Chapter 10
Fibers for Other Technical Textiles Applications

Zuhaib Ahmad, Muhammad Salman Naeem, Abdul Jabbar, and Muhammad Irfan

Abstract During the past few years, the use of technical textiles has grown rapidly. Natural, synthetic, and high-performance fibers are being used in many technical textile applications. Some of which are explained in detail, while others are in brief in this book. This chapter reviews the application and use of natural, synthetic, and high-performance fibers for Indutech, Hometech, Clothtech, Buildtech, Packtech, and Oekotech. As the strength of natural fibers is not so good, the use of synthetic and high-performance fibers is increasing in industrial and technical products. One of the major applications of technical textiles is in the filtration media. The performance of a specific filter is based on the selection of fiber, textile material, and the way they have been assembled. The properties of fluid for which the filter has to be designed must be considered carefully as well. Human beings have been using regular clothing to protect themselves from a very hot and cold environment. The workers in some occupations (like military, police, firefighting, and healthcare) are exposed to different hazards, so they are required to wear protecting textile clothing, which is discussed further in the chapter. For centuries, textiles are being used for construction materials whether it is for insulation or reinforcement of any other application. However, the use of advanced construction material specifically textile fibers has increased extensively these days. It is important to have appropriate knowledge about textile fibers in the light of current climate change and other global challenges, as textiles in any form (fiber, yarn, or fabric) provide excellent thermal and mechanical properties with low weight. Today the people around the world have become more educated with higher living standards. Therefore, the use of high technology products, which offer enhanced performance, durability, hygienic conditions, and

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Table 10.1 Classifications of Technical Textiles

1. Protech	2. Sportech	3. Mobiltech	4. Geotech
5. Agrotech	6. Medtech	7. Indutech	8. Hometech
9. Clothtech	10. Buildtech	11. Packtech	12. Oekotech

Table 10.2 Industrial applications of remaining classifications of Technical Textiles

#	Type	Industry	Application
(a)	Indutech	Electronics, Filtration, and other industrial materials	Textile-reinforced rubber products, filtration, lifting, composites, cleaning, electronic components, pulling, others
(b)	Hometech	Furnishing, floor coverings, and habitat	Carpet and furniture components, filtration, cleaning, tarpaulins, coverings, etc
(c)	Clothtech	Shoes and clothing	Shoe components, sewn products, structure, and insulation
(d)	Buildtech	Building and construction	Construction materials and building components, protection, screen, reinforcement
(e)	Packtech	Packaging	Block and disposable packaging, ties, and others
(f)	Oekotech	Environmental protection or shield	Transverse field, products obtained from previous sectors

aesthetic, has become the need of the day. The demand for eco-friendly and biodegradable packaging is growing now as they have a great impact on human health and the environment. The use of natural fibers for environmental protection is not new. While the use of synthetic and high-performance fibers for environmental protection is a revolutionary change in the current century. One of its uses is in protecting the crops and soil artificially by weather changes to increase productivity. The new and advanced developments for environmental protection keep on increasing across the world in the coming years. In this chapter, an overview of such types of textiles; fibers being used; and their applications, advantages, and drawbacks have been provided briefly.

There are 12 classifications of technical textiles according to the market sector [1], which are given in Table 10.1. The first six classes have been discussed comprehensively in the previous chapters of this book. The applications of fibers in the remaining classes of technical textiles will be discussed in this chapter. The industrial applications of these technical textile classes are given in Table 10.2.

10.1 Natural Fibers

The natural fibers are categorized into three main categories which are animal, vegetable, and mineral fibers. Natural and other fibers differ from each other due to their structures. Cotton, silk, wool, and other natural fibers have uneven and non-homogeneous surfaces [2]. The applications of natural fibers in the technical textiles are discussed in the following sections.

10.2 Applications

(a) **Indutech**

Industrial textiles or Indutech can be defined as specially designed materials and structures that are used in the manufacturing and processing of different industries. Different applications of industrial textiles can be summarized as battery separators, transmission/conveyor belts, safety belts, high-temperature bearing belts, sound-absorbing materials, filters (air filter, oil filter, cigarette filters, fuel filter), nuclear biological protection masks, ropes, tire cords, automobile usage, and textiles in civil engineering.

Natural fibers can be used as a constituent fiber in composites, where the direction of placement of fibers can affect the properties of the composites. They can also be converted into sheets to manufacture materials such as fabric, paper, and felt.

Natural fibers are also used for high-tech applications, for example, composites used for automobiles. Composites containing natural fibers have improved thermal insulation, low density, and decreased skin irritation as compared to those containing glass fibers. Natural fibers are also biodegraded by bacteria once they are no longer used [3]. The most commonly used natural fibers for industrial and technical applications are cotton and some coarser vegetable fibers, including jute, sisal, and flax. Usually, heavy canvas type fabrics, ropes, and twines have been produced by them. The importance of natural fibers is increasing in fiber-reinforced composites, packaging, automotive, aerospace, and other high-performance textile applications.

(b) **Hometech**

The importance of Hometech has been recognized and the role of technical textiles in this field is increasing at a substantial pace. It comprises household textiles, upholstered furniture industry (like wadding and fiberfill applications in sleeping bags, cushions, and bedding.). Both natural and synthetic fibers are also used in household textile materials, unlike other kinds of high-performance textiles. These fibers come from the same sources used for common fabrics such as wool (for carpets), cotton (for towels), and polyester (for curtains).

Solar textiles which are inspired by the biological models (such as polar bear fur) are used for the semi-transparent thermal insulation of the buildings. The dark absorber sheet behind the transparent front sheet warms up when the sun shines through the front sheet. The heat is converted through the brick walls in the house by an absorber. A coated flexible spacer textile containing smooth foils on both sides is responsible for insulation. The top side functions according to lotus effect for self-cleaning purposes and the bottom part in the form of a black pigmented coating functions to absorb sunlight and converts it into heat [1, 4].

Insulating textiles, being flexible and lightweight, are becoming an important part of wall constructions. In combination with suitable fabric finishes, novel systems like aerogel impregnated textiles, that can act as insulating core, can be easily installed [5]. Instead of falling under the category of "household" or "home", such textiles (solar and wall covers) are included under the category of "construction building" textiles. Hence, it is clear that hundreds of square meters in a house could be covered by textiles.

The textiles are also being used to get fire resistant and flame retardant properties and the commercial examples of fire resistant and flame retardant textiles comprise of the Ultem® 9011 Polyimide, the Visil® rayon fibers, Pyrovatex®CP cotton, the Basofil® melamine, and the Tes-firESD® fabrics which are both flame retardant as well as antistatic [1].

