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Carbon Fiber and Its Composites: Synthesis, Properties, Applications

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Review

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Abstract

Carbon fiber is often preferred in composite production as it is a light and strong material. Traditionally, it is produced based on Polyacrylonitrile (PAN) and Pitch. Today, biomass-based carbon fiber production has studied as an alternative to these petroleum-based initiators. Accordingly, cotton, wood, and cellulose are the most commonly used biomass types. However, environment-friendly carbon fiber does not yet possess as good tensile strength as petroleum-based ones. So, researchers added PAN during the production of bio-based carbon fiber. Carbon fiber can be produced as a composite with many materials like polymers, metals, ceramics, and cement. It has a wide range of uses. Nowadays, researchers try to improve the interface between epoxy and carbon fiber to increase the functional properties of the composite. By preparing carbon fiber-reinforced metal, it can be possible to use composite as a catalyst. Carbon fiber is used as filler in concrete production to avoid crack formation and thus, carbon fiber composites are crucial in preventing earthquake disasters. In brief, one can enable comprehensive and contemporary information about the synthesis and applications of all types of carbon fibers (PAN, Pitch, bio-based) and their composites (polymer, metal, ceramic, concrete, carbon nanotube, and graphene).

Keywords: PAN, pitch, carbon fiber, carbon fiber reinforced composite

Karbon Fiber ve Karbon Fiber Kompozitler: Sentezi, Özellikleri, Uygulama Alanları

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Öz

Karbon fiber hafif ve sağlam bir malzeme olduğundan kompozit üretiminde sıklıkla tercih edilmektedir. Geleneksel olarak Poliakrilonitril (PAN) ve Zift temelinde üretilir. Günümüzde bu petrol temelli başlatıcılara alternatif olarak biyokütle-temelli karbon fiber üretimi üzerinde çalışılmaktadır. Bu amaçla pamuk, odun ve selüloz en çok kullanılan biyokütle türleridir. Ancak çevre dostu karbon fiber henüz petrol temelli olanlar kadar iyi bir çekme mukavemetine sahip değildir. Bu nedenle, araştırmacılar biyo temelli karbon fiber üretimini PAN eşliğinde gerçekleştirmektedirler. Karbon fiber, polimerler, metaller, seramikler ve çimento gibi birçok malzemeyle kompozit olarak geliştirilebilmektedir. Geniş bir kullanım alanına sahiptir. Günümüzde araştırmacılar, kompozitin fonksiyonel özelliklerini arttırmak için epoksi ve karbon fiber arasındaki arayüzü iyileştirmeye çalışmaktadır. Karbon fiber takviyeli metal hazırlanarak kompozitin katalizör olarak kullanılması mümkün olabilir. Beton üretiminde çatlak oluşumunu önlemek amacıyla dolgu maddesi olarak karbon fiber kullanılmaktadır. Deprem felaketlerini önlemekte karbon fiber kompozitler önem taşır. Kısacası, bu çalışma ile tüm karbon fiber türleri (PAN, Zift, biyo temelli) ve kompozitlerinin (polimer, metal, seramik, beton, karbon nanotüp ve grafen) sentezi ve uygulamaları hakkında güncel ve kapsamlı bilgi sağlanabilir.

Anahtar Kelimeler: PAN, zift, karbon fiber, karbon fiber destekli kompozitler

Introduction

Carbon fiber is defined as fiber that is at least 92% carbon by weight [1]. The most crucial feature of carbon fiber is that it is a light and strong material [2]. Because of their high strength, they are preferred in the production of composite materials [3]. Figure 1 shows the material types which can be used to make composite involving carbon fiber. The figure covered Scanning Electron Microscope (SEM) images of composite materials. As shown in Figure 1, carbon fiber is a so thin and long filament-like material. It can be used by cutting it upon request. The need for carbon fiber has been increasing since 2010. This year, 51 thousand tons of carbon fiber were produced. For 2023, this amount is expected to reach 200 thousand tons. In addition, the amount of waste carbon fiber in Europe isabout 3 thousand tons in 2020 [4].

The top 5 countries which have share in carbon fiber importation are USA, Germany, Italy, China, and United Kingdom based on 2022 data. Hence, the United States of America was the first country in ranking concerning the import of nearly 250 thousand tons of carbon fiber derivatives [5]. However, the top 5 countries for carbon fiber exportation worldwide were China, Japan, Germany, USA and France in 2022. China has a giant share of about 580 thousand tons among the other countries in the top 5 [6]. Introducing carbon fiber into the scientific literature was carried out by Thomas Edison. Edison produced carbon fiber from cotton and bamboo fibers while researching materials for use as lamp filaments. Commercialization of carbon fiber was made after the invention of the Polyacrylonitrile (PAN) process. The PAN process is an economically high carbon yield process. The PAN process is a process that still maintains its importance today. Later, a pitch-based process of carbon fiber emerged. Pitch is an inexpensive initiator which is able to be produced from petroleum, asphalt, coal tar, and polyvinyl chloride. However, the properties of pitch-based carbon fibers are not as good as PAN-based carbon fibers [3]. The wet spinning technique is generally used for PAN-based carbon fiber synthesis. However, hazardous solvents are utilized in wet spinning. Besides that, during its carbonization, toxic gaseous occurs because of nitrile groups in the PAN precursor. Because of these reasons, researchers find new precursors to obtain carbon fibers. Biomass, lignin, and cellulose are the main bio-based precursors for this approach [7]. Today, biomass-based carbon fibers have been synthesized for composites and found several applications. Huang et al. (2024) synthesized polar poplar carbon fiber and suggested that the carbon fiber can be used for the production of fire warning sensors [8]. Liu et al. (2023) improved a solvent-free method to synthesize easily down cluster-based carbon fiber aerogel. They suggested using this carbon fiber in solar steam generation [9]. Wang et al. (2022) synthesized cotton-based carbon fiber and then used it to produce a carbon fiber/metal-organic framework composite. They used this composite as an electrode for the electro-Fenton process [10]. Carbon fiber generally is used as composites. The Matrix of the composite can be polymer, ceramic, metal, and carbon. Matrix protects the structure against high temperatures and humidity. Carbon fiber-reinforced polymer is produced for aviation and space applications. They have high strength, low weight, and fatigue behavior [11]. Today, the main research topics of carbon fiber-reinforced polymers are manufacturing heat exchangers [12] and heat pumps [13]. Besides that, recycling of waste carbon fiber reinforced polymer is a hot research topic regarding environmental concerns [14]. Carbon fiber-metal composites are used as anode material for microbial fuel cells [15], laminate production [16], hydrogen evolution [17], and benzene oxidation [18] reactions. Matrices of carbon fiber composites can be also carbon nanotubes [19] and graphene [20]. Carbon fiber is combined with ceramics to prevent crashes. Carbon fiber-reinforced ceramics have thermal stability, low density, high mechanical strength, and resistance against corrosion and oxidation. Due to these eminent properties, they can be utilized in aerospace, aviation, electronics, chemical, and medical fields [21]. To increase the tensile strength and toughness of concrete, carbon fiber reinforcement can be applied [22]. Nowadays waste carbon sources are utilized to obtain carbon fiber-reinforced concrete such as preg carbon cloth [23].

