1. What is carbon fiber

Carbon fiber is, exactly what it sounds like – fiber made of carbon. But, these fibers are only a base. What is commonly referred to as carbon fiber is a material consisting of very thin filaments of carbon atoms. When bound together with plastic polymer resin by heat, pressure or in a vacuum a composite material is formed that is both strong and lightweight.

Much like cloth, beaver dams, or a rattan chair, the strength of carbon fiber is in the weave. The more complex the weave, the more durable the composite will be. It is helpful to imagine a wire screen that is interwoven with another screen at an angle, and another at a slightly different angle, and so on, with each wire in each screen made of carbon fiber strands. Now imagine this mesh of screens drenched in liquid plastic, and then pressed or heated until the material fuses together. The angle of the weave, as well as the resin used with the fiber, will determine the strength of the overall composite. The resin is most commonly epoxy, but can also be thermoplastic, polyurethane, vinyl ester, or polyester.

Alternatively, a mold may be cast and the carbon fibers applied over it. The carbon fiber composite is then allowed to cure, often by a vacuum process. In this method, the mold is used to achieve the desired shape. This technique is preferred for uncomplicated forms that are needed on demand.

Carbon fiber material has a wide range of applications, as it can be formed at various densities in limitless shapes and sizes. Carbon fiber is often shaped into tubing, fabric, and cloth, and can be custom-formed into any number of composite parts and pieces.

Some would argue, though, that the possibilities for carbon fiber are limited only by demand and the manufacturer's imagination. Now, it's common to find carbon fiber in:

- Aeronautics and aerospace industries
- Oil and gas industry
- Unmanned aerial vehicles
- Formula 1 race cars
- Satellites
- Musical instruments
- Furniture
- Art
- Structural elements of buildings
- Bridges
- Wind turbine blades

Carbon fiber is an incredibly useful material used in composites, and it will continue to grow manufacturing market share. As more methods of producing carbon fiber composites economically are developed, the price will continue to fall, and more industries will take advantage of this unique material.

2. History of carbon fiber

The 20th century saw a roller coaster ride in the demand for carbon fiber. Threats to peace increased the demand for carbon fiber for defense purposes mid-century. A downturn in defense needs result in a reduction in production of carbon fiber toward the close of the century. By the beginning of the 21st century, new applications and new markets sent the production of carbon fibers on an upswing. Despite a downturn in 2007-2008, worldwide demand increased to approximately 40,000 metric tons in 2010.

Carbon fibers have revolutionized the technology of materials. It is no wonder that the National Academy of Engineering voted carbon fibers one of the 20 top engineering achievements of the 20th century and the American Chemical Society named the development of high performance carbon fibers a National Historic Chemical Landmark in September 2003.

2.1 Historical Timeline of Carbon Fibers

Late 1800s **-** Thomas Edison carbonized cotton and bamboo to make filaments for his early incandescent light bulbs.

Late 1950s **-** Rayon made high tensile strength carbon fibers. Rayon later replaced by pitch and polyacrylonitrile (PAN).

Early 1960s **-** First practical commercial uses of carbon fibers. With high performance, light weight, and high stiffness and strength, the use of carbon fibers resulted in lighter and faster aircraft. Plus, aircraft were better able to withstand the extremely high temperatures of atmospheric re-entry because of the heat resistance of carbon fiber.

1960s, 1970s, and 1980s **-** Carbon fibers were produced mainly for the Department of Defense. Carbon fibers were also used in NASCAR and Formula 1 cars to make them lighter and more efficient.

Late 20th century **-** Reduced defense needs following the end of the Cold War and the collapse of the Soviet Union resulted in a decrease in the demand for carbon fiber.

Early 21st century **-** Carbon fiber production expanded significantly due to increased demand in the industrial, sporting goods, energy, aerospace, and wind energy industries. Production capacities expanded in Asia, the United States, and Europe.