(c) **Clothtech**

The role of clothing is very important in human life, as it protects them from their surrounding environment. In some fields, workers are open to some hazards like chemical substances (e.g., acids or flammable materials), hot liquids splash, chilled air, heavy rain, high heat (e.g., flash fires, steam, electric arc), bullets or knives, nuclear elements biological materials (e.g., bacteria, viruses), radiological threatening agents, and/or extreme cold air/water [6–8]. Employees (e.g., healthcare staff, military personnel, police officers, and firefighters) have to wear textile-based personal protective clothing (PPC), in order to get protection from such hazardous working environments [9, 10]. After the selection of suitable fibers (e.g., natural, synthetic, or a blend of different fibers), various spinning techniques (e.g., ring spinning or rotor spinning) are used to spin them into different types of yarns [11].

Keeping in view the properties (tenacity, temperature, elasticity, limiting oxygen index (LOI), combustion, and moisture regain (MR)), two natural fibers are most commonly used for PPC. These are cotton and wool. In recent times, some other natural fibers such as flax, silk have been introduced for use in the manufacturing of PPC. It is noted that these naturally occurring fibers are quite expensive. Therefore, a less costly regenerated natural cellulosic fiber known as "viscose" is used nowadays for the manufacturing of PPC. A few, regenerated natural inorganic fibers (e.g., eco-friendly glass and ceramic fibers) have also been used for the manufacturing of PPC along with natural or regenerated organic fibers (e.g., cotton, flax, silk, and wool) [12–14].

(d) **Builtech**

It is not known exactly when the textiles were introduced to be used as a construction material. But, nowadays textile materials are being used in the construction of public spaces (temporary or permanent) on a large scale. The building or construction applications, mostly include textile-reinforced concrete (TRC), architectural textiles, insulation, and house wraps [1]. For non-structural applications such as filters, bags, fishnet, broom, and multipurpose rope, natural fibers have been cultivated and used extensively in rural developing countries. These fibers have also been used for housing applications such as roof material and wall insulations. The composites of natural fibers may be a combination of either natural fibers and a synthetic resin or natural fibers and bio-resin (biodegradable resin). Another idea of a natural fiber composite beam was an I-shaped beam developed using vacuum-assisted resin transfer molding (VARTM) or resin vacuum infusion process method. The woven jute fabric known as burlap and soybean oil-based resin system has been used to develop this composite beam structure [15]. The woven mat of sisal fibers or cashew nut shell liquid (CNSL) [16] and recycled paper reinforced with a foam core is one of the natural fiber composites for making roof materials [17]. Recycled paper composites have also been used to develop a natural fiber composites panel appropriate for housing construction materials and furniture [18]. Jute mats reinforced composites have been used for the trenchless restoration of underground drain pipes and water pipes in the areas of structural rehabilitation [19]. According to the previously mentioned studies, it has been highlighted that natural materials can be used successfully to develop a load-bearing material for roofs, beams, and panels. It has been observed that for many infrastructure applications, the natural fibers are being used as compared to the synthetic fibers [20]. The heat flow through building components is reduced by the insulation, which is a thermal barrier layer and it improves the building's energy efficiency. Mostly, the insulation materials are either in the form of fibers or foam. As shown in Fig. 10.1, fibrous insulation materials may be fiberized as inorganic fiber–fiber products or organic fiber-based products [1].

As compared to organic fibers, inorganic fibers have been developed to give higher performance. Precisely, inorganic fibers show improved product lifetime and better thermal stability [21]. The use of organic fibers is limited in the insulation field due to their lower resistance to high temperatures and environmental extremes [22].

(e) **Packtech**

In the current age, people are shifting their focus toward the use of smart packing materials. Packtech is among the most essential areas of technical textiles. Packing materials should possess strong mechanical and physical resistance to thermal processes [23]. Natural and synthetic fibers are equally being used in packaging. Such fibers originate from the same sources used in common fabrics such as jute (e.g., for food sacks) and polyamide (e.g., for packaging bags). Bast fibers are lingo cellulosic plant fibers. These have been used for years in the manufacturing of packaging and bagging materials from hemp, flax, and ramie [1].

The bio-based packaging materials are being preferred for packaging. In this group of materials, the special interest has been given to fibrous cellulose for packaging.

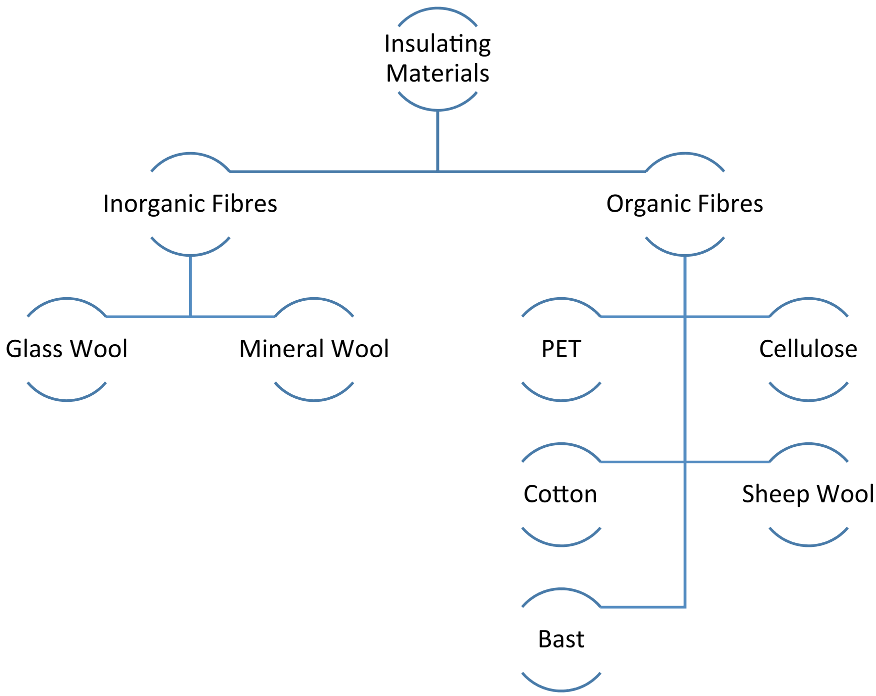

Fig. 10.1 Insulation material types [1]

The foams based on cellulose nanomaterial are being studied for packaging uses in substitution to polystyrene-based foams. The polymer which is being produced from fossil fuel is replaced by a renewable material, i.e., the webs of cellulose nanomaterials. In packaging, it is advantageous due to a reduction in weight and being environmentally friendly [24].