The study aimed to present the synthesis, properties, and applications of carbon fiber and its composites. Carbon fiber was investigated as PAN, Pitch, and bio-based. All composite matrices were taken into consideration which were polymer, concrete, metal, ceramic, and carbon. In literature, review articles about carbon fiber are based only on one property its mechanical characteristic [24, 25], and just one type of composite the polymer-carbon fiber [26]. This study enables us to gain comprehensive and contemporary information contributing to current review studies in literature.

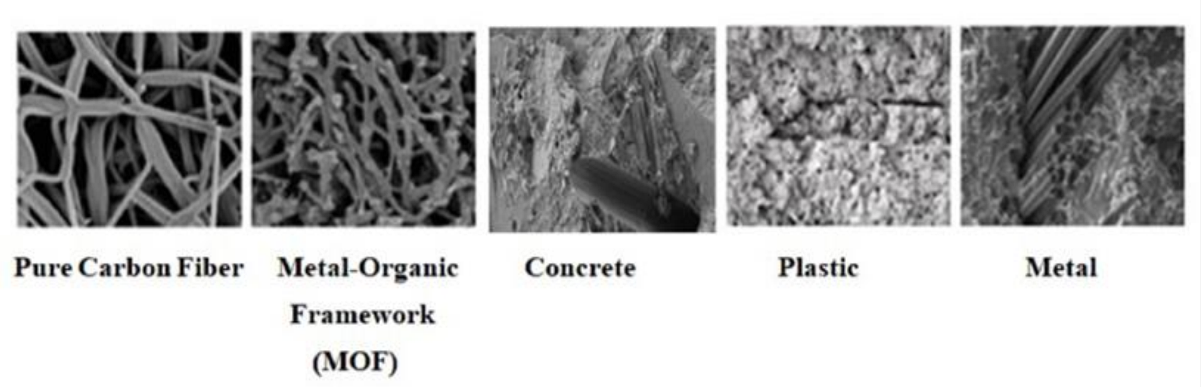

Figure 1. *Several materials for Carbon fiber composites [27-30]*

Types of Carbon Fibers

PAN based Carbon Fiber

Synthesis

PAN-based carbon fibers can quickly be synthesized. The manufacturing processes involve several steps shown in Figure 2.