2008 **-** Technical problems and global recession slowed plans for expanding manufacturing of carbon fiber.

2.2 Outlook for Carbon Fibers

Despite the economic slowdown, particularly around 2008-2009 , the outlook for carbon fibers is positive.

The automotive industry currently uses carbon fiber almost exclusively in the manufacturing of high performance vehicles. Forecasters expect the industry to expand its use of carbon fiber materials to general production vehicles in the near future.

Ford Motor Company will soon be using lightweight carbon fibers to reduce the weight of its vehicles in order to meet strict fuel efficiency goals. German automotive manufacturer BMW plans to expand its use carbon fibers to conventional vehicles, and General Motors has announced plans of developing carbon fiber composites for mass production.

Additionally, China is expected to promote carbon fiber use in the field of civil engineering, which has been reluctant to embrace carbon fiber as a replacement for steel.

According to The Future of Carbon Fiber to 2017: Global Market Forecasts, this is what the future looks like for the carbon fiber market:

- Annual growth rate of 17 percent through 2017.
- Production of 118,600 metric tons with a market value of $7.3 billion by 2017.
- For carbon fiber-reinforced plastics, annual growth rate of 16 percent through 2012.

Composite World's Carbon Fiber conference in 2009 forecasted the increase in the demand for carbon fiber through 2018, as shown in the table.

With solid growth in supply and demand anticipated, carbon fiber should be an exciting material to watch the 21st century. There is a reason this material is experiencing growth and acceptance. This is because carbon fiber is extremely easy to work with and has tremendous properties which allow for higher performing products.

3. Current usage of carbon fiber

Global demand for high-strength, light-weight and durable fiber is growing; typical applications in:

- Portable power
- Rechargeable batteries and fuel cell electrodes
- Fiber reinforced plastics, FRP
- Energy production; windmill blades
- Building and construction materials: concrete and asphalt reinforcements, soil erosion barriers
- Electronics, composite materials for automotives and general transportation,
- Specialty and niche markets.

3.1. Short carbon fiber reinforced concrete

Short carbon fiber reinforced concrete was an area of intense activity in Japan. Although carbon fibers are still used in cement slurry and concrete, this area is no longer being pursued as aggressively as it once was, primarily due to economics and codes that do not take into account the higher levels of performance. Although concrete is good in compression, it lacks toughness, tensile capacity and flexural strength. In fact, Portland Cement Paste does not compare very favorably even to aluminum in terms of standard properties.

Although steel reinforcement (rebar) is conventionally used in reinforced concrete to provide tensile reinforcement, there are a number of applications such as curtain walls, fascia panels, paneling for access ducts, barriers, and other cases in which cement mortar by itself could be used if tensile strength, flexural capacity and toughness could be improved. Asbestos fibers traditionally have been used as reinforcement in the chopped fiber form for applications such as thin sheet-like materials or boards (where reinforcing bars cannot be used due to thickness constraints), structural and architectural panels that must withstand high loads and/or deformations, and structural components where the fibers are added to obtain toughness and prevent cracking. The overall use of asbestos prior to the determination of it as a health hazard has been estimated to be as high as 2.5 to 3 million tons. Potential replacements for asbestos have ranged from steel fibers, polypropylene, nylon and polyethylene to glass, carbon and aramid fibers. A potential replacement for asbestos must be able to match most of the attributes that made asbestos a useful additive to cement mortar. These attributes are:

- strain to failure significantly higher than that of concrete mortar
- small fiber diameter
- hydrophilic surfaces that lend to good dispersion and bonding
- long term durability in an alkaline environment (fresh concrete can have a pH as high as 13)
- high strength and modulus
- overall durability in a harsh external environment

Carbon fibers are the closest to asbestos in a number of properties. The focus of this section is on Japanese developments in the use of chopped and short carbon fibers in concrete in a form known as carbon fiber cement concrete (CFCC) or carbon fiber reinforced concrete (CFRC).