(f) **Oekotech**

Oekotech is a class of technical textiles that involves preservation/protection of the environment through the use of technical textiles. Textiles are used in different ways in environment protection and conservation like providing alternatives to polythene bags, use of different woven or knitted fabrics in air filtration like simple filtration, pressure filtration, activated carbon-coated cloth, air filtration in vehicles, manufacturing plants, personal protective air filtration masks, advanced water treatment through different membranes by using different technical textiles and different innovative technologies for recycling. As we know that textiles are deteriorating our planet. Not only natural fibers, but also synthetic fibers are equally participating their role in increasing population. Natural fibers, like cotton and jute, are although biodegradable, but their growth demands an enormous amount of water together with a huge amount of pesticides. An estimate tells us that the production of 1 kg of textiles requires nearly 200 L of water and around 50% of the total pesticides for growing cotton [25, 26].

Advantages and Drawbacks

Natural fibers show excellent specific tensile strength and stiffness, in some cases better than glass fibers but slightly similar to synthetic fibers. In addition, they also show other advantages like production flexibility, enhanced energy recovery, production simplicity, and carbon dioxide sequestration. They are also eco-friendly and are obtained from renewable natural resources. The industrial sector requires materials that are durable as well as biodegradable at the end of service life [27]. An effective contrast of mechanical properties should be done in terms of their specific mechanical properties. According to it, certain tensile strengths of some of the natural fibers, such as flax, hemp, kenaf, and Caraua are quite similar to that of the E-glass fibers. Hence, natural fiber-based products are usually used in technical textiles and as reinforcements in composite products used in transportation sectors [28].

In case of home textile applications, each textile has a different flammability grade regarding fire resistance and flame retardation, depending on the type of fiber being used. Considering the example of wool, it does not burn easily as compared to synthetic fabrics like polyester which catch fire easily. To improve the performance and safety features of the products such as carpets and curtains, flame retarding agents are used [29].

Any type of natural fiber is said to be ecologically sustainable when it is biodegradable and requires less industrial processing to be produced. Therefore, it is required to study the use of other natural organic fibers (such as jute, ramie, and hemp) except for cotton, flax, viscose, silk, and wool for personal protective clothing and other technical applications [30].

The composition of packaging materials has made recycling costlier as compared with the disposal in the landfill. These facts have led to the development of biodegradable plastics for sustainable packaging applications from renewable raw materials like cellulose or starch. Waste management of such plastics is done by composting or anaerobic digestion. Materials have been manufactured from a combination of paper fibers (virgin or recovered wood fibers) and textile dust, fibers (waste from mechanical recycling of textiles) in the case of innovative packaging [1].

In building materials, the natural fiber composites are gaining attention again due to the need for more environmentally friendly materials. Presently, the growing use of natural fiber composites is due to environmental and low-cost benefits rather than their strength capabilities [20].

There are some limitations of natural fibers as they have a comparatively high weight, low resistance to water, fungal, and microbial attacks as well as weak flame retardancy. The use of synthetic products in structural and infrastructure applications has gained attention, due to the main drawback of natural fiber composites which is the enormous variation in the properties of the natural fibers, their treatments, and manufacturing optimization. These problems need to be considered in order to produce and develop better structural elements that can be used for both infrastructure and structural applications [20].

The textile sector is among one of the few sectors which are increasing at a rapid pace because of the increase in population. Although this expansion is providing jobs and boosting the economy of many countries, but at the same time creating serious environmental hazards in the form of land pollution, air pollution, and water pollution. Every year a huge burden of used textile waste is increasing. More than 83.5 million tons of textile waste are produced currently which is expected to increase up to 62% by 2030. The major portion of which goes to landfills which have been banned in some European countries. Therefore the concept of circular economy, sustainability, organic cotton, and eco-friendly textile products gained more attention.

10.3 Synthetic Fibers

The properties of naturally occurring animal and vegetable fibers have been improved by extensive research, resulting in synthetic fibers. Side by side with natural fibers, the use of synthetic materials like polypropylene, polyamides, polyethylene, polylactide, and others is increasing because of versatility, enhanced strength, resistance to different chemicals, hydrophobicity, abrasion resistance along with a prolonged life cycle [2].

Applications

(a) **Indutech**

As different industries require special characteristics so different kinds of polymeric materials are used for different applications depending upon end usage. Nowadays the filtration industry is not only technically sophisticated but it is a huge market with annual sales around $100 billion [1]. The filtration and other related separation techniques and equipment are divided into two sectors. One of which is a commercial and domestic sector with water, coffee, and suction cleaner filters and the other one is transport system with coolants and engine filters for the intake of fuel and air. The required characteristics in fabrics used for filtration are tensile strength, chemical resistance, permeability, and abrasion resistance [31]. However, it depends upon the chemical and thermal conditions of gas and liquid that needs to be filtered out. The most widely used synthetic material in the filter media is polyester (around 70%). The strong base causes degradation of polyester fibers. The polyamide fibers also lose strength and degrade in the presence of a strong base, although they provide good abrasion resistance. Polypropylene is most widely used in filtration media because of its inert nature in the presence of chemicals; however, oxidizing agents cause negative effects on the stability of polypropylene. It is suitable for melt-blown and spun-bond non-wovens. Yet, it has a low melting point as compared to others [32]. Polytetrafluoroethylene (PTFE) which is an expensive fiber has the potential to be used in the presence of different chemicals [1].

The invention of conveyor belts and transmission belts brought about a revolution in industrial manufacturing. The usage of synthetic fibers in this segment is more as compared to natural fibers as they possess poor strength. The key features required in ropes are flexibility, durability, strength, handle, and shock resistance. Synthetic fibers are used both in staple fiber or filament form. Polyamides have elasticity, high level of extension, flexibility, high abrasive resistance, and high level of energy absorption capability. However, in wet form, they have poor abrasion resistance, loss of strength (10–20%), and kink formation. Polyester fibers are strong, abrasion-resistant in wet conditions, have less elongation than nylon but better fatigue properties than nylon. Polypropylene is softer in handling and cheaper than polyester and nylon. But it is 30% weaker in strength than polyester and nylon and also degrades in the sunshine.

(b) **Hometech**

Globally household textiles, whether derived from natural, synthetic, or special fibers account for nearly 7% share of the total market of technical textiles [33]. Home textiles have improved the status of houses through peculiar designs. The usage of home textiles is increasing day by day as with better living standards people want well-furnished homes with improved aesthetic and functional home textiles. The key to their success depends on their way of fabrication along with the coating.

The Hometech products can be categorized as towels which are used for drying, wipes for cleaning and other purposes, woven or non-woven blinds for windows and doors, bed linen and comforters for sleeping, blinds for hanging at the doors and windows, carpets for increasing aesthetics of house, tents, and nets for giving protection from sun or rain also protecting from insects (mosquito nets), home wear clothing for personal clothing, napkin for cooking, filtration cloth for home vacuum cleaners, ventilation systems, and air conditioners, non-woven wipes for personal hygiene, non-woven make up wipes, table covers, and a number of other applications [1].