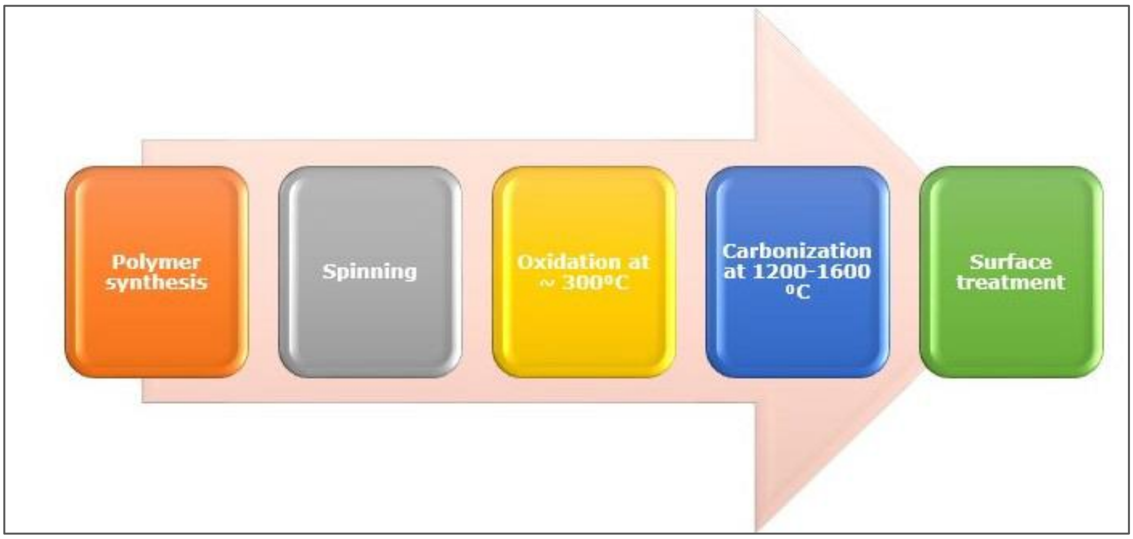

***Figure 2.** PAN-based carbon fiber synthesis [31]*

The polymerization of acrylonitrile is crucial as it is highly effective in the subsequent synthesis steps of PAN-based Carbon Fiber [31]. Salts of Persulfate ($S_2O_8^{2-}$) and Iron (Fe^{3+}, Fe^{2+}) ions can be utilized as polymerization initiators [32-34]. However, since transition metals such as iron cause impurities, modifications have currently been studied [35]. Acrylonitrile (AN) can be polymerized in bulk, suspension, solution, or emulsion. Solution and suspension polymerization are the most widely used methods for the synthesis of PAN-based copolymers [31]. Solution polymerization is carried out using Dimethylacetamide (DMAc), Dimethylformamide (DMF), Dimethylsulfoxide (DMSO), or aqueous Sodium Thiocyanate solutions as solvents [36]. Since the produced copolymers have high molecular weight, diluted solutions should be used in polymerization reactions. With solution polymerization, it is possible to quickly obtain a fiber-spinning solution. However, solution polymerization has a significant disadvantage. The conversion value for obtaining PAN from acrylonitrile by this method is around 50-70%. Acrylonitrile is known to be carcinogenic. Therefore, unreacted acrylonitrile must be removed from the fiber-spinning solution. On the other hand, no by-product formed in suspension polymerization. Besides, the polymer can easily be separated by filtration and drying. The molecular weight and particle size of the polymer can be adjusted as desired and, 90% efficiency can be achieved with this method [31]. For PAN-based polymers to spin, it is necessary to work at temperatures below the melting point of the polymer. In this case, the application of molten spinning a traditional spinning method is nearly impossible. Because this method can be applied to the PAN polymer only with the addition of high amounts of solvent additives and plasticizers. So, wet spinning is preferred for spinning PAN polymer. In wet spinning, selecting a solvent in which the PAN polymer can dissolve is so crucial. For this purpose, ionic liquid, DMAc, DMF, DMSO, Zinc Chloride, and Sodium Thiocyanate solutions can be used as solvents [31]. In the wet spinning method, the polymer spinning solution is squeezed into the spin tube and it enters into the coagulation bath. The coagulation bath contains coagulants, that is, non-solvent liquids. The coagulant penetrates the extruded polymer and turns it into fiber [37]. The two controllable variables in wet spinning are the spinning bath and the temperature and concentration of the spinning solution. At this point, generally increasing the solvent content and decreasing the bath temperature reduces diffusion. In this case, the solvent released from the polymer and the coagulant flow into the polymer decrease. The post-spinning procedure is the same for all spinning methods: washing, drawing, drying, relaxing phase, and collecting. Washing is done with water or steam. The drawing process is carried out in the environment of ethylene or glycerol in the range of 120-180 ºC. Before drying, the fibers are soaked in aqueous emulsions of esters such as polyoxyethylene derivatives. Drying and relaxation steps are crucial in removing water [31].

The oxidation is carried out at 200-300 ºC in an oxidizing atmosphere. In the oxidation stage, the density of the PAN fiber increases. Its mass composition is usually around: 70% carbon, 20% nitrogen, 10% oxygen, and a small amount of hydrogen [31]. As an alternative to oxidation in the oven, this stabilization step can be performed with plasma treatment or microwave-assisted lower energy and time [38,39]. PAN fibers stabilized in the carbonization stage are converted into carbon fibers by thermal pyrolysis in an inert atmosphere at high temperatures. The volatile components are removed. So, the carbon yield can reach around 50% by mass, depending on the PAN initiator [40]. The carbon fiber forms after carbonization and contains approximately 95% carbon and 4% nitrogen. Concerning not to damage the fiber, the heating rate is selected low. Most volatile components are removed from the structure in the range of 200-1000 ºC. The gas formed as a result of pyrolysis may contain HCN, H_2O, H_2, CO, NH_3, and CH_4 [41]. Graphite fibers form after heating above 2000 ºC [40]. Carbonization is applied to improve the adhesion of carbon fiber in the composite [42]. At surface treatment stage, fiber can be protected from high-temperature degradation. The tensile strength of carbon fiber increases [43].

Properties

The most prominent feature of PAN-based carbon fiber is its high tensile strength. Reductions in tensile strength are due to defects that occur during the synthesis process of the material. These defects occur since the PAN polymer loses about half its weight before it converts into carbon fiber. As a result of defects, various mechanical, electrical and thermal properties of carbon fiber, especially tensile strength, are affected. It is known that surface defects are more effective on tensile strength than defects that occur inside the material. Surface defects can be caused by oxidation and carbonization, as well as thermal processes used in surface treatments [2].

The thermal conductivity of PAN-based carbon fiber can be increased by using carbon nanotubes. It can be known that carbon nanotubes have high thermal conductivity. They can be grafted on PAN-based carbon fiber [44].

Application Area

Especially in the field of energy, the application areas of PAN-based Carbon Fiber are wide. It is known that successful results are obtained when integrated into carbon fibers in hydrogen storage. In addition, researchers have obtained successful results in the use of PAN-based carbon fibers as anode material in lithium-ion batteries [45]. Besides that, PAN-based carbon fiber reinforced concrete is important for the construction industry. An environmentally friendly process can be achieved by replacing heavy and corrosive steel with carbon fiber in concrete production [46]. Table 1 displays some of the PAN-based carbon fibers in current literature.