As developed in Japan, CFCC has little resemblance to conventional concrete. It contains no coarse aggregate and typically contains between 3 to 15 percent by volume chopped and short carbon fiber elements. Three types of carbon fiber are used in CFRC in Japan: pitch-based carbon fiber, polyacrlonitrile-based carbon fiber, and Mitsui Mining form.

The first two materials are well known to the composites industry. The last was developed by the Mitsui Mining Co. as a cheaper material form with affinity for concrete slurry. A major concern in the addition of fibers to concrete is the bonding between the two. The resulting fiber has a "fuzzy" form with a strong affinity for concrete. The outcome is due to a combination of factors including the surface fuzziness and surface chemistry obtained by skipping the stabilization stage during pyrolysis.

In its use in polymer concrete, as with fiber reinforced concrete, the optimum form of the fiber may well be different from that used in aerospace applications. Further, the different requirements for civil engineering applications could result in the viability of lower cost fuzzy forms that could not be used previously in composites. Not all production is used in concrete and often special varieties are produced for use in CFCC for chemical stability, bonding issues and economics.

Based on the specific needs for a commercially viable form usable in concrete, Mitsubishi Kasei introduced the DIALEAD chopped fiber form made of pitch some years ago. Due to improved surface characteristics, it can be mixed in a normal top loading mixer without the need for special additive or a special mixer.

Although the performance levels of the fiber used in concrete are lower, they are at levels sufficient to show significant improvement in the performance of concrete. In addition to the direct improvements in performance in tensile and flexural strengths, the use of chopped carbon fibers in concrete results in other generic advantages, especially in building construction.

3.2. Carbon reinforced concrete

Reinforced concrete is cement in which bars ("rebars") or fibers have been incorporated to strengthen a material that would otherwise be brittle. Nearly all cement used in construction today is reinforced. Reinforcing cement to keep it from cracking is nothing new - even the earliest civilizations used natural fibers to inhibit cracking in masonry structures. The most widely-accepted form of enhancement is welded-wire fabric, a mesh of steel wires that is placed in cement. Synthetic-fiber can also used and can reduce the labor costs and difficulty in placement of the welded-wire mesh. These reinforcing methods are incorporated into the cement when it is made.

But what happens when structures crack, begin to fail, or the initial construction did not account for additional strength needed for unpredictable circumstances, such as wind loads? Rebar or other synthetic reinforcing materials cannot be added to existing structures.

Employing carbon-fiber kevlar technology, have been used in a wide range of applications to provide reinforcement to existing structures. When it comes to concrete reinforcement of existing structures, nothing beats our carbon-fiber kevlar sheet straps.

Concrete reinforcement with carbon-fiber sheet straps is a time-proven and tested method of reinforcing existing concrete and masonry structures for the purposes of repair or to strengthen the integrity and load tolerance of existing structures.

3.3. Carbon reinforced asphalt

Fiber reinforcement of concrete has been very popular and a common method to increase the strength and cracking resistance of the material. In fact, fiber reinforcement dates back to the 1950's when modern methods of the practice were first developed . Although fiber reinforcement has been extensively studied for concrete, these pavements only make up a small portion of the United States infrastructure system. In comparison, hot-mix asphalt (HMA) accounts for approximately 94% of the paved roadways in the United States and the trend is similar for airfield pavements. This type of paving material can provide a cost-effective method of surfacing roads, airfields and improving the world's transportation infrastructure system. However, like any type paving material, HMA is subjected to distress mechanisms which lead to deterioration and failure over time.

Distresses are the result of one or more factors, including magnitude of load, type of load, climatic conditions, material characteristics and material interactions. Major pavement distresses that challenge pavement engineers include permanent deformation (rutting), fatigue cracking, thermal cracking and raveling . Hoping to minimize or slow these pavement distresses, research has explored mixture modification through the use of fibers. Inclusion of fibers in paving materials serves to reinforce the material by adding additional tensile strength to the material that results from interconnection between aggregates.