Natural fibers, synthetic fibers, and high-performance fibers along with different construction techniques are being used in home textiles. Different synthetic fibers find different applications in different fields like polyester fibers are widely used for curtains along with the filling of pillows, comforters, bolsters, soft toys, furniture back, sleeping bags in the form of small fibers, ball fibers or as a lining material. For carpet backing cloth, polyester, polypropylene, or their blends are used as polyester provides strength, mildew, and abrasive resistance [34]. Polypropylene is also employed for filtration cloth as well. Viscose and polyester also find their application in non-woven wipes. However, acrylic (PAN) is mostly used for sweaters, rugs, socks, and water bath mats as it has a wool-like structure and wrinkle resistant but at the same time, it melts when burning.

In a study, woven polyester fabrics have been used to manufacture sound-absorbing curtains to achieve high performance of textile structures. Three to five types of yarns with different linear mass densities and different weaving patterns were used to produce fabrics of increasing area density, cutoff frequency, and specific airflow resistance [35].

(c) **Clothtech**

Clothtech is a class of technical textiles that consists of special materials and constructions primarily used in apparel and shoes. Most of these components are hidden as they are used as an interlining or lining purpose. The most promising products that come under Clothtech can be classified as sewing thread, labels, interlining, zip fasteners, umbrella cloth, shoelaces, and Velcro. Sewing thread accounts for nearly 60% of total technical textile consumption under the category of Clothtech followed by labels 19% and interlinings around 8%.

Sewing thread can broadly be divided into two categories like industrial sewing thread (used for joining different elements together) and surgical sutures. Surgical sutures (biodegradable or non-biodegradable) and industrial sewing threads have different requirements from manufacturing and usage point of view. Technical sewing threads have been established to meet particular applications like sewing of leather items, filtration items, heat resistant sewing threads, for sewing apparel, tents, sleeping bags, and in automotive industries [36]. Sew ability of sewing thread can be influenced through different parameters like extensibility in sewing thread, the balance of twist among different plies, and thread friction (due to the interaction of sewing thread with machine components and fabric) [37]. Mostly spun threads are made by using different materials like polyester, cotton, cotton-polyester blends, Kevlar, Nomex, wool, viscose and acrylic fibers. These kinds of threads have a fuzzy surface. In core-spun yarn, polyester is mostly used in the core while different materials are used as a sheeth. However, for elastic yarns, different elastomers are used in the core which give a higher extension for sewing thread [1].

Lining and interlining materials in garments are used to support and enhance the aesthetics of the outer shell in garments. Careful selection of lining material is very important, particularly inside coats and in lightweight materials as low-quality interlining can spoil the aesthetics and performance of high-quality apparel. Differential shrinkage, bubble formation on outer shell fabric and losing the grip of interlining with outer fabric are the most common problems faced with the application of interlinings. Interlining can be woven or non-woven which can be stitched or heat set with the fabric depending upon the end usage. The raw material used in linings is a lustrous fabric with a good hand feel like cotton or silk. While in interlining polyester, cotton, nylon, viscose, and wool are preferred choices [38].

The textiles are used in shoes as the upper part, lower part, and laces. The upper part of shoes comprises 40% cost of sports shoes. The inside layer of the upper part of the shoes is equipped with special characteristics like porosity and comfort. The most commonly used synthetic materials for shoe linings are vinyl and tricot [39]. Vinyl and tricot are mostly used because they are inexpensive materials and are impermeable. Textile materials are incorporated into the footwear in different ways like non-woven absorbent material (Cambrella), a combination of hydrophobic and hydrophilic layers, different types of air meshes, special membranes (Gore-Tex) for selective transport of moisture and air, breathable foam or backing material [39]. Shoelaces are mostly constructed in woven or braided form with different kinds of materials like cotton, polyester, or nylon.

Sometimes, synthetic fibers or filaments are directly used in the non-woven processes such as chemical bonding, mechanical bonding, and electrospinning to yield non-woven fabrics [40]. The moisture regain (MR) and glass transition temperature is dependent upon the polymer composition of the fibers. It is noteworthy that the LOI values of the fibers produced artificially (regenerated natural fiber, viscose, and synthetic fiber polyester, etc.) could be improved by doping the phosphorous-based flame retardant (FR) chemicals within their polymer compositions. The improvement of LOI could help to convert an unsuitable and non-fire retardant fiber (viscose and polyester) for PPC into a suitable and fire retardant fiber (Fire Retardant viscose and Fire Retardant polyester) [1].

(d) **Buildtech**

Food, cloth, and shelter are among the basic needs of human beings. Humans are in a continuous struggle to improve the construction of living through the use of different styles of architecture for better protection against rain, wind, cold, hot, and for personal protection. Since the living conditions vary in the different parts of the world, so the architecture style also changes like open houses in a hot climate while closed structures are observed in cold regions of the world. However, in recent years mega structures like huge bridges, big dams, long tunnels, multi-story buildings and shopping malls, heavy-duty roads, etc. have been evolved which require special characteristics not only to increase the life of these structures but also to reduce cost, improve protection of human beings from breakdown, and other hazards like fire and earthquake. In general, while selecting material for Buildtech following things must be kept in mind like mechanical stability (fatigue limit, creep, tensile strength, foldability, and tenacity), barrier or resistance functions (UV and IR radiation, excess amount of water, insulation from hot and cold weather, humidity, and corrosive gases), light transmission or translucency, burning behavior, sound damping, and ease of cleaning.

Different lightweight structures and membranes find different applications like permanent placement as cover in a sports stadium, marriage halls, temporary, or portable construction. However, in both cases strength, cost-effectiveness, and durability are prime factors. Mostly the membranes are made of PTFE-covered glass fibers and polyvinyl chloride coated polyester fibers, while in new structures high strength polyester with different coatings is also being used. Polyethylene terephthalate (PET) is used to give superior strength, tenacity, and high bending recovery values. It does not absorb moisture, which is the main reason for its chemical inertness along with its low cost makes it an ideal candidate to be used in Buildtech.

Because of climate change, environment is getting severe day by day. In hot areas, every year temperature is increasing while in cold climate temperature is getting cold. So, builders are trying difficult strategies in order to cope with the issue of environmental extremities as a significant amount of energy that is spent on cooling and warming buildings can be avoided. The insulating material can be used in different forms like roll, loose-fill, and rigid form or reflective foams the choice of insulation material depends on the application, cost as well as desired characteristics in material [41]. Different materials are available for thermal insulation like cotton, cellulose, glass fiber, polystyrene, foamed rubber, polyethylene, polyisocyanurate, polyurethane, and other polymers.