Pitch Based Carbon Fiber

Properties

Pitch-based carbon fibers are divided into two as isotropic and anisotropic mesophase [47]. Anisotropy is a property in which the properties of the material change depending on the direction. In isotropy, the material has homogeneous properties in all directions [48]. Mesophase pitch is a liquid crystal material. It consists of various types of aromatic hydrocarbons. These hydrocarbons are stacked planarly in the structure and optical anisotropy is provided. It is known that mesophase pitch-based carbon fiber is a very light material with a tensile strength up to 4GPa, a thermal conductivity of 1000 W/mK, and a density of around 2 g/cm^3 [49]. Isotropic pitch-based carbon fibers are inexpensive but have low tensile strength (approximately 500-1000 MPa pressure) [50].

Synthesis

Carbon fiber synthesis is similarly done for both isotropic and anisotropic pitch sources. For this purpose, the synthesis procedure includes the following steps as shown in Figure 3. The raw materials of both pitch types are the same. These can be pure chemicals (aromatic compounds and polymers), petroleum, and mixtures of polyaromatic hydrocarbons, which are by-products in the production of coal. Tar initiators are pre-treated to remove impurities (coke, inorganic substances, heavy components, etc.). For this purpose, cheap and practical methods are applied in industrial production. These can be distillation, pressure use, extraction, or centrifugation [47].

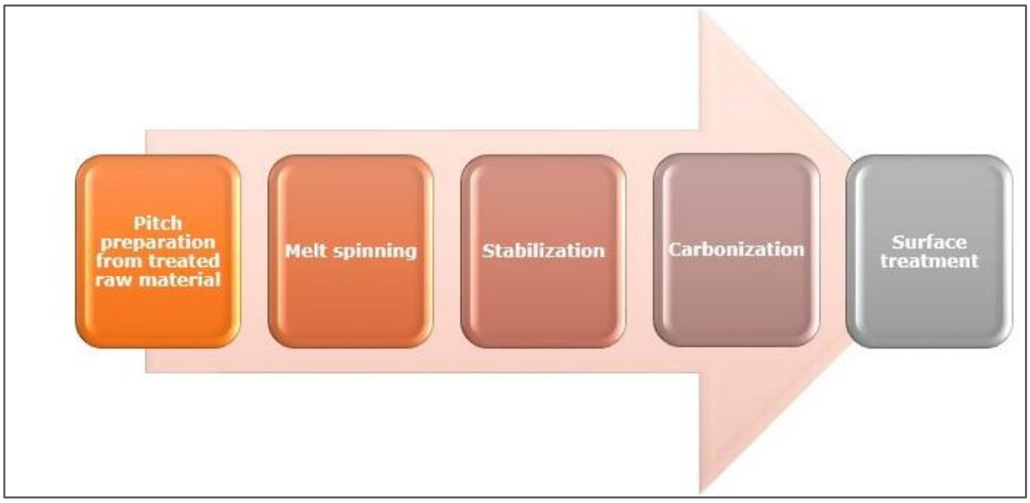

Figure 3. *Pitch-based carbon fiber synthesis [47]*

The preparation of pitch from the raw material is done under controlled conditions. Temperature, pressure, heating rate, atmosphere, and mixing speed affect pitch production [47]. The pitch is then melt-spinned and fibers are formed. For this purpose, pitch is first melted in an inert atmosphere. The melted pitch is taken from the spinning tube as fibers as a result of increased pressure [47]. The purpose of stabilization is to provide the transition of pitch fibers from thermoplastic to thermoset by oxidation. Thus, the structure and shape of the pitch fibers do not change during carbonization. The softening temperature for both pitch fibers is approximately the same (around 250 ºC). Temperature and heating rate are important in the oxidation stage. The reason is that, if the temperature is chosen lower than the softening point, there will be little change in the weight of the pitch fibers, indicating that oxidation is not taking place effectively. If the temperature is chosen too high than the softening temperature, the pitch fiber oxidizes quickly and starts to burn. On the other hand, at high heating rates, oxidation cannot be completed and the fibers stick together [47].

By carbonization, non-carbon atoms (oxygen and hydrogen) and side chains of the aromatic ring are removed. Thus, the carbon aromaticity is increased. As a result of carbonization, with increasing temperature, aromatic groups are cross-linked, condensed, and polymerized, respectively. The carbonization temperature is selected according to the characteristics of the initiating pitch. Generally, the range of 300-500 ºC is the pre-carbonization range, the main carbonization takes place in the range of 500-1400 ºC. The precise mechanical, physical, and chemical properties of carbon fiber are formed after carbonization [47].

Table 1. *PAN-based carbon fibers in current researches*

Application	**Reference**
Cathode material for electrochemical production H_2O_2	Xia et al. (2020) [51]
Sensor for detection of electric field in ocean	Zai et al. (2020) [52]
Separator in Li‖$LiFePO_4$ battery	Deng et al. (2023) [53]
Electromagnetic wave absorption material	Li et al. (2023) [54]
Adsorbent for CO_2	Ma et al. (2022) [55]
Adsorbent for Phosphate Ions	Matsuzawa et al. (2022) [56]
Adsorbent for Acetone	Shi et al. (2022) [57]
Hydrogen Storage	Hwang et al. (2021) [58]
Catalyst for selective hydrogenation of pyrolysis Gasoline	Wu et al. (2021) [59]
Adsorbent for p-nitrophenol	Yue et al. (2021) [60]
Reinforced material for concrete	Patchen et al. (2023) [61]

Application Area

It has been proven that mesophase pitch-based carbon fiber can be used as a heat management material in composite with aluminum as a material with high thermal conductivity and low thermal expansion coefficient [62]. In another application, pitch-based carbon fiber was loaded on the carbon nanotube in the cement and increased the electrical conductivity by acting as a bridge between the nanotube particles [63]. Pitch-based carbon fiber is simultaneously used with graphite at the anode and cathode in bidirectional batteries. Thus, a lithium-ion electrolyte bidirectional battery with high local capacity and stability was produced [64]. Table 2 shows some of the PAN-based carbon fibers in current literature.