This interconnection may allow the material to withstand additional strain energy before cracking or fracture occurs.

Over the years, researchers have experimented with many different types of fiber reinforcement, including polyester, asbestos, glass, polypropylene, carbon, cellulose, Kevlar and recycled waste fibers. In addition, fiber-reinforcement of HMA has evolved to include a blend of different fibers to achieve different performance aspects.

3.4. Fiber reinforced polymers

FRPs are typically organized in a laminate structure, such that each lamina (or flat layer) contains an arrangement of unidirectional fibres or woven fibre fabrics embedded within a thin layer of light polymer matrix material . The fibres, typically composed of carbon or glass, provide the strength and stiffness. The matrix, commonly made of polyester, Epoxy or Nylon, binds and protects the fibers from damage, and transfers the stresses between fibers.

The strength properties of FRPs collectively make up one of the primary reasons for which civil engineers select them in the design of structures. A material's strength is governed by its ability to sustain a load without excessive deformation or failure. When an FRP specimen is tested in axial tension, the applied force per unit cross-sectional area (stress) is proportional to the ratio of change in a specimen's length to its original length (strain). When the applied load is removed, FRP returns to its original shape or length. In other words, FRP responds linear-elastically to axial stress.

The response of FRP to axial compression is reliant on the relative proportion in volume of fibers, the properties of the fiber and resin, and the interface bond strength. FRP composite compression failure occurs when the fibers exhibit extreme (often sudden and dramatic) lateral or sides-way deflection called fiber buckling.

FRP's response to transverse tensile stress is very much dependent on the properties of the fiber and matrix, the interaction between the fiber and matrix, and the strength of the fiber-matrix interface. Generally, however, tensile strength in this direction is very poor.

Shear stress is induced in the plane of an area when external loads tend to cause two segments of a body to slide over one another. The shear strength of FRP is difficult to quantify. Generally, failure will occur within the matrix material parallel to the fibers.

Among FRP's high strength properties, the most relevant features include excellent durability and corrosion resistance. Furthermore, their high strength-to-weight ratio is of significant benefit; a member composed of FRP can support larger live loads since its dead weight does not contribute significantly to the loads that it must bear. Other features include ease of installation, versatility, anti-seismic behaviour, electromagnetic neutrality, excellent fatigue behaviour, and fire resistance.

However, like most structural materials, FRPs have a few drawbacks that would create some hesitancy in civil engineers to use it for all applications: high cost, brittle behaviour, susceptibility to deformation under long-term loads, UV degradation, photo-degradation (from exposure to light), temperature and moisture effects, lack of design codes, and most importantly, lack of awareness.

There are three broad divisions into which applications of FRP in civil engineering can be classified: applications for new construction, repair and rehabilitation applications, and architectural applications.

FRPs have been used widely by civil engineers in the design of new construction. Structures such as bridges and columns built completely out of FRP composites have demonstrated exceptional durability, and effective resistance to effects of environmental exposure. Pre-stressing tendons, reinforcing bars, grid reinforcement, and dowels are all examples of the many diverse applications of FRP in new structures.

One of the most common uses for FRP involves the repair and rehabilitation of damaged or deteriorating structures. Several companies across the world are beginning to wrap damaged bridge piers to prevent collapse and steel-reinforced columns to improve the structural integrity and to prevent buckling of the reinforcement.

Architects have also discovered the many applications for which FRP can be used. These include structures such as siding/cladding, roofing, flooring and partitions.

Intelligent Sensing for Innovative Structures (ISIS) Canada is a program that consists of collaborative research and development efforts of Canadian Universities in various engineering disciplines. Its primary mission is in the development of innovative uses of FRPs in concrete structures.

In Canada, engineers have integrated fibre optic sensors into numerous FRP-reinforced systems to ensure that adequate supervision of the systems is provided.

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