

Chapter 4

Fibers for Protective Textiles



Khubab Shaker and Yasir Nawab

Abstract “Protective Textiles” is collectively used for the textiles and clothing employed necessarily in a specific work environment, either in labs, hospital, battle-field, rescue, or industrial applications. These textiles and clothing normally focus on the functional aspects rather than the aesthetics. The recent trends in these protective clothing include strong, lightweight and safer product for a particular end use. This chapter is focussed on the fibers used for protection against certain hazards/phenomenon like impact, chemicals, fire, heat, ballistics, etc. The majority of these application areas use high-performance fibers, to meet the challenges. But, the textiles for protection are highly specific, depending on the application area. The product for a particular end application needs to exhibit properties that may not be required for other applications. The products based on these fibers are also discussed briefly in this chapter.

4.1 Introduction

The term “Protective Textiles” is collectively used for the textiles and clothing employed necessarily in a specific work environment, either in labs, hospital, battle-field, rescue, or industrial applications. These textiles and clothing normally focus on the functional aspects rather than the aesthetics. The recent trends in these protective clothing include strong, light weight, and safer product for a particular end use. Therefore, the manufacturers are constantly improving the existing products and introducing new materials to meet the constantly increasing/ever changing demands. This chapter is focussed on the fibers used for protection against certain hazards/phenomenon like impact, chemicals, fire, heat, ballistics, etc. The majority

K. Shaker (✉) · Y. Nawab

Faculty of Engineering and Technology, National Textile University, Faisalabad, Pakistan
e-mail: shaker.khubab@gmail.com

Y. Nawab

e-mail: yasir.nawab@yahoo.com

© Springer Nature Switzerland AG 2020

S. Ahmad et al. (eds.), *Fibers for Technical Textiles*, Topics in Mining, Metallurgy and Materials Engineering, https://doi.org/10.1007/978-3-030-49224-3_4

of these applications areas use high-performance fibers, to meet the challenges. The products based on these fibers are also discussed briefly in this chapter.

The textiles for protection are highly specific, depending on the application area. The product for a particular end application needs to exhibit properties that may not be required for other applications. For example, in case of ballistic protection, the chemical resistance is a very less concerned phenomenon, the mechanical behavior of fiber is more concerned in ballistics, but it is of little use in heat resistant applications. Some of the main properties concerned for protection include tensile properties, temperature resistance, flammability, chemical resistance, impact behavior, and limiting oxygen index (LOI). These properties largely determine the behavior of a fiber in a particular application.

4.2 Material Selection Criteria

Therefore, it is necessary to define a basic criterion for the selection of material for textile product design. It is required to define a material selection process based on the properties of materials available. A problem statement is established first, keeping in mind the performance criteria. The material is then selected by careful consideration of its performance, specific design and cost parameters. Some of these parameters are discussed below in detail.

4.2.1 Mechanical Performance

The mechanical performance of the material is the most critical parameter while selecting the fibers. The mechanical performance is necessary for the durability and structural integrity of the structure. Therefore, it is necessary to identify the stresses that will be acting on the product. Stresses may be either tensile, tearing, compression, bending, shear, etc. Hence the mechanical properties that need to be considered include breaking strength, yield strength, elongation, toughness, and stiffness. Based on these parameters, the materials may be termed as brittle, strong, ductile, or plastic material (Fig. 4.1).

Therefore, a sound knowledge of the mechanical properties of the material is necessary for a particular application. These properties have been defined and discussed below:

Breaking strength

Breaking strength is generally the most important parameter considered before the selection of material for a particular application. The high strength fibers (e.g., para-aramid) offers up to 8 times high breaking strength as compared to the steel. These fibers also have a high strength-to-weight ratio making an ideal choice for lightweight and enhanced strength applications. In case of applications where strength is not of

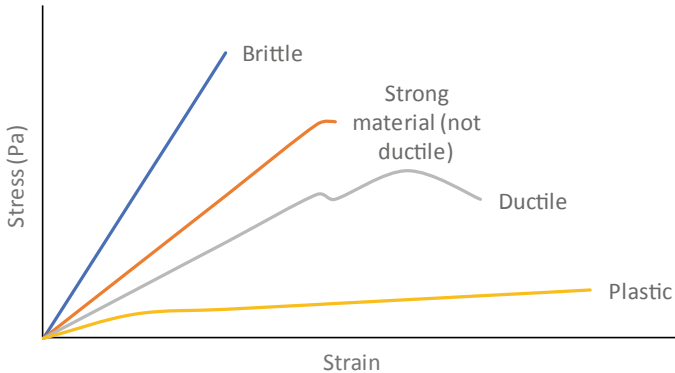


Fig. 4.1 Stress strain curves of different materials

principal importance, other mechanical properties are considered before material selection.

Yield strength

The yield strength explains the material strength at the end of elastic region. It approximates the elastic limit of the fiber, i.e., the upper limit of load that can be applied to the fiber. It is defined as the maximum amount of stress that a fiber can bear before it undergoes permanent deformation. Therefore, it is an important parameter in the product design.

Elongation

The ductility or brittleness of the material is best explained in terms of its elongation (strain). It is the % change in the material length from original length, either at yield point or failure. Ductility is the ability of a material to be stretched without becoming weaker/brittle in the process. The more ductile it is, the more formable the product is.

Toughness

The resistance offered by a material to fracture when it is stressed is termed as material toughness. It is also expressed as the ability of a material to absorb energy and deform plastically without fracture and is calculated as the amount of energy or energy per unit volume of the material. The toughness is a time/temperature dependent phenomenon sensitive parameter, particularly at elevated temperatures. The toughness of the material must be considered in impact and shock absorption applications. The parameter is highly application oriented and requires extensive testing to realize the effectiveness of a material for particular application.

Stiffness

Stiffness is the ease of deformation produced in the material under an applied load. The elastic modulus, defined as the ratio of stress over strain in the elastic range is a measure of material stiffness. As it is a material property, therefore it remains constant

for a particular fiber. The modulus is measured under tensile, flexural, compression or torsion load.