Alternative Bio-Based Carbon Fiber Resources

Lignocellulosic biomass (containing lignin and cellulose) is naturally abundant, renewable, inexpensive, and has a low environmental impact. Therefore, optimizing the carbon fiber production method from this material is important to commercialize it to replace petroleum-based carbon fiber [65].

Table 2. *Pitch-based carbon fibers in current researches*

Application	Reference
Cement reinforcement material to cool pavement	Wei et al. (2023) [66]
Adsorbent for iodine, methylene blue and cadmium ions	Wang et al. (2022) [67]
Adsorbent for formaldehyde	Ryu et al. (2019) [68]
Adsorbent for CO_2	Sugiyama and Hattori (2020) [69]
Adsorbent for chloroform	Yoshikawa et al. (2021) [70]
Anode material for potassium-ion batteries	Wei et al. (2021) [71]

The production of short-length carbon fiber from sustainable biomass is important because of its low environmental impact and the cheapness of its initiators compared to PAN and petroleum-based pitch. In addition, if cellulosic materials are used for this purpose, the CO_2 that plants take from the atmosphere can be stored in the form of carbon. Bamboo with high cellulosic content can be used for this purpose. The electrical conductivity of bamboo-based carbon fiber has been proven to be high [72]. There are studies using lignin-based carbon fiber in terms of environmental improvement. In one of them, the removal of methylene blue textile dye from water was studied [73]. However, the production of high-performance carbon fiber in this way is not yet possible due to the following obstacles: 1) Carbon fiber has a high ash content. 2) It does not have high strength. Mixing PAN and other polymer initiators with lignocellulosic biomass can remedy this situation. However, in this case, the process would not be environmentally friendly. Therefore, mixing lignin with other biomass may be a more effective strategy.

3) Sensitive to the spinning process [65]. Table 3 shows several materials which can be used for biomass based carbon fiber.

Table 3. *Lignin-based carbon fibers in current researches*

Biomass Type	Application	Reference
Cotton	Adsorbent for methylene blue	Chiu et al. (2012) [74]
Wood	Electrode material for supercapacitor	Jin et al. (2014) [75]
Sisal plant	Adsorbent for phosphate	Hu et al. (2018) [76]
Cotton	Electrode material for water-splitting	Hong et al. (2022) [77]
Cellulose	Adsorbent for flüoride	Zhang et al. (2019) [78]
Waste rabbit hair	Photocatalyst for methylene blue degradation	Chen et al. (2022) [79]
Cotton	Electrode for electro-Fenton degradation of Tetrabromobisphenol A	Wang et al. (2022) [10]

Carbon Fiber Composites

Properties

A composite is formed by the combination of two or more materials with different physical and chemical properties. It is possible to physically separate the materials in the composite from each other. Generally, it consists of a composite matrix and supporter. The matrix is a soft and weak material that is embedded in the support material. The support material, on the other hand, is a strong and hard material that is distributed throughout the matrix. The main purpose of composite production is to obtain a material with strong mechanical properties by combining individual components with low mechanical properties. In addition, the composite is expected to be a lightweight material [11].

The surface of carbon fiber is smooth, chemically inert, and non-polar naturally. Therefore, it is crucial to treat the carbon fiber surface to reach good interfacial adhesion between the matrix and carbon fiber and low cohesion behavior in the matrix of the composite. This can be ensured by forming chemical or physical bonds between two components of the composite such as Van der Waals attraction, hydrogen bond, and mechanical interlocking [80, 81]. For interfacial treatment of carbon fiber in the composite, three methods can be followed three methods which are wet, dry, and multi-scale. In a multi-scale approach, carbon fiber is coated with some materials. The material used at the interface of a composite is so crucial. Since the material used at the interface has a great effect on the formation and propagation of cracks and the distribution of stresses in the composite. In addition, this material affects the strength, toughness, moisture, and heat resistance of the composite. If there is poor adhesion between the fiber and the matrix, there are deficiencies in the interface material and the performance of the composite will be poor. Rare earth nanoparticles and carbon nanotubes have been the most studied interface materials for carbon fiber composites [81]. Another choice is wet or chemical treatment. These are liquid-phase oxidation, electrochemical oxidation, and catalytic oxidation [82]. Amine groups can help to improve the surface polarity and wettability of carbon fiber. Correspondingly, amino groups connect to carboxylic groups to reach good adhesion between carbon fiber and epoxy, after oxidation treatment with acids [80]. The last route is dry or gaseous treatments such as plasma surface modification [81].

The matrices of carbon fiber composites can be very diverse. These are 1) thermoset (cyanate ester, epoxy, phenolic, polyester, polyimide, and vinyl ester) or thermoplastic (acrylonitrile butadiene styrene, polyamide, polycarbonate, polyethersulfone, polyethylene, polypropylene, and so on) polymers, 2) carbon (C-C composites), 3) metals such as nickel, 4) ceramics, 5) cement can be used [83].