The geopolymers have some additional benefits over conventional cement but due to their cross-linked structures, geopolymers are found brittle and can form crack easily as compared with ordinary cement [42, 43]. Therefore, more and more research is undergoing in order to improve the fracture characteristics of a geopolymer through different means like the incorporation of different types of fibers (basalt fibers, polyvinyl chloride, polypropylene, and steel fibers). These fibers found to be effective in improving mechanical properties, especially increasing fracture energy.

(e) **Packtech**

From heavyweight woven structure of lightweight materials, continuous sheets of plastic, flexible intermediate bulk containers (FIBC), biodegradable materials, wrapping materials for textiles and food materials (tea bags, packing of food containers for temporary and prolonged time), perforated structures combined with knitted and non-woven materials come under the category of Packtech. Almost all Packtech except jute bags come under the category of flexible packing materials. A smart or active packing system can be explained as a packing system in which the shelf life of the product is enhanced through the combined action of packing material, environment, and the product. Different factors contribute toward enhancing the shelf life of a product like releasing or retaining moisture transportation, removal of oxygen, controlling of temperature, etc [1].

Leno bags for packing, preserving, and carrying vegetables and fruits are preferred choice which is made from polyamides or polypropylene. These bags are suitable to be placed in cold storage, with good aesthetic and mechanical properties. Further, these are able to be recycled, reused, and are easy to handle. However, jute bags are used for storing grain and rice and in the cement industry as well. These bags are environment-friendly, but they are coarser and loose strength in getting moisture.

The luggage materials are categorized as soft luggage and hard luggage material. Molded plastics that come under hard luggage are mostly used for travel bags. Outside shell requires strength, abrasion resistance, nice color, and flexibility that is why polyester, nylon, polypropylene, leather, and other high-performance fibers are used. However soft luggage comprises woven fabrics made from nylon, polyester, and Cordura®. Ballistic nylon as compared with other materials is very lightweight, easy to clean, and durable. However, polyester is the most liked soft material because of its lower price. Currently, soft luggage is getting popular because of its flexibility, lightweight, and easy to handle characteristics. It includes athletic backpacks, briefcase, wallet, military backpacks, and handbags.

(f) **Oekotech**

The synthetic fibers are not biodegradable and are a severe threat to the environment in the form of solid waste management. This situation has been further aggravated because of excessive use of transportation and discharge of polluted air without purification into the environment [44]. Particulate matter at the base of particle size is categorized as PM2.5 (i.e., particle size less than 2.5 μm) and PM10 (i.e., particle size less than 10 μm). The earlier one is more dangerous and hazardous because it can go up to the lungs because of small particle size [45]. There are two different types of filters which are available in the market:

1. The first type of air filter comprises fibrous materials. These kinds of filters trap air particles through adhesion and thick structure. For effective working on these types of filters more thickness is required. The main problem associated with these kinds of filters is their thick structure.
2. The second type of filter comprises a porous membrane filter which is developed by creating porosity in the surface of the material. The presence of pores on the surface of materials helps in providing clean air to its wearer [46].

Different techniques and materials are being applied to the elimination of different pollutants from the polluted air. Polyamide filters are capable of removing PM2.5 at high temperatures [47]. Yang developed Nanoporous polyethylene membrane masks for indoor and outdoor applications.

Filters can be classified on the basis of materials used for their construction like linen, wool, carbon black having high porosity, glass fibers, rayons, and metal powders. Different types of new polymeric materials are also being employed individually or in combination with different materials through different mechanisms like chemical coagulation methods, biological breakdown methods, physical or chemical adsorption, and different types of membrane filtration. However, some of the famous textile materials find special applications like glass fiber for concentrated hot acids and chemical solutions, orlon for acids (including chromic acid) and petrochemicals, vinyon for acids, alkalis, solvents and petroleum products, dynel for acids, alkalis, solvents and petrochemicals, polypropylene for acids, alkalis and solvents (except for aromatics and chlorinated hydrocarbons), polyethylene for acids and alkalis, PTFE for all chemicals, PVC for acids and alkalis, polyester for acids, organic solvents and oxidizing agents and nylon for acids, petrochemicals, organic solvents and alkaline suspensions [48].

10.4 Advantages and Drawbacks

Due to the availability of the latest biodegradable polymers such as polylactic acid (PLA) obtained from corn, the market demand for natural fibers is also changing. To keep a balance between price, performance, quality, ecological regulations, and supply of natural fibers, a number of high-performance fabric and composite manufacturers are developing novel facilities to use alternative fibers. The durability of synthetic fibers is good and the tensile properties of E-glass are better than natural fibers [1].

Conventional filter fabrics were made from cotton fiber whose efficiency increases by absorbing moisture as they swell, but they work best at a lower temperature, in the absence of acidic conditions, having a shorter life cycle. Synthetic fibers as compared with natural fibers are more durable and possess superior mechanical, chemical, and physical characteristics. The use of synthetic fiber cloth as filtration media offers several advantages like higher filtrate purity, reducing the weight of fabric filter, higher mechanical strength, and chemical resistance combined with easy washing and drying. Similarly, the synthetic fibers have their own advantages, in use for home textiles, that are difficult to achieve in natural fibers like high strength, abrasive resistance, hydrophobicity, durability, and many others [34]. The PET fibers have a major disadvantage when used in Buildtech, they lose 50% of their strength on exposure to UV radiation.

Most of the materials used today for packaging are non-degradable, and they greatly affect human health and the environment. Hence, the demand for finding advanced and eco-friendly packaging materials is growing which may have greater mechanical, physical, and barrier properties [1].

Currently, the packing industry is dependent on petrochemical-based materials which are a serious threat to the environment and are also burdened on the economy [49]. Now the trend is shifting toward the use of conductive, antibacterial, and biodegradable plastic materials in order to avoid problems of microbial interference, improving quality, and conserve the environment [50].

Every year a huge burden of used textile waste is increasing, which is affecting our environment. To reduce textile waste around 7% of polyester production is being made from recycled polyester worldwide [51]. Most of the recycled nylon is used in the carpet industry and mostly nylon-6,6 is mechanically recycled from pre-consumer fibers [52].

10.5 High-Performance Fibers

As compared to conventional fibers the high-performance fibers have been developed with improved physical properties and have enhanced performance such as heat resistance (high decomposition temperature and high melting point). These super fibers have strength more than 20 g/den (2.2 GPa) and modulus more than 500 g/den (55 GPa) [2].

10.6 Applications

(a) **Indutech**

Technical textile fibers containing superior mechanical, thermal, and chemical characteristics have offered a unique generation of composite materials. The increasing pollution mainly air and water pollution and its effects on humans and filtration processes have become significant. Filtration has presented surface modification for better health and a cleaner environment [53–57]. Air and water filters are of great significance and high-performance textile structures are mostly used for the filtration process of these fluids. Technical textile engineering gives 3D networks of fibers for effective filtration. The surfaces of these textile fibers capture particles. Consequently, fiber surface structures are critical to filtration efficiency. The efficiency of a technical fiber depends upon the boundary between the fiber surface and the matrix in the composite filter media [58]. Glass fibers and Teflon are used for high-temperature filtration. Glass fibers have a strong particle capturing capacity, whereas ceramic fibers are suitable for hot glass filtration [32].