4.2.2 Chemical Resistance

The shape/properties of a material are largely affected by certain chemicals/solvents. The ability of a fiber to maintain its properties and shape in a certain chemical environment for a specific time is termed as its chemical resistance [1]. The chemical resistance offered by a fiber depends on its molecular structure, concentration of chemical reagent, exposure time, temperature, and applied stresses. A mixture of chemicals may also affect the material in a more detrimental way as compared to a single chemical, e.g., one chemical may swell the material while the other may saturate the material and react with it. The additives present in the material (colorants, fillers, contaminants, etc.) also affect the chemical resistance of material. Hence, it is important to know how a material will behave in a chemical environment.

These materials are affected by chemical reagents in two possible ways:

1. Chemical reagent dissolves the polymeric material by acting as a solvent.
2. Chemical reagent act as a stress cracking agent.

The first technique results in dissolution of material, leading to the loss of properties (physical, mechanical, thermal, electrical, etc.), dimensional change (swelling, mass loss, etc.), degradation, etc. This approach helps to determine the solvent resistance of a fiber, and the solvent may also initiate cracks in the fiber. But the test conditions and procedures for chemical resistance are not standardized in terms of reagent concentration, time, and temperature. Also reporting the effect of chemical reagent on the material varies, e.g., volumetric swelling, dimensional change, weight pickup, mechanical performance, etc.

The chemical resistance of a material is determined by its chemical structure including type of bonds, bond length, branching, crystallinity, and energy required to break the bond. For example, polytetra-fluorethylene (PTFE) is resistant to majority of chemicals due to its crystalline structure, strong C–F covalent bonds, and lack of branching. In case of nylon fiber, the regular symmetrical structure produces a highly crystalline fiber, while the strong intermolecular attractions give a strong, rigid, and chemical resistant. The amorphous materials are more susceptible to chemical attacks, while semi-crystalline materials perform better than the amorphous materials.

4.2.3 Thermal Resistance

Thermal resistance defines the ability of a textile fiber to serve as a heat insulator. Higher the value of thermal resistance, lower is the loss of heat across its surfaces.

$$R = \frac{\Delta T \cdot A}{\dot{q}},$$

where ΔT is the temperature difference between material surfaces, q is the heat flow, and A is surface area [2]. It is the most critical parameter for the applications where change in temperature is unavoidable. The temperature deteriorates the mechanical/chemical performance of material, also the phenomenon of oxidation and corrosion is expected to increase with rise in temperature. The thermal resistance is a function of fabric thickness and structure. It also depends on the thermal conductivity of the material. The higher value of thickness results in an increase in thermal insulation provided by the fabric.

Different approaches/devices are being used to determine the thermal resistance of textile fabrics. Some of these include Permetest, Skin model, Thermo Labo, Guarded hot plate, and Thermal Manikin system [3]. In case of guarded hot plate, the sample is placed over a hot metal plate, and change in temperature on both sides of sample is recorded. Thermal resistance is then calculated using plate surface area and temperature difference between the fabric surfaces. The resultant value of thermal resistance includes intrinsic resistance of the specimen and some transition resistance from fabric to air (corresponding to the heat loss from fabric surface to the environment).

4.2.4 Flammability

The ability of a material to burn/ignite, causing its combustion. It is generally determined by fire testing, as the degree of difficulty to cause combustion of material and classified into highly flammable, flammable and non-flammable materials. Owing to the flammable nature of the material, its use may be limited for a certain application [4]. The flammability is improved by the addition of flame retardants that work by delaying the ignition or retarding the burning process once it starts, and/or suppressing the formation of smoke [5]. The flammability of a material is expressed in terms of its ignitability, burning/heat release rate, flame spread, smoke generation, and toxicity [6]. These terms have been discussed briefly.

Ignitability

It is the resistance offered by the material to ignition and is the most serious parameter of flammability because in the absence of ignition, there will be no fire.

Burning/heat release rate

The solid fuel pyrolyzed per unit area in a unit time explains the burning rate of the material. the burning rate determines the heat release rate and the combustion products generated due to burning.

Flame spread

Another important measure of flammability is the flame spread. It is an indicator of fire hazard because burning area is increased due to flame spread resulting in a

higher heat release rate. The flame spread may be considered as a series of piloted ignitions giving rise to increased burning area. The ratio of a heating length ahead of pyrolysis front to the ignition time s termed as the flame spread rate.

Smoke generation and toxicity

In addition to the fire itself, there are some other causes of death due to fire. The two major factors include the reduced visibility due to smoke generation (reduced wayfinding ability), and suffocation, unconsciousness or incapacitation (by inhaling toxic gases) may lead to death. The reduced visibility during a fire is caused by smoke opacity and its irritant nature. The presence of soot particles makes the smoke opaque while irritation is caused by irritants like hydrogen halides (HCl, HBr, and HF), formaldehyde, nitrogen oxides, sulfur dioxide, phosphoric acid, etc. The overall toxicity is dominated by the presence of carbon monoxide and then HCN. The intoxication by CO is quite slow while that of HCN is rather sudden.

Flammability tests

The common flammability tests to identify the material properties are performed as follows.

Ignition

The ignition test is generally conducted at a small-scale using Cone Calorimeter, Fire Propagation Apparatus (FPA), or LIFT apparatus. These tests involve the irradiation of a small sample at a prescribed radiant flux. The time for piloted ignition in the presence of a small pilot is recorded. The sample size is 100×100 mm in Cone Calorimeter and 155×155 mm in the LIFT. Both LIFT and Cone Calorimeter are performed in the normal air, while FPA is performed in 40% oxygen concentration. The resulting parameters include critical heat flux for ignition and ignition time as a function of applied heat flux. Another measure of ignition/flame spread in a polymer is the Limiting Oxygen Index (LOI). It is the lowest fraction of oxygen that will support burning on a small sample. This test is frequently applied to polymers according to the ASTM D 2863.