Synthesis and Application Area

Discovered in 1960, this type of composite is used in automotive, civil, mechanical engineering, aerospace, shipbuilding, and wind turbine applications. Since carbon fiber is a durable and light material, it is preferred as a polymer composite material. In addition, the cost is low compared to other fibers used for filling purposes. It is preferred since it improves the thermal, mechanical, and electrical properties of the polymer [83]. Today, research on carbon fiber-polymer composites is mostly aimed at strengthening the physicochemical interaction between these two materials. This interaction is mostly made possible by Van der Walls and hydrogen bonds. The researchers aimed to improve the properties of the composite by reaching bonding energy that exceeds the cohesion forces of the polymer and carbon fiber. In addition, increasing the amount of carbon fiber in the composite can lead to brittleness in the composite [83]. Often used with thermoset matrix, especially epoxy, and carbon fiber. Furfuryl and phenolic resins form other types of thermoset matrix. Today, thermoplastic matrices (polyethersulfone (PES), polyphenyl sulfide (PPS), polyetherimide (PEI), and polyimide (PI)) have also been used. The properties of thermoplastics are that they have high ductility, withstand high temperatures, and can be produced in a shorter time [83]. The production of Carbon Fiber-Polymer composites can be in traditional ways such as extrusion, compression molding, injection molding, resin transfer molding, and vacuum transfer molding [83]. There are many types of research in the current literature about carbon fiber-polymer composites. Tam et al. (2023) investigated the effect of moisture on carbon fiber-epoxy composite interface via computational ways [84]. Chauhan et al. (2023) assessed the effect of chemical surface functionality on carbon fiber regarding its thermal conductivity effect in carbon fiber-epoxy composites [85]. Darıcık et al. (2023) used carbon nanotubes to develop the electroconductivity of carbon fiber-epoxy composites [86]. Figure 4 shows the general structure of carbon fiber-polymer composites.

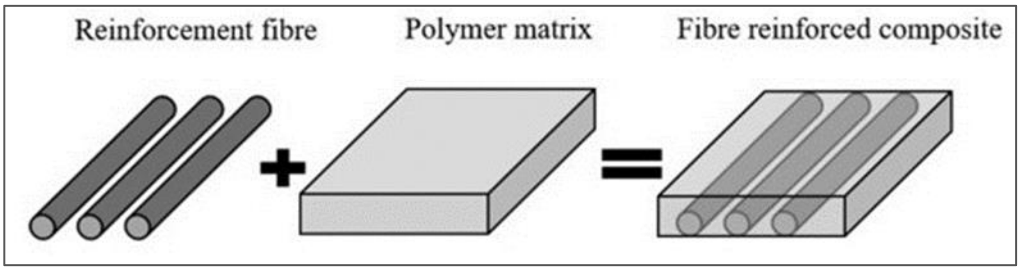

Figure 4. *General scheme for carbon fiber reinforced polymer composites [87]*

Carbon Fiber-Carbon

Various methods can be used for their synthesis. These are vacuum filtration, pressure filtration, dry synthesis, and powder molding [88]. They are used as a thermal insulator by NASA in space vehicles. It can withstand up to 2800 °C in airless conditions. It can also be used as a thermal insulator in vacuum electric furnaces. In addition to this application area, carbon fiber-carbon composites can be used for gas adsorption and separation and as cathode material in batteries. Its density is low and its porosity is high (70-90%). The disadvantages are that their mechanical properties are low and they have the potential to undergo oxidation. For this purpose, in recent years, researchers have tried coating with pyrolytic carbon, ceramics, aerogel, and nanostructures. Among these, coating with aerogels has come to the fore and is under development [88]. There are many kinds of research in literature about carbon fiber-carbon composites. Wang et al. (2023) synthesized the composite to use as a thermal insulator for electromagnetic heating furnaces. They utilized the vacuum filtration method to synthesize the composite [89]. Ding et al. (2023) developed the composite by growing carbon nanotubes on carbon fibers. They used the composite as an additive to cement. They aimed to increase the mechanical and electrical performance of the material. Besides that, this material had the property of sensing crack formation [90]. Wu et al. (2022) also investigated carbon fiber-carbon nanotube composite. They used polydopamine between interlayers of these materials. In this way, they achieved higher mechanical stability and homogenous distribution of carbon nanotubes on the surface of carbon fiber [91].

Carbon Fiber-Metal

Various metallic matrices can be composited with carbon fiber. Studies with Aluminum (Al), Titanium (Ti), Magnesium (Mg), Copper (Cu), Nickel (Ni), Tin (Sn), and Zinc (Zn) matrices are available in the literature [92-98]. To composite the carbon fiber and the metallic matrix, the surface of the carbon fiber is first treated. This process is important to strengthen the bond between the carbon fiber and the matrix. Surface treatment can be carried out by oxidative or non-oxidative means. Composite synthesis can proceed using three routes: the solid or liquid state process and the precipitation process [30]. Today, carbon fiber-metal composites can be used in the automobiles, aerospace, and petrochemical industries where metal and metal alloys are used. These materials are strong composites, have high mechanical resistance, can be easily produced, have advanced thermal and electrical properties, and have a low friction coefficient. Researchers continue their studies to make the carbon fiber distribution in the composite more regular. In addition, mathematical modeling techniques such as fuzzy logic and neural networks can be used to examine the mechanical properties of the composite [30].

Carbon Fiber-Ceramic

Silicon carbide (SiC) composite reinforced with carbon fiber is a material developed especially for use in aerospace applications and incorporates the properties of high-temperature resistance, fracture toughness, abrasion, and thermal shock resistance. It is therefore a composite being investigated for use in rocket engines. The properties that the researchers are trying to develop for this composite are to increase the oxidation and mechanical strength of the material at ultra-high temperatures (above 3000 °C) [99]. Apart from SiC, ZrC, ZrB_2–ZrC –SiC, ZrB_2–SiC, SiC–TaC ceramics can be used as a matrix [100-103]. Currently, chemical vapor infiltration/deposition is considered as the best method for composite synthesis [99].