Because of the poor strength of natural fibers, the usage of high-performance fibers (fiberglass, Kevlar fiber, and aramid fiber) for conveyor belts and transmission belts is increasing. Kevlar has a high modulus, strength to weight ratio greater than other synthetic fibers, less extension as compared with polyester and nylon low corrosion, and creep.

(b) **Hometech**

A high-tech category of household textiles also contains luminous embroidered fabrics. As compared to traditional embroidered ones, they show both a decorative and a luminous effect after absorbing visible light, storing energy, and releasing it as a light in the dark for more than 10 h. Generally, luminous fabrics are manufactured by weaving, knitting, or embroidering the rare-earth luminous fibers such as europium ions and activated strontium aluminate phosphors onto fabrics.

Most modern high-performance household textiles are those protecting from electromagnetic radiation. Such a quality can be achieved by using electro-conductive covers. They can generate and transport free charges. E-glass/polypropylene commingled yarn is an example of conductive polymer coated yarn manufactured by the P-D Fiberglass Group (Germany) [59].

Chlorofibers (CLF) is a flame retardant fiber, which gives real protection against the danger of fire. It has hydrophobic nature, dimensionally stable, and acoustic insulation properties as well. Whether used pure or in blends, the CLF fibers retain all its characteristics and can be made into all sorts of fabrics. The non-flammable nature of the fiber makes it ideal for wall coverings, hangings, curtains, and upholstered furniture [60].

(c) **Clothtech**

The textile materials are being used in footwear in different ways, one of which is odor-absorbing textiles like carbon-coated soles [39]. Besides the use of natural and synthetic fibers in shoelaces, the use of velcro, loop closures, and specialty yarns like Kevlar is also common in mountaineering products in order to impart durability and strength. In special dress like bikers clothing, high-density panels of foam in shoulders, hips, back, elbows and knees are used which are made by Kevlar, leather, and other polymeric materials.

In multifilament threads, different materials can be used depending upon end applications like polyester, nylon, coated E-glass, Nomex, polyether ketone, spectra, and different types of metalized threads are also being used [1]. The use of conductive sewing yarns is also gaining importance in Clothtech [36].

(d) **Builtech**

Humans are already in use of different materials like the incorporation of straw in mud to increase the strength of reinforcement. Now the trend of adding different types of fibers (natural fibers, synthetic fibers, metal fibers, high-performance fibers, special fibers for special properties like carbon fibers for enhanced thermal properties), high strength and high modulus fibers like aramid, glass fiber, polyester fiber, PBO for advanced mechanical properties and other stuff for special characteristics come under this category.

The membrane structures used for architectural structures are of two types:

1. A coated or laminated fabric consisting of a textile substrate (nonwoven or woven) with a coating of protective polymer.
2. A single-layer polymeric films or foils.

Normally, the fabric layer of the coated fabric is woven from polyester, aramid, or yarns [62]. Fiberglass or glass wool, a material made from very fine glass fibers is one of the most used insulation materials [1]. The most commonly used fiber types of textile-reinforced composites (TRCs) are the alkali resistant (AR) glass fibers and carbon fibers. Alkali resistant glass fibers and carbon fibers are not easily corroded and also have high strengths [63]. Alkali resistant glass and carbon fibers are used as filament yarns or rovings as shown in Fig. 10.2. These materials show low material strain under tensile load which is necessary for reinforced concrete structures. Lately, in the area of TRCs, basalt fibers have gained attention due to their low cost and property of being environmental-friendly [64]. TRC has been

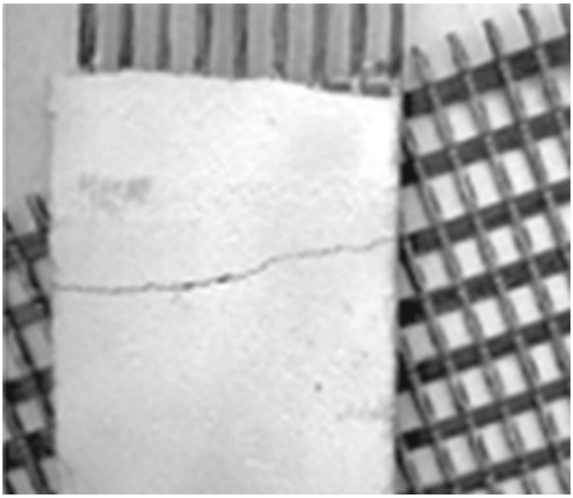

Fig. 10.2 Carbon fiber textile structure and its incorporation into the concrete. *Source* Images from [61]

used in many applications such as facades, noise barriers, roofs, balconies, tanks, furniture, bridges, and pipes.

The geopolymers are not able to resist elevated temperatures because of their inadequate and non-consistent properties, especially if the building gets fire [65–67]. It is therefore required that in new constructions such types of fibers or filler particles should be incorporated that can enhance the mechanical properties of cement even at higher temperatures [68]. Different materials are being used by different researchers and carbon materials appear to be a potential candidate for reinforcing geopolymers because of their enhanced thermal and mechanical properties. In this regard different carbon materials like carbon nanofibers, carbon nanotubes, graphene, etc. are being incorporated in geopolymer for enhanced mechanical, high energy for fracture, and thermal resistance at elevated temperatures [69, 70].

(e) **Packtech**

In molded plastic bags polycarbonate, carbon fiber, and composites are being used as they provide high strength and abrasion resistance. High modulus polypropylene is used in luggage, cases, and other fields where safety, toughness, and further high-performance factors are crucial [60].

(f) **Oekotech**

Different methods like physical, biological, and chemical methods are being employed to treat industrial waste effluents from different hazardous materials like synthetic dyes, chemicals, acids, oil components, and more specifically heavy metals. The type of material and method employed for waste treatment depends on the kind and size of particulate matter in wastewater. In this regard, cellulose acetate and different kinds of aramid hollow fibers are used in fiber-based filtration media [71]. Out of different technologies, carbon-based air filters seem to be more effective not only because of less thickness, but also due to enhanced inter particulate surface area and higher porosity. They used to filter air particles mostly through physical adsorption [72]. Around 20% of the total production of activated carbon is utilized in air filtration in different industries [73].

The textile materials selected for water filtration must possess some special characteristics like high biological resistance, hydrolytic nature, resistance against a wide range of pH, temperature and different types of chemicals used in manufacturing sectors. Aramids, fluorocarbon, polysulfone, phenylene sulfide, polyimide, PEEK (Victrex) are among famous examples used in liquid filtration under different types of environmental conditions [74].