Heat release rate

The heat release rate (HRR) measurement is generally performed using Cone Calorimeter or Fire Propagation Apparatus. HRR is calculated on the basis of oxygen consumption during a calorimetric measurement, as the amount of heat released per unit mass of oxygen consumed remains approximately constant. These tests also provide transient measurements of mass loss rate and specimen generation (yield) rate in addition to HRR.

Flame spread

The flame spread is tested for lateral and upward direction separately. The lateral flame spread is evaluated using LIFT apparatus. Initially a sample having dimensions 155×800 mm is exposed to a decaying heat flux from methane fired radiant panel. After reaching the thermal equilibrium, sample is ignited in the high heat flux region.

The flame spread in lateral direction is measured as a function of radiant heat flux (incident).

The upward fire propagation test is performed according to the ASTM E2058 using FPA. The sample used for testing has a width and height of 100 mm and 600 mm, respectively. The pilot flame is used to ignite bottom 120–200 mm of sample at a heat flux of 50 kW/m². The pyrolysis front is tracked during the test as a function of time. The spread is then recorded in terms of fire propagation index (FPI) using thermal inertia, heat release rate and effective ignition temperature.

Smoke production and toxicity

The toxicity of a flame is usually expressed in terms of LC50 concentration. It is defined as the mass of material per unit volume that results in death of 50% of the exposed animals. It is performed by gasifying the material under non-flaming conditions at 25 °C less than its ignition temperature and measuring the chemical composition of the atmosphere.

4.3 Fibers for Impact/Crash Applications

The terms impact or crash are associated with the sudden and abrupt change in velocity imposed to the human body. The abrupt acceleration imposed on the human body may cause injuries, damage to property, or may be fatal. The level of injury is defined by the magnitude, duration, and direction of application of accelerating forces. The inertial forces resulting from the application of acceleration cause displacement of organs within the body with equal and opposite acceleration and may cause damage to the vitals [7]. Few examples of crash impact from daily life include:

- Collision of a vehicle with another vehicle, obstruction, or pedestrian.
- Falling from height on the ground.
- Thrust on the crew in military jet aircraft during crash.
- Physical assaults with unconventional weapons e.g., bottles, bats, metal bars.

Keeping in view the above discussion, it is important to introduce/implement the restraint systems to limit the human body damage during a crash event. For example, the use of seat belts while driving and the use of helmets while driving a motorcycle has been enforced by law in many countries. These measures, enforced by law or adopted by choice, help to reduce the risk of serious injury from crash impact. Some of the restraint systems and fibers used for these systems are discussed in detail.

4.3.1 Seat Belt

In a vehicular collision, seatbelt is a vital product for energy ingesting, keeping the passengers safe from injuries and casualties. It keeps the passengers being ejected from the vehicle and reduces the actual force of impact. Seatbelts comprise of one or more straps, secured across the trunk of seated individual by means of a quick-release buckle. The conventional type is the lap strap, which is easy to use but does not restrains the upper trunk and may result in serious injury. The three-point seatbelt was developed by the addition of a diagonal strap that runs from one of the lap straps, passes over the front of trunk and then over the top of opposite shoulder, and finally secured to the vehicle/seat.

The five-point harness is introduced for use in modern fighter aircrafts it comprises of two lap straps, two shoulder straps and a strap between legs from seat structure to the quick-release box. This harness provides excellent restraint properties for maneuvering, crash impact, or ejection. The seat belt has to resist a load of approximately 14KN during a crash event and performance of the complete seat belt system is measured. Seat belts are equipped with a load limiting retractor, a pre tensioner and a D-ring which helps in reeling out of the belt from the retractor [8, 9].

The mechanical performance of webbing (seat belt structure) is established in terms of different properties like breaking strength, elongation at break, width and thickness of webbing and abrasion resistance. These properties are determined at conditions that resemble the real-life scenario. For example, the strength of seatbelt structure is usually determined by means of conventional slow strain rate (so-called static tension testing). The test method AS 1753–1990 [10] is implemented to test the tensile strength of structure.

The initial seatbelts were produced from natural fibers like cotton, flax, and wool but filament yarns are preferred these days due to their enhanced strength. The filament yarns used include synthetic fibers like Nylon, Polyester, Polypropylene, p-aramid, UHMWPE, etc. The synthetic materials mostly preferred are the polyamide (Nylon 6.6) and polyester. Polyamide is used to produce Lap belts, while polyester is preferred for the diagonal range of seatbelts. The properties of both these fibers have been compared in Table 4.1. The polyester is considered superior due to high stiffness and low extensibility and better UV degradation resistance [11].

Table 4.1 Comparison of polyester and nylon 6.6 basic properties [12]

	Polyamide (Nylon 6.6)	Polyester
Specific gravity (g/cm^3)	1.12	1.39
Specific heat capacity, Cp (J/kg.K)	1670	1300
Melting point ($^{\circ}\text{C}$)	265	255
Glass transition temperature ($^{\circ}\text{C}$)	50	75
Energy to melt (kJ/kg)	589	427

The seatbelts are usually woven structures that are 48 mm wide [13]. These structures are woven using coarser yarns, for better abrasion resistance. Another objective of using coarser yarn is to achieve maximum yarn packing factor and strength. The polyester seatbelts are woven with a warp and weft yarn linear density of 110 tex and 55 tex, respectively, are used, with 320 warp yarns giving 46 mm wide belt. The polyamide seatbelts have warp and weft yarn linear density of 18 tex and 47 or 94 tex, respectively [12]. Generally, 110–167 tex is the most optimum choice for body warp yarns and 27–55 tex is used for selvedge yarns. The weft yarns are either of the same linear density as selvedge yarns or slightly coarser. For warp yarn having linear density of 110 tex, 320 threads are used, while 260 yarns are used for linear density of 167 tex.