Carbon Fiber-Concrete

Concrete is a composite material used in building applications. Concrete contains cement, pebbly sand, water, and some additives [104]. Various types of concrete are used in large quantities throughout the world. For this reason, researchers are currently conducting research on improving the engineering properties of concrete. Developing concrete with especially high strength, toughness, and durability is the main goal of researchers. For this purpose, the prominent ones among the new types of concrete developed by researchers in literature are high-performance concrete and high-performance fiber-reinforced concrete. High-performance concrete has superior mechanical properties and durability compared to conventional concrete. In addition, high-performance concrete can be produced by mixing various mineral-containing materials to further improve its mechanical, physical, and durability properties. These materials are silica fume, ground blast furnace, and fly ash. It is possible to obtain concrete except for cement. The use of these materials in the production of high-performance concrete has several advantages. These are as follows: 1) Additional materials increase the fullness of the cement mixture due to their small size, 2) Additional materials increase the final compressive strength of the concrete, and 3) Additional materials increase the durability of the concrete. On the other hand, these additional materials have advantages as well as disadvantages. They increase the brittleness of concrete, so cracks occur over time. The formation of cracks reduces the water resistance of the cement. And as a result, the interior of the cement is exposed to moisture, bromine, and acid sulfates [105]. Different factors such as shrinkage, overloading, and adverse environmental conditions due to thermal factors may also be effective in the formation of cracks in concrete, and it is not possible to escape from the crack formation. Over time, the cracks expand in size and increase in number. Cracks can be large (over 200 microns wide) or small. Due to large cracks, water and other impurities such as sulfate, chloride ions can penetrate the concrete. In addition, microcracks, which are considered insignificant in conventional concrete, actually disrupt the structural integrity. Microcracks have an opening between 0.1-0.3 mm. In general, researchers recommend that the maximum surface crack opening should not exceed 2 mm. Various strategies have been developed to prevent crack formation. The first of these is the manual repair of cracks. In this traditional method, cracks are filled. In this way, the penetration of corrosive substances into the concrete is prevented and the tensile strength is restored. Another strategy is to modify the concrete composition. To this end, researchers intervene during the concrete production phase to reduce the cost of repairing cracks. Fibers are additives used for this purpose. Self-healing concrete is another way of preventing crack formation [106]. Fibers can also be used for self-healing of concrete. Healing agents can be added to the concrete mix by encapsulation, vascular, or immobilization methods. In encapsulation, the capsules withstand the mechanical stress in the concrete and release their healing agents into the cracks in the concrete [107]. The crack width can be controlled by the use of fibers in concrete. In this way, the durability and tensile strength of concrete can be increased. Fibers frequently used in cement-based concrete are as follows: steel, glass, polypropylene (PP), polyvinyl alcohol (PVA), and carbon [105]. It is known that the fiber type used affects the concrete properties. Accordingly, since steel fibers have higher strength compared to PVA and PP fibers, they can reduce shrinkage in concrete and have higher resistance to cracking [108]. Glass fiber has higher chemical resistance and is lighter than steel fiber. In addition, glass fiber has a higher resistance to water and gas permeability than steel fiber [109]. Besides, it is known that steel fiber is susceptible to thermal expansion and corrosion problems [110]. The coefficient of elasticity of carbon and steel fiber reinforced concrete has proven to be higher than that of glass fiber reinforced concrete. In addition, it has been seen from previous studies that the compressive strength of carbon fiber-reinforced concrete is higher than that of glass and steel-reinforced concrete. In addition, studies have shown that the durability of carbon fiber-reinforced concrete is higher than that of steel fiber-reinforced concrete [109]. It is possible to use carbon fiber-reinforced concrete composites in columns, floors, and beams in structural applications. An example of a carbon fiber concrete composite is presented in Figure 5. Carbon fiber is not directly composited with concrete, usually, polymer additives are also used [111-113]. There are various studies on carbon fiber-reinforced concrete composites in the literature. In this review, a literature analysis was conducted in terms of the importance of the effects of these composites on the crack resistance of concrete. Liu et al. (2019) stated that the addition of polymer to carbon fiber-reinforced concrete has positive effects on the static strength of the composite. To reach this conclusion, they tested mixtures containing polymer: cement in different ratios by mass. The best results were obtained with the composite with a polymer: cement ratio of 8% by mass. In this case, they found the tensile strength for bending and splitting to be 36% and 61%, respectively. The compressive strength remains low in this case. They also observed with Scanning Electron Microscopy (SEM) images that the polymer emulsion acts as a bond between the matrix and the fiber interface. In this way, the resistance of the composite to crack formation has been increased [114]. Liu et al. (2020) investigated the effect of polymer: cement mass ratio (0-12%) on mechanical properties at different deformation rates (45-150 s^{-1}) in carbon fiber reinforced polymer concrete. Accordingly, at the same deformation rate, with the increase of polymer content, the compressive strength first increased and then decreased. When they plotted the stress versus deformation, they found that only micro-cracks formed at low stress. The reason for this is that the elastic modulus of concrete and polymer film is approximately the same. Therefore, the polymer additive did not affect the cement behavior. However, when the peak point was exceeded, it was observed that the cracks widened. The reason for this is that the researchers showed an increase in the toughness of the composite as a result of the increase in the bond strength of the polymer and the resistance of the carbon fiber against cracking. The researchers found that 8% by mass polymer: cement ratio was optimal when considering compressive strength, toughness, and deformation [115]. Wang et al. (2021) commercially purchased PAN-based carbon fiber (tensile strength: 3530 MPa, density: 1.78 g/mL). Then they put the carbon fiber into the cement mixture in different proportions by volume. The formed sludge was molded in the presence of polycarboxylic acid and beams were produced. As a result of the impact resistance tests, the tensile and compressive strengths of the beam against time were recorded at the endurance speed of 3 m/s. Accordingly, with the increase in the carbon fiber volume in concrete, the time to reach the surface, that is, the propagation of the crack, did not change much and remained around 0.6 ms. However, with the increase in the fiber amount, the vertical displacement increased and reached 0.45 mm. This is desirable because the ductility of the beam increases with increasing vertical displacement [116]. Huang et al. (2022) wrapped the carbon fiber-reinforced polymer in fiber-reinforced concrete and examined the splitting behavior by impact test. Crack propagation in unwrapped concrete continued throughout compression. In the case of wrapping with carbon fiber composite, cracks were found during compression, but the crack width and number were less. They also investigated the effects of deformation rate and wrapping ratio on crack formation. Accordingly, at low deformation rates, the main crack was formed narrower in the carbon fiber-wrapped concrete than in the unsupported concrete, and as expected, a decrease in the main crack width was observed with the increase in the jacket ratio. As a result, they observed that the resistance to separation of concrete with carbon fiber reinforced polymer increased. However, at high deformation rates, fragmentation of the concrete was observed and the location of the main crack became undetectable. In addition, the increase in the carbon fiber ratio at high speeds greatly increased the deformation [117]. Farooq and Banthia (2022) investigated the effect of PVA, glass, steel, and carbon fiber additives on polymer cement. Besides the different fibers, the effect of the curing condition of the composite (room temperature or an oven at 80 ºC) and the resin ratio (15 or 18) were also investigated. They stated that keeping the resin ratio low is economically important. They kept the fiber amounts constant at 2% by volume in all composites. Among these fibers, the highest compression strength was obtained with the carbon fiber reinforced composite containing 18% resin (74%). They observed that the effect of composite curing at thermal or room temperature was negligible [118].