10.7 Advantages and Drawbacks

The tensile properties of high-performance fibers (Kevlar, Carbon) are better than natural and synthetic fibers. Liquid crystal polymers are aromatic polyesters with high mechanical properties because of high crystallinity. They are also inert along with high thermal stability. Aramid fibers were developed in order to increase chemical stability. Due to the stability of aromatic rings, they have higher thermal resistance and tensile strength as compared with aliphatic polyamides, so they can be preferably used in Buildtech. The most common issue related to fiberglass insulation in buildings is its tendency to break. The glass fibers can cause lung damage when inhaled [1].

References

1. R. Paul, *High Performance Technical Textiles*. Wiley Online Library (2019)
2. T. Hongu, G.O. Phillips, M. Takigami, New millennium fibers. Cambridge CB1 6AH, (Woodhead Publishing Ltd., England, 2005)
3. H. Abou-Yousef, T.A. Khattab, Y.A. Youssef, N. Al-Balakocy, S. Kamel, Novel cellulose-based halochromic test strips for naked-eye detection of alkaline vapors and analytes. Talanta **170**, 137–145 (2017)
4. T. Stegmaier, M. Linke, H. Planck, Bionics in textiles: flexible and translucent thermal insulations for solar thermal applications. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. **367**(1894), 1749–1758 (2009)
5. G. Masera et al., Development of a super-insulating, aerogel-based textile wallpaper for the indoor energy retrofit of existing residential buildings. Procedia Eng. **180**, 1139–1149 (2017)
6. D. Ceballos, K. Mead, J. Ramsey, Recommendations to improve employee thermal comfort when working in 40 F refrigerated cold rooms. J. Occup. Environ. Hyg. **12**(9), D216–D221 (2015)
7. S. Mandal, Y. Lu, F. Wang, G. Song, Characterization of thermal protective clothing under hot water and pressurized steam exposure. AATCC J. Res. **1**(5), 7–16 (2014)
8. S. Mandal, G. Song, M. Ackerman, S. Paskaluk, F. Gholamreza, Characterization of textile fabrics under various thermal exposures. Text. Res. J. **83**(10), 1005–1019 (2013)
9. P. Bajaj, Ballistic protective clothing: an overview (1997)
10. R. Rossi, Fire fighting and its influence on the body. Ergonomics **46**(10), 1017–1033 (2003)
11. W. Klein, Practical guide to ring spinning. Textile Institute (1987)
12. I. Shalev, R.L. Barker, Analysis of heat transfer Characteristits of fabrics in an open flame exposure. Text. Res. J. **53**(8), 475–482 (1983)
13. I. Shalev, R.L. Barker, Protective fabrics: A comparison of laboratory methods for evaluating thermal protective performance in convective/radiant exposures. Text. Res. J. **54**(10), 648–654 (1984)
14. N. Mao, High performance textiles for protective clothing, in High Performance Textiles and their Applications, Elsevier, 2014, pp. 91–143
15. J.B. Alms, P.J. Yonko, R.C. McDowell, S.G. Advani, Design and development of an I-Beam from natural composites. J. Biobased Mater. Bioenergy **3**(2), 181–187 (2009)
16. E.T.N. Bisanda, The manufacture of roofing panels from sisal fibre reinforced composites. J. Mater. Process. Technol. **38**(1–2), 369–379 (1993)
17. M.A. Dweib, B. Hu, H.W. Shenton Iii, R.P. Wool, Bio-based composite roof structure: manufacturing and processing issues. Compos. Struct 74(4), 379–388 (2006)
18. J. Grandgirard, D. Poinsot, L. Krespi, J.P. Nénon, A.M. Cortesero, Natural fiber composites with plant oil-based resin. Entomol. Exp. Appl. **103**(3), 239–248 (2002)
19. H.N. Yu, S.S. Kim, I.U. Hwang, Application of natural fiber reinforced composites to trenchless rehabilitation of underground pipes. Compos. Struct. **86**(1–3), 285–290 (2008)
20. M.H. Norhidayah, A.A. Hambali, Y.M. Yuhazri, M. Zolkarnain, Taufik, H.Y. Saifuddin, A review of current development in natural fiber composites in automotive applications. Appl. Mech. Mater. **564** 3–7 (2014)

21. R. Fangueiro, *Fibrous and composite materials for civil engineering applications*, 1st edn. (Woodhead Publishing, Cambridge, 2011)
22. R. Paul, *High Performance Technical Textiles* (John Wiley & Sons Ltd, Hoboken, USA, 2019)
23. K. Galić, M. Ščetar, M. Kurek, The benefits of processing and packaging. Trends Food Sci. Technol. **22**(2–3), 127–137 (2011)
24. H.P.S. Abdul Khalil et al., A review on nanocellulosic fibres as new material for sustainable packaging: Process and applications. Renew. Sustain. Energy Rev. **64**, 823–836 (2016)
25. S.C. Bhatia, *Pollution Control in Textile Industry*. WPI Publishing (2017)
26. M. Tausif, A. Jabbar, M.S. Naeem, A. Basit, F. Ahmad, T. Cassidy, Cotton in the new millennium: advances, economics, perceptions and problems. Text. Prog. **50**(1), 1–66 (2018)
27. T.H. Shah, A. Rawal, Textiles in filtration, in Handbook of Technical Textiles (Elsevier, 2016), pp. 57–110
28. C. Stevens, Industrial applications of natural fibres: structure, properties and technical applications, vol. 10. (Wiley, 2010)
29. C. Hagn, Textile, particularly household, home or furnishing fabrics, item of clothing or accessory, piece of furniture and furnishing. Google Patents, 08 Jan 2009
30. M. Adnan Ali, M.I. Sarwar, Sustainable and Environmental freindly fibers in Textile Fashion (A Study of Organic Cotton and Bamboo Fibers). University of Borås/Swedish School of Textiles (2010)
31. R.S. Kumar, *Textiles for Industrial Applications*. CRC Press (2016)
32. Y. Yang, S. Zhang, X. Zhao, J. Yu, B. Ding, Sandwich structured polyamide-6/polyacrylonitrile nanonets/bead-on-string composite membrane for effective air filtration. Sep. Purif. Technol. **152**, 14–22 (2015)
33. A. Chaudhary, N. Shahid, Growing importance of hometech textiles in India. Int. J. Mark. Financ. Serv. Manag. Res. **1**(6), 127–142 (2012)
34. H. Eberle et al., Fachwissen Bekleidung. Haan-Gruiten Eur., pp. 156–182 (2013)
35. R. Pieren, B. Schäffer, S. Schoenwald, K. Eggenschwiler, Sound absorption of textile curtains—Theoretical models and validations by experiments and simulations. Text. Res. J. **88**(1), 36–48 (2018)
36. J.O. Ukponmwan, A. Mukhopadhyay, K.N. Chatterjee, Sewing threads. Text. Prog. **30**(3–4), 1–91 (2000)
37. M.S. Naeem, A. Mazari, I.A. Khan, F. Iftikhar, Effect of sewing speed on seam strength. Immobil. Esterase Enzym. Onto Silica NANOFIBERS Biomed. Appl., 24
38. J. Fan, W. Leeuwner, L. Hunter, Compatibility of outer and fusible interlining fabrics in tailored garments part I: desirable range of mechanical properties of fused composites. Text. Res. J. **67**(2), 137–142 (1997)
39. R. Shishoo, *Textiles in Sport*. Elsevier (2005)
40. W. Albrecht, H. Fuchs, W. Kittelmann, Nonwoven fabrics: raw materials, manufacture, applications, characteristics, testing processes. (Wiley 2006)
41. M.S. Al-Homoud, Performance characteristics and practical applications of common building thermal insulation materials. Build. Environ. **40**(3), 353–366 (2005)
42. F.U.A. Shaikh, A. Hosan, Mechanical properties of steel fibre reinforced geopolymer concretes at elevated temperatures. Constr. Build. Mater. **114**, 15–28 (2016)
43. P.K. Sarker, S. Kelly, Z. Yao, Effect of fire exposure on cracking, spalling and residual strength of fly ash geopolymer concrete. Mater. Des. **63**, 584–592 (2014)
44. M.L. Terranova, S. Orlanducci, M. Rossi, *Carbon nanomaterials for Gas Adsorption*. Jenny Stanford Publishing (2012)
45. C.A. Pope III, D.W. Dockery, Health effects of fine particulate air pollution: lines that connect. J. Air Waste Manage. Assoc. **56**(6), 709–742 (2006)
46. W.C. Hinds, Aerosol technology: properties, behavior, and measurement of airborne particles. (Wiley, 1999)
47. R. Zhang et al., Nanofiber air filters with high-temperature stability for efficient PM2. 5 removal from the pollution sources. Nano Lett. **16**(6), 3642–3649 (2016)
48. K.S. Sutherland, G. Chase, *Filters and Filtration Handbook*. (Elsevier, 2011)