In addition to the material, the interlacing pattern of warp and weft also decides the wearer protection during an impact. The seatbelts are either single layer or double-layered structures, with plain, twill, and satin weave designs [14]. The initial webbings were produced in plain weave using either wool, cotton or flax yarn. Currently, the 2/2 herringbone twill is widely used because it gives a compact structure with maximum threads density [15].

4.3.2 Airbag

Another restraint system in automobiles is the airbag system that enhances the human tolerance during impact acceleration. The air bag is located at the front of seat occupant and inflates automatically (inflation time < 0.1 s) in response to deceleration and prevents the occupant from moving forward and striking the vehicle structure. The airbag, jointly with seat belts assures passengers safety in the case of a car accident and reduces front-seat occupants' fatality risk by 61% [17]. The four common types of airbags are: side airbags, front airbags, knee airbags, and inflatable seat belts. Airbag system uses a textile cushion, folded and tucked in the steering wheel along with propellant and inflator assembly and crash sensor. The crash sensor detects the collision and triggers the gas generator to inflate the textile cushion. The airbags are prepared traditionally by cutting the fabric in proper shapes and sewing, internally and externally, to join the two sides properly. However, the one-piece-weaving (OPW) technology is also being used to eliminate the need for cutting and sewing.

The airbags were also used in Mars missions to cushion the spacecraft while landing on the rocks or rough terrain and allow it to bounce across the surface of Mars. These airbags were produced with high strength Vectran fiber [16]. The linear density of HS Vectran used was 200 den and woven in plain weave. The fabric areal density was 92 grams/m², while its tensile and tear strength was 85 N/mm and 665 lbs, respectively. It was then coated with low-temperature silicone to minimize the air permeability. The adhesion strength of this coating was 31.2 N, the coating weight was 54.25 grams/m² and coated fabric weight was 146 grams/m². To protect this airbag from sharp edges of rocks during impact landing, an outer abrasion layer was used. This multi-layer approach allowed the movement of inner airbag in the

event of rock impingement, and damage was limited to the outer layers only. It was also woven using 200 denier Vectran in a ripstop weave with an areal density of 82 grams/m², and 4 plies were used as outer layer [17]. Vectran is spun from liquid crystal polymer (LCP) and exhibits exceptional strength and rigidity. The unique properties of Vectran include [18]:

- High modulus and strength.
- Excellent creep and flex properties.
- High abrasion and chemical resistance.
- Minimal moisture absorption.
- Low thermal expansion coefficient (CTE).
- Excellent property retention at high/low temperatures.
- Outstanding cut resistance and vibration damping.
- High impact resistance.

The fibers used for weaving airbag fabrics for automobiles are required to possess high strength, energy absorption capacity, thermal stability, better coating adhesion, and functionality in extreme environmental conditions (cold and hot). The fabric may be coated or uncoated but it must be impermeable to air. In majority cases, the fabric for airbags is woven using Nylon 6.6 multifilament yarn (linear density 420 to 840 den), but other materials like polyester, nylon 4.6, nylon 5.6, and nylon 6 are also used [19]. The uncoated fabric weighs about 170 and 220 grams/m². The polyamides are usually preferred due to:

- High-strength-to-weight ratio, resulting in strong woven fabrics.
- High elongation, helping in circumferential stress distribution uniformly.
- Material toughness, enables to withstand stresses during airbag deployment.
- High specific heat capacity, heat of fusion and melting point.

A comparative analysis of the fibers used for the seatbelts and airbags is given in Table 4.2. The polyester is not preferred development of airbags due to its lower thermal properties. Contrary to the nylon 6.6, polyester needs about 40% less amount of heat to melt and the fabric has high permeability allowing the diffusion of hot gases [14].

4.3.3 Safety Helmets

The protection of head is most important as one third to half of car crash fatalities are due to the head injuries. The head injuries may include fracture of skull bone, tearing of membrane lining inside skull or localized damage to the brain. The brain may be damaged either by physical damage to the skull or by the blow (acceleration of the head) in the intact skull, where brain moves within the skull. The blow head blow may result in concussion (transient paralysis of cerebral function), leading to unconsciousness. These conditions are followed by complete recovery.

Table 4.2 Yarns used for seatbelts and airbags

Application	Fiber	Fineness	Strength	Modulus	Elongation (%)	References
Seatbelts	Nylon 6.6	18 tex, 47/94 tex	40–60 cN/tex	20–35 cN/tex	20–30	[12, 15, 20]
	Nylon 6.6	130 tex, 65 tex				
	Polyester	110 tex, 55 tex	25–85 cN/tex	800–1000 cN/tex	10–20	[12, 15, 20]
	Polyester	130 tex, 65 tex				
Airbags	Polyester	330–470 dtex	60–75 cN/tex	–	15–30	119–120
	Nylon 6.6	630 denier	9.3 g/den	–	15–30	122
	Nylon 6.6	350 dtex	60 cN/tex	–	15–30	118
	Nylon 6.6	100–800 dtex	5–11 cN/tex	–	15–35	124
	Polyester	540–650 denier	5.1–8.5 g/denier	–	15–20	
	Vectran	200 denier	24.4 g/denier	838 g/den	2.8	[18]

The head injury is not only limited to the head protection but also includes other factors like trunk restraint and space free of rigid structures around head. Another aspect is the use of a surface that deforms when head may come in contact, allowing maximum energy absorption without damage. However, the most satisfactory solution is the provision of personal head protection.

A protective helmet usually comprises of an outer shell, with a layer of crushable foam inside and a strap harness. The shell helps to distribute the impact energy, while gap between shell, and head (18–25 mm) reduces the acceleration applied to the head during impact. The strap harness helps to fasten the helmet on head and avoids taking off. Thus the protective helmets help to reduce the fatalities and head injuries in car/motor cycle crash [7].