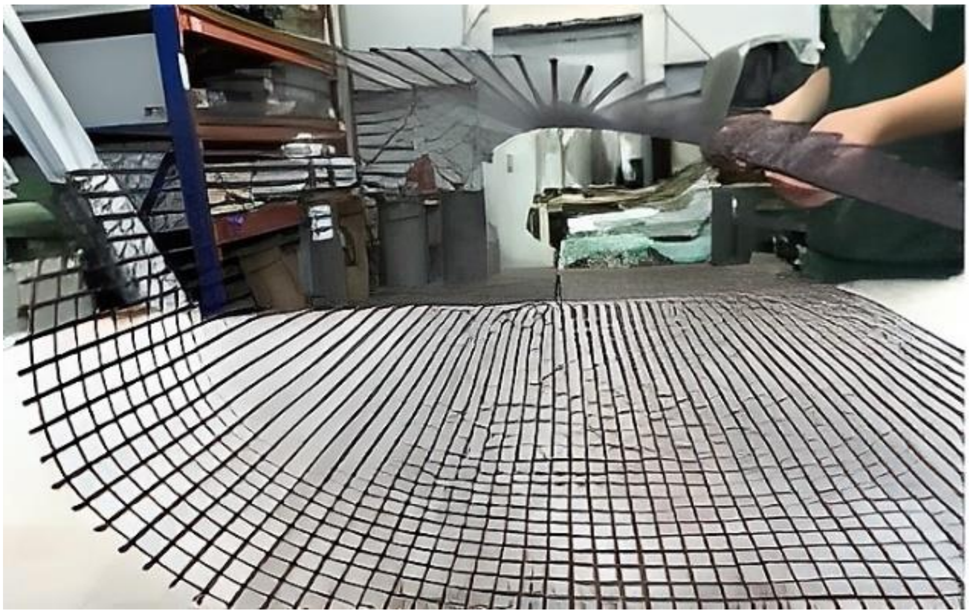

Figure 5. *Carbon fiber fabric-concrete composite [119]*

It is known that there is no escape from the formation of cracks in reinforced concrete structures. Thermal factors and overloading are among the factors that cause crack formation in concrete structures. Tensile strength of concrete, steel, glass, polymer and carbon fibers are the materials preferred during the production phase of concrete or for later reinforcement. Among these, carbon fiber reinforced concrete stands out due to its high compressive strength and elasticity coefficient. In addition, compared to the widely used steel fiber, its corrosion resistance, light weight and ability to be produced from biomass-based sources make carbon fiber a good alternative. When the literature is examined, it has been seen that polymer-added carbon fiber-concrete composites come to the forefront in terms of reducing the crack width and number of concrete as a result of strength tests. As seen in literature, researchers are trying to reduce the amount of polymer additives used in carbon fiber-concrete composites and to synthesize carbon fiber from lignin-derived biomass, which is a more environmentally friendly procedure. In addition, studies are continuing to improve the mechanical properties of the composite at high deformation rates.

Conclusions

This study aims to display the features, synthesis, and applications of carbon fibers and their composites. Besides general information, one can reach current literature about carbon fibers. The most important property of carbon fiber is that it is a light and strong material. Because of their high strength, they are utilized in the production of composite materials. Carbon fiber can be the matrix for polymer, concrete, metal, and ceramic composites. Among them, carbon fiber-reinforced polymer is the hottest study topic of today. Nowadays, researchers try to develop properties of these composites to improve the interface between the materials. This improvement aims to increase carbon fiber surface energy. Increasing surface energy means good adhesion of carbon fiber to the matrix. It can be expected that carbon fiber has higher surface energy than matrix [120]. Carbon fiber can be based on biomass (lignin, cellulose), PAN, and Pitch. In general, carbon fiber synthesis covers five steps: precursor preparation, spinning, oxidation, carbonization, and surface treatment. Researchers heavily have studied PAN-based carbon fiber. However, the PAN-based synthesis procedure has a risk because of the emission of toxic gaseous. So, waste carbon sources such as used clothes have been alternative fiber materials. PAN, Pitch, and lignin-based carbon fibers have been mostly synthesized for use in electrochemical applications, adsorption, and concrete production. Among the other fibers which are glass and steel, carbon fibers are especially important materials for construction applications to prevent concrete deformation. However, it can not be used directly without any addition of polymer in the production of concrete.

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