2.5in in length.

The addition of polypropylene fibers to a concrete mix can be added in at the concrete plant or at the site depending on how far away the construction site is. Generally, 30 minutes are needed. This means that if the job site is less than 30 minutes away, the fibers are added at the plant. On the other hand, if the site is more than a half-hour drive the fibers are mixed in at the job site.

3.4 Advantages

The addition of polypropylene fibers has effects on fresh and hardened concrete. In the case of fresh concrete, plastic shrinkage is reduced. This is because the fibers increase the rate of drying. It should also be noted that workability is also increased, but by an insignificant amount.

In the case of hardened concrete, polypropylene fibers tend to prevent cracks. Even in the case that cracks to form, they prevent or slow down the spreading of cracks. One study shows that the addition of polypropylene fibers can also increase the compressive, splitting tensile, and flexural strength of concrete mixes [12]. Results of the study can be seen in **Table 3.2**. The notation PPO.15 corresponds to the percentage by volume of polypropylene fibers used in the mixture. For example, PPO.15 means that 0.15% of the mixture was polypropylene.

In addition to crack prevention, this test shows the increase in various strengths.

Table 3.2 Compressive, splitting tensile, and flexural strength test results [12]

Mix no.	Mixture ID	28-day Compressive strength (MPa)	28-day Splitting tensile strength (MPa)	28-day Flexural strength (MPa)
1	Plain	82.6	5.27	7.81
2	PPO.15	91.2 (10%)	5.95 (13%)	8.50 (9%)
3	PPO.30	91.5 (11%)	6.10 (16%)	8.59 (10%)
4	PPO.45	92.8 (13%)	6.30 (20%)	8.84 (13%)

3.5 Applications

Polypropylene FRC is used in water pipes, utility buildings, retaining walls, pavements, and more. Basically, where cracking would raise complications, polypropylene FRC is used.

3.6 Restrictions

The arrangement of fibers in the concrete is usually random, however, when pouring concrete, it is important to ensure that fibers face the direction in which stress is applied. Aligning this way enables the structure to have a greater flexural strength and a higher tensile strength. The compaction should be properly done so that the polypropylene fibers are equally distributed in the mixture and the flow of the fresh concrete is satisfactorily. The fiber should neither sink nor float on the concrete surface.

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Chapter 4 - Carbon Fiber

4.1 Introduction

Carbon fibers are available in many forms and grades. The strongest carbon fiber is about five times stronger than steel in tension. In addition to strength, carbon fibers have a lower density.

4.2 Composition

90% of the carbon fibers are made from polyacrylonitrile, a synthetic semi-crystalline organic polymer resin. The other 10% are usually made from petroleum products [13].

Fiber lengths used in Carbon FRC range from 3-12.7 mm [14]. Like all other concrete mixes, this one includes cement, water, and aggregates.

4.3 Production

Adding in the fibers to the concrete mix can be done in two ways. The fibers can be mixed in with the aggregates or mixed in with the water. It should be noted that fibers can be damaged during the mixing procedure. A study reported that when using 12 mm long fibers, the fibers decreased in length to an average of 7 mm [14].

4.4 Advantages

As discussed earlier, concrete is famously strong in compression, but weak in tension and flexure. Given that, compressive strength gains are not discussed. Increases in flexural stress were recorded in various studies and are shown in **Table 4.1.**

In this study, the lengths of the fibers that were used was 3 mm. This study also had various test such as looking at chemical additives and experimenting with optimal fiber length/content. It was concluded that the optimal fiber content is 1% by weight and 5.1 mm in length.

Table 4.1 Increases in 14-day flexural strength with the use of carbon fibers [14]

Fiber content (% by total weight)	Flexural strength (MPa)
0	4.80
0.5	5.28 (+7.6%)
1.0	6.41 (+5.3%)
2.0	6.45 (+8.9%)

4.5 Applications

Carbon FRC is used mainly in precast concrete. Carbon FRC is preferred in situations where corrosion is an issue. This is because the fibers are non-corrosive in nature. They are also used in cases where weight and thermal efficiency is desired. They can be applied in bridge construction since they weigh less making the footbridge lighter.

4.6 Restrictions

The carbon fibers should be handled with a lot of care because they conduct electricity and may lead to electric shock when mishandled. High temperatures should be avoided because the fibers can oxidize forming, other compounds that do not have the characteristics that carbon fibers have [15].

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