Two major components distinguished in the helmets are the outer shell and the inner layer for shock absorption. The materials that are commonly used in the motorcyclist helmets shell are carbon fiber, polycarbonate, and fiberglass. Thermoplastics as well as composite materials are in practice to apply for helmets. Standard helmets shell is usually made of polycarbonate and inside this a layer of expanded polystyrene foam (EPS) is inserted [1]. This combination will provide a stiff material but also perfectly crushable during impact. In advanced helmets multiple densities of EPS in various layers and locations are used. This creates a smarter helmet, which have ability to absorb the crash depending on the severity and location of impact. The

drawback of using EPS is that denser foam will bear high impact energy, but it eventually increases the weight of product and make it uncomfortable for users as a thick, heavy foam helmet is simply not comfortable to wear on the other hand soft foams will crash easily. Expanded polyurethanes foam is also in practice to apply as inner layer but it is heavier than EPS.

Other high-performance materials used in advance helmets are, Zorbium, SALi (Shock Absorbing Liquid), ABS plastic and Nylon [21]. The manufacturing process for shell used for helmets from thermoplastics materials (PC, ABS) is injection molding in which molten material is injected into die having core and cavity at specific temperature and pressure.

4.3.4 Shock Absorption

The term shock describes a sudden acceleration or deceleration, due to a strike, drop or other external factors. While the impact is an extreme shock applied over a short time period, e.g., due to collision of two or more objects. Some other examples include vehicular accidents, physical assaults with bats, metal bars, bottles, or falls from height. Shock-absorbing cushions are used specifically for these situations. It is recommended to use viscoelastic materials, that absorb the impact effectively. Dupont has introduced a multi-threat-protection (MTP) armor for chock protection, in addition to other threats.

4.3.5 Parachutes

Parachutes are the devices that help to slow down the descent of the body falling from the atmosphere or the velocity of the body traveling horizontally. It is a combination of two French words para (means protect) and chute (means the fall), giving it the literal meaning of fall protection. Hence it can be defined as a protection device when one falls from height under the action of gravity [1]. The parachutes are being routinely used for sky jumping activities both in the military and sports area, decelerating race cars, boats, aircraft seat ejection system, and bombs stabilization.

The main parts of a parachute are the canopy, suspension line, slider, and brake loop. Canopy is a structure made of fabric cells that forms a rectangular surface when filled with air, with the aerodynamic properties of an airplane wing. Suspension line is the set of cables that connect canopy to harness (straps) connected to the sky diver. Slider slows down the deployment of canopy to absorb the impact of deceleration as it opens up, while brake loop is the cable that helps to control the direction of parachute [22].

The parachute canopy was initially made of canvas (plain-woven fabric from cotton or linen) but was replaced by silk in due course of time. The silk fabric was selected due to its lightweight, strength, fineness (thin), fire resistance, and easy of

Table 4.3 Properties of fibers used for parachute canopy

Parameter	Cotton	Linen	Silk	Nylon
Fineness (dtex)	1–4	10–40	1–3.5	14–330
Fiber length (mm)	10–60	200–800	700–1500	Continuous
Density (g/cm ³)	1.5–1.54	1.43–1.52	1.37	1.15
Moisture regain (%)	8.5	12	9–11	4
Breaking strength (cN/tex)	25–50	30–55	25–50	40–60
Elongation (%)	5–10	2–3	10–25	20–40

folding. The shortage of silk was observed during World War I and II, leading to the idea of replacing the silk with some synthetic fiber like nylon. It was selected due to its good elasticity, mildew resistance, better strength, and relatively low cost. Recently, other fabrics like p-aramid and Dacron polyester are also used for canopies, but nylon is still the most popular material (Table 4.3).

The nylon fabric for parachute canopy is woven in plain weave to give a pattern of small squares. These squares are created by using an extra-thick thread, that helps to avoid tearing of the fabric. Such type of weave design is also referred to as ripstop and is produced using either a double or extra-thick thread at regular intervals. The ripstop structure enhances tear resistance and keeps small tears from spreading [22]. Being lightweight, strong, and flexible, the nylon is also used to make harness straps and suspension lines of the parachute.

The overall comparison of the fibers used in impact/crash applications is given in Table 4.4, w.r.t the strengths, weakness, and uniqueness of each fiber.

4.4 Chemical Resistant Fiber

The chemically resistant fibers are designed to offer resistance in chemical environments for a certain period during their service life at ambient and elevated temperatures. Some of the common areas of application include gas and liquid filtration fabrics, braiding materials in chemical plants, protective textiles, high-performance sewing threads, and conveyer belts. The chemical protective clothing requires specific chemical resistance for a relatively small period of time intermittently at elevated temperatures, while a long-term durability to less corrosive environments is demanded in geotextiles, where ambient conditions prevail. The chemical inertness in these fibers is obtained either by strong chemical bonds in the polymer backbone, absence of reactive side groups, or backbone free of hydrolysable groups (e.g., ester, amide) [23]. Owing to the chemical inertness of these fibers, they may also overlap with other fibers more often considered to be heat resistant or flame-resistant fibers.

Hence the polyethylene and polypropylene fibers offer acceptable resistance to chemicals at ambient temperature only and resistance is limited at temperatures

Table 4.4 Comparison of high-performance fibers used in impact/crash applications

	Strength	Weakness	Uniqueness
Para-aramid	Excellent Tenacity (19–25 g/d) High Modulus (550–1300 g/d) Outstanding Toughness Excellent Resistance to heat Continuous operating temp 375 °C Low elongation (1.3–4.4%) Good abrasion resistance	Low resistance to strong acids and alkalis Strength loss when exposed to: Saturated steam UV light Temp > 180 °C Combustion produce toxic gases	Solvent spun Better Cut resistance Little loss in modulus at 200 °C Strength and Modulus increase in arctic conditions. Show –ve thermal expansion Technora: good resistance to strong acids and alkali
Ultra high molecular weight polyethylene	High Tenacity (30–42 g/d) High Modulus (850–1400 g/d) Unaffected to strong acid & alkali Good light stability, abrasion and UV resistance Biologically inert High impact strength	Strength loss in strong oxidizing media Low compressive yield strength Hydrophobic in nature Prone to creep	Gel spun Low density (0.97 g/cm ³) Low melting point (150 °C) Visco-elastic material Insulator with high dielectric strength.
Thermotropic liquid crystal polymers	Good Tensile strength (12–36 g/d) High Modulus (600–1150 g/d) Low elongation (1.3–4.4%) Negligible creep High impact and high abrasion resistance Good resistance to conc acids	Strength loss when exposed to temper greater than 100 °C Stable to base only at conc < 30% Poor UV resistance	Melt Spun Good low temp properties Moisture regain nearly zero Vibration dampening
Poly (p-phenylene benzo dioxazole)	High Tensile strength (42 g/d) High Modulus (1300–1950 g/d) Excellent thermal stability Good resistance to creep Good abrasion resistance Stable to alkali at room temp	Poor compressive strength Strength loss when exposed to sunlight and UV Exposure to strong acids causes strength loss	Dry jet wet spinning Highly flame-resistant (LOI 68) Coefficient of thermal expansion is negative

(continued)

Table 4.4 (continued)

	Strength	Weakness	Uniqueness
Carbon fiber	High Tensile strength High elastic modulus Good compressive strength Good electric & heat conductivity Low thermal expansion coefficient Good chemical stability	Carbon dust may cause health and electrical hazards Brittle in nature	Electro-magnetic wave shielding Self-lubrication property X-Ray permeability
Glass fiber	High Tensile strength Good impact resistance More temperature resistance Fatigue resistance	Tensile Modulus less than aramid and carbon Brittle in nature Inhaling reduces lung function	Radar transparency Good stiffness High Resistance to flame Enhanced cost advantage

above 50 °C, especially in the presence of an oxidizing agent. Also, the polyester and nylon fiber lack chemical durability due to the presence of hydrolysable groups in the backbone of fiber. However, the aromatic polyesters show greater chemical as well as heat resistance. The polycarbonates lacking in intermolecular attractions are easily attacked by solvents. The polymeric hydrocarbons are easily attacked at room temperature by chromic acid. The low intermolecular attraction and molecular inflexibility makes polystyrene rigid, but it is susceptible to chemical attacks.

The halogenated derivatives of polyethylene, polyvinylidene chloride ($-\text{CCl}_2\text{.CCl}_2-$) are the polymers with better chemical resistance and a high degree of order. But these polymers are difficult to process, and therefore copolymers with other vinyl or acrylic monomers (less than 15% by weight) are used. For example, Saran is a copolymer with vinyl chloride [24]. The fluorinated ethylene fibers offer maximum chemical inertness but are more expensive. The polytetrafluorethylene ($-\text{CF}_2-\text{CF}_2-$), PTFE fibers withstand a temperature of up to 300 °C. Poly vinyl fluoride ($-\text{CH}_2-\text{CHF}-$), poly vinylidene fluoride ($-\text{CH}_2-\text{CF}_2-$), and other fluorinated ethylene polymers and copolymers have good chemical resistance, but their performance is limited by the lower melting points [25].

Polyetherketones are formed into fibers by high-temperature melt-spinning (at 260 °C, with short excursions to 300 °C). These fibers resist majority of chemical and high-temperature steam, except strong oxidizing acids. The Polyphenylene Sulphide (PPS) is a melt-spun fiber with excellent chemical resistance. A low second-order transition temperature of PPS (93 °C) limits its use in applications above 100 °C. The polyether-imide (PEI) has good chemical resistance and is cheap but slightly inferior heat resistance as compared to Polyetherketones (PEEK). Properties of chemical-resistant fibers and their limitations are given in Table 4.5.

Table 4.5 Properties of chemical-resistant fibers and their limitations

Name	Structure	Max service temperature	Tenacity (cN/tex)	Strain (%)	Chemical resistance	Limitations
Polyvinylidene chloride, PVDC	$(-\text{CCl}_2.\text{CCl}_2-)$	100–115	20	15–30	Better	Difficult processability
Polytetra-fluoroethylene, PTFE	$(-\text{CF}_2-\text{CF}_2-)$	290–300	14	20	Excellent	Expensive
Poly vinyl fluoride, PVF	$(-\text{CH}_2-\text{CHF}-)$	150	19–39	15–30	Good	Low melting point
Poly vinylidene fluoride, PVDF	$(-\text{CH}_2-\text{CF}_2-)$	150	43	25	Good	Low melting point
Polyether ketones, PEEK		260	61	19	Good, except strong oxidizing acids	High-temperature melt spinning
Polyphenylene sulphide, PPS	$(\text{C}_6\text{H}_4\text{S})_n$	190	18–23	12–16	Excellent	Notch sensitive
Polyether-imide, PEI	$(\text{C}_{37}\text{H}_{24}\text{O}_6\text{N}_2)_n$	200		30	Good	Inferior heat resistance

4.5 Heat Resistant Fibers

The heat/temperature resistance plays a basic role, while selecting a fiber for high-temperature applications. Most of the conventional fibers are degraded by heat/high temperature (below 300 °C) depending on the fiber composition, exposure time, and atmospheric conditions. The heat resistance of a fiber is generally measured in terms of its continuous operating temperature. When used at temperatures higher than the operating temperature, fibers may survive but the high heat start fiber degradation, leading to reduction in the mechanical performance of the fiber and ultimately destroy its integrity. The heat resistant fibers should not be confused with the flame-retardant fibers, but some fibers may offer both flame and heat resistance.

A most common example of heat resistant fibers is the use in firefighter clothing, oil and gas industry workers, etc. to protect them from thermal exposures (e.g., flame, hot surface, radiant heat, steam, molten metal substances, hot liquids, etc.). The thermal insulation of these clothing is strongly controlled by various factors like fiber, yarn, fabric properties, and clothing features. Another factor that needs to be considered in these clothing is the comfort performance of the clothing. Therefore, the thermal protective clothing should be designed in such a way to provide best thermal protection and also comfort to the wearer. The thermal protective clothing is composed of three main components, i.e., shell fabric, thermal liner, and moisture barrier [26].

The shell is generally produced from a plain-woven fabric using flame-retardant fibers like PBI, aramid, or a compatible blend. The thermal liner is a combination of woven fabric (face) and a batting. The face fabric is produced from flame-retardant fibers and sewn with the batting. The batting is produced from long flame-retardant fibers using a nonwoven technique and bonded either by chemical, mechanical, heat, or solvent treatments. Commercially used batting fabrics (needled felt) are Nomex, Kermel, semi-carbon, and polysulfonamide. The thermal liners commonly used are either combination of Kevlar/Nomex batting and aramid woven fabric (plain) or spun-laced nonwoven fabric. Some of the popular commercial thermal liners are AraliteGold, OMNIQuilt, Flame Quilt, and Quattro-tech.

Asbestos is a mineral fiber existing in nature and is heat resistant inherently, however it is a health hazard due to extreme fineness. The glass fibers offer heat resistance up to 450 °C, but these fibers have poor aesthetics and are difficult to process. The dominant heat- and flame-resistant fibers are the aramids and arimids. The most commonly used fiber, with good textile properties, is the meta-aramid produced with commercial names of Nomex (Dupont) and Conex (Teijin) [27]. The m-aramids can resist temperature of up to 250 °C for 1000 h with only 35% deterioration in the strength. At temperatures above 400 °C, the aramids form char and survive short exposures up to 700 °C. This char is tough acts as a thermal protective layer, making it a good candidate for fire protection applications [28].

The poly (p-phenylene benzobisoxazole), PBO is another heat resistant aromatic fiber made from linear polymers. It has remarkably high thermal stability (thermal degradation onset up to 600 °C). owing to stiffer chains, PBO is considered as the

most thermally stable commercial fiber available currently. Additionally, these fibers have very high flame resistance and good resistance to creep, chemicals, and abrasion, but exhibits poor compressive strength. Para-aramids, (Kevlar, Technora, Twaron) are also used for thermal protection, either alone or in blend form. They have the additional property of high degradation temperature, high strength, and stiffness.

The P84® polyimide fibers are made of poly[4,4'-diphenylmethane-co-tolylene benzophenotetra-carboxylic-imide] and manufactured by Evonik. The base material for P84® fibers is composed of aromatic backbone units only and is highly non-flammable with an LOI of 38. The fiber offer outstanding chemical, thermal and flame-retardant properties as compared to m-aramid. These fibers are preferred for applications including protective clothing, heat insulation, high-temperature filtration, etc.

Kermel is a polyamide-imide fiber (categorized in the meta-aramid family), with no melting/burning at extremely high temperatures, making it an ideal choice for heat and flame-retardant textiles [29]. Additionally, it also exhibits good mechanical performance and chemical resistance. The salient features of this fiber include lifelong colourfastness (due to solution dyeing), no pilling, lightweight, comfort, minimal shrinkage, etc.

PBI (polybenzimidazole) is an organic high-performance fiber originally developed by Celanese for NASA Apollo space program. The fiber has inherent flame resistance properties along with heat and chemical stability. It does not burn, melt, or aid in flame propagation [30]. Currently, PBI Performance Products is the sole producer of this fiber globally. The PBI fibers have a long chain aromatic polymer as backbone with recurring imidazole groups as repeat units in the polymer backbone, that results in high glass transition temperature (425 °C) with no melting.

The heat resistant fibers are also produced from thermoset polymers by extruding the partially cured or uncured resin with subsequent cross-linking. Such fibers advantageous in terms of high flame resistance and minimal smoke emission with no toxic gasses in flame. The Kynol novoloid (phenol aldehyde) is the earliest example of these fibers and exhibits remarkable resistance to solvents, acids, steam, or other chemicals in addition to excellent thermal resistance. Basofil is a melamine-formaldehyde-based fiber with a service temperature of 190 °C.

4.6 Flame Retardant Fibers

The flame-retardant (FR) fibers need to be distinguished from the temperature-resistant fibers, although some fibers fall in both the categories. The flame retardancy is generally determined in terms of Limiting Oxygen Index, and the fibers having LOI greater than 25 are termed as flame retardant. It means that at least 25% oxygen must be present in atmosphere for ignition of such fibers. Some of the fibers are inherently flame retardant while others can be made FR by adding/applying a flame-retardant finish [31]. The flame-retardant chemicals are either added to the polymer solution

before or during extrusion process. Additionally, impregnating the fiber/fabric adds flame retardant properties directly to the fabric (e.g., FR treated cotton fabrics).

The inherently flame-retardant fibers include m-aramid (Nomex) that was initially developed for fighter pilots, astronauts, tank crews, military personnel, and certain industrial applications. The aramid fibers do not have any FR elements/groups, but their FR behavior is due to the chemical structure (as it does not break into combustible fragments). Some m-aramid fabrics shrink and break open under heat and are therefore blended with 5% Kevlar fibers. Teijin introduced a FR denim (Xfire DENIM), like aramid fiber for firefighting uniforms. It is made of Teijinconex meta-aramid fiber [32].

The flame-retardant cellulosic fibers are categorized into two types, i.e., silica containing and phosphorus-containing [33]. The commercial fiber of first type is VISIL® (Sateri, Finland), that is permanent FR fiber owing to the high polysilicic acid complex content (30–33%) added during manufacturing. It does not melt/flow when in contact with flame and no toxic fumes are emitted. Its other advantages include blending with natural fibers, environmentally benign manufacturing, and bio-degradability. The example of second type is Lenzing FR® (Lenzing), which is a regenerated cellulosic fiber-containing organophosphorus additives introduced during manufacturing. It forms char when in contact with flame and offers protection from flame and heat. It can be blended with other inherently FR fibers like modacrylics and aramids. Common FR fibers, their properties and applications have been compared in Table 4.6.

4.7 Conductive Fibers

The conductive fibers are widely used for smart textile applications like sensors, heating element, static dissipation, EMI shielding, etc. The term smart textile describes the textile materials that can sense, react or adapt to some stimuli (internal or external) and are produced by integrating smart functions in textiles (mostly conductive fibers circuits are woven into fabric) [34]. To incorporate conductive fibers in textiles, it is desirable that these fibers should be strong and flexible, in addition to the conductivity. In terms of clothing comfort, it is required that the fabric should have properties like stretch ability, shear, and soft handle (fabric feel).

The conductive fibers consist of a blend of less-conductive/nonconductive substrate, that contains either conductive elements or coated with conductive elements [35]. The intrinsically conductive materials are directly spun into directly yarn or blended with/wrapped over textile fibers, e.g., conductive metals like stainless steel, copper, aluminum, nickel, titanium, etc. The most common example of blended conductive yarns is Bekaert Bekinox® (fine stainless-steel fibers) blended with different staple fibers to get anti-static yarn. The concentration of Bekinox® in the blend depends on the nature of fiber and requirements of the applications. Silk organza is the example of wrapped conductive yarn (thin copper foil is wrapped over silk fiber).

Table 4.6 Properties of flame-retardant fibers

Fiber	Common name	LOI	Tenacity (cN/Tex)	Other	Applications
FR viscose	Lenzing FR	28	16–24	El = 14–22	Electrical arc (at temp up to 10000 °C)
FR polyester	Trevira CS				Upholstery, drapes, blinds, seat cover, wall coverings, partitions, curtains, beddings, etc.
m-aramids	Nomex, Conex	28–31	206		Racing suits for driver and crew, Flight suits used by fighter pilots, EMS (emergency medical service)
Polyimide	P84, Kermel	38	38	El = 30 De = 1.41	Kermel A90 is used for military applications, flight suits and gloves, riot suits, fire fighter clothing, etc.
Polybenzimidazole	PBI	> 41	24	El = 28.5 De = 1.43	Aircraft furnishing, escape suits for astronauts, fire-fighting suits
Poly(p-phenylene benzo bisoxazole)	PBO, Zylon	68	370	El = 3.5 Tm = 650	Electronic insulation, military and aerospace applications
Melamine formaldehyde	Basofil	32	20	El = 15–18 MR = 5	Racing garments, fire fighter clothing, non-woven inter liners for gloves, jackets, etc.
Novoloid	Kynol	30–34	12–16	El = 30–60 MR = 6	Protective apparel, safety accessories, flame barriers, liners for upholstery, etc.
Poly phenylene sulphide	PPS	40	43	El = 34.5 Tm = 285 De = 1.34	High-temperature electrical applications
Oxidised acrylic	Panox, Pyron	55	20–30	MR = 10	Insulation, home furnishing, air craft brake, friction applications

(continued)

Table 4.6 (continued)

Fiber	Common name	LOI	Tenacity (cN/Tex)	Other	Applications
PTFE	Teflon	95	9–60	MR = 0	Flame retardant, thermal insulation, fire curtain, smoke barrier

El: elongation (%), De: density (g/cm^3), MR: moisture regain (%), Tm: melting temperature ($^{\circ}\text{C}$)

Table 4.7 Advantages and limitations of intrinsic and extrinsic conductive fibers

	Advantages	Limitations
Intrinsic conductive fiber	High conductivity and mechanical resistance Low weight High fatigue resistance	Difficult to integrate into woven/knitted fabrics Health hazards (carbon fiber) Low flexibility
Extrinsic conductive fiber	High conductivity and mechanical properties	High manufacturing cost High weight Washability (surface coated conductive fibers)

Another approach is to produce conductive yarns by using conductive fillers. It is specifically used for thermoplastic polymers (e.g., PE), the dope is charged with conductive fillers and then spun to get conductive yarns. It is also accomplished by the deposition of conductive particles on the surface of yarns [34]. The conductive particles (e.g., carbon) are dispersed in polymer melt before extrusion or deposited (e.g., nano-silver) on fiber surface. It gives an excellent control of static electricity but these conductive yarns are usually black in appearance and limits the use in industrial fabrics and apparel [36]. Other techniques of producing conductive textiles include padding of electrolyte solution on yarn, by printing or lithography [37]. The advantages and limitations of intrinsic and extrinsic conductive fibers are given in Table 4.7.

A fully conductive fiber is supposed to suffer from surface modification, while a core conductive fiber is generally used to avoid the surface modification.

4.8 Fibers for Military/Defense Application

The military forces are widely using textiles for protection against ballistic impact, chemical protection, flame resistance, thermal protection, communications (e-textiles), etc. The fibers for communications, chemical, thermal, and flame protection have been discussed earlier. Ballistic protection is the ability of a material to stop bullets or small object by absorbing energy locally and spreading it out quickly and efficiently without injury to the wearer. Generally, it is considered that ballistic

protective material has minimum blunt trauma (back side deformation). It could be said that the protection against bullet means to stop bullets in minimum accessible distance of the vest. The ballistic protection is achieved by protective body armor. This protective armor absorbs impact energy from fire arms, projectile, short gun projectiles, and hand guns [38, 39].

Ballistic protection has become a necessity of every security individual due to advancement in the ballistic threats. Different materials and techniques have been used by human beings for ballistic protection throughout its history, as per demand and availability of materials. The history of protection starts from the animal skin to wood, steel/metals, and then different types of fibers. Some recent trends involve the ballistic protection using nanomaterials. In the era of swords, the warriors used to wear metal jackets for protection. The importance of shielding from ballistic projectiles gained importance in the twentieth century.

The English produced shield design for body parts (including having padded neck and ballistic vest) commercially from materials like cotton and silk [40]. From 1914 to 1918, different types of body armors (metal plates for front and back) were introduced. Japanese used first soft body armor made of silk fiber, but the idea was not successful commercially due to high cost of silk [41]. Flake jacket made of nylon, with steel plate inside, was new revolution in field of protection during World War II. These jackets were heavy and rarely used for military purpose. A new generation of fibers (para-aramid) was introduced