49. N. Lavoine, C. Givord, N. Tabary, I. Desloges, B. Martel, J. Bras, Elaboration of a new antibacterial bio-nano-material for food-packaging by synergistic action of cyclodextrin and microfibrillated cellulose. Innov. Food Sci. Emerg. Technol. **26**, 330–340 (2014)
50. K.K. Samanta, S. Basak, S.K. Chattopadhyay, Potentials of fibrous and nonfibrous materials in biodegradable packaging, in Environmental Footprints of Packaging (Springer, 2016), pp. 75–113
51. T. Exchange, *Preferred Fiber and Materials Market Report 2017* (Texas, USA, 2017)
52. Y. Wang, *Recycling in Textiles*. Woodhead publishing, 2006
53. S.C.A.A. Richard Horrocks, *Handbook of Technical Textiles*. (Woodhead Publishing, Cambridge, 2016)
54. H. Takeuchi, P.E. Raimund, United States Patent (19), 19, 1–6 (1997)
55. S. Sakthivel, J.J. Ezhil Anban, T. Ramachandran, Development of needle-punched nonwoven fabrics from reclaimed fibers for air filtration applications. J. Eng. Fiber. Fabr. **9**(1), 149–154 (2014)
56. W. Zhong, “Textiles for medical filters,” in Handbook of Medical Textiles, Elsevier, 2011, pp. 419–433
57. H.H. Forsten, High performance fabrics for cartridge filters. Google Patents, 15 Aug 2000
58. R.L. Chapman, Multilayer composite air filtration media, U.S. Patent No. 5,419,953 (1995)
59. A.M. Grancarić et al., Conductive polymers for smart textile applications **48**(3) (2018)
60. SWICOFIL, “SWICOFIL,” 2020. [Online]. https://www.swicofil.com/commerce/products. Accessed 02 Mar 2020
61. B. Plaggenborg, S. Weiland, Textile-reinforced concrete with high-performance carbon fibre grids: Reinforcement. JEC Compos. **44**, 32–35 (2008)
62. L.S. João, R. Carvalho, R. Fangueiro, A study on the durability properties of textile membranes for architectural purposes. Procedia Eng. **155**, 230–237 (2016)
63. C. Kulas, Actual applications and potential of textile-reinforced concrete. GRC **2015**, 1–11 (2015)
64. Y. Du, M. Zhang, F. Zhou, D. Zhu, Experimental study on basalt textile reinforced concrete under uniaxial tensile loading. Constr. Build. Mater. **138**, 88–100 (2017)
65. M. Saafi et al., Multifunctional properties of carbon nanotube/fly ash geopolymeric nanocomposites. Constr. Build. Mater. **49**, 46–55 (2013)
66. S.M. Abbasi, H. Ahmadi, G. Khalaj, B. Ghasemi, Microstructure and mechanical properties of a metakaolinite-based geopolymer nanocomposite reinforced with carbon nanotubes. Ceram. Int. **42**(14), 15171–15176 (2016)
67. J. Yuan et al., Effect of curing temperature and SiO2/K2O molar ratio on the performance of metakaolin-based geopolymers. Ceram. Int. **42**(14), 16184–16190 (2016)
68. D.L.Y. Kong, J.G. Sanjayan, Effect of elevated temperatures on geopolymer paste, mortar and concrete. Cem. Concr. Res. **40**(2), 334–339 (2010)
69. M. Saafi, L. Tang, J. Fung, M. Rahman, J. Liggat, Enhanced properties of graphene/fly ash geopolymeric composite cement. Cem. Concr. Res. **67**, 292–299 (2015)
70. S. Yan et al., Effect of fiber content on the microstructure and mechanical properties of carbon fiber felt reinforced geopolymer composites. Ceram. Int. **42**(6), 7837–7843 (2016)
71. M. Eyvaz, S. Arslan, E. Gürbulak, E. Yüksel, Textile materials in liquid filtration practices. current status and perspectives in water and wastewater treatment. Text. Adv. Appl. InTech **11**, 293 (2017)
72. O. Yildiz, P.D. Bradford, Aligned carbon nanotube sheet high efficiency particulate air filters. Carbon N. Y. **64**, 295–304 (2013)
73. R.C. Bansal, M. Goyal, *Activated Carbon Adsorption*. (CRC Press, 2005)
74. M. Polk, T.L. Vigo, A.F. Turbak, High performance fibers, Encycl. Polym. Sci. Technol. (2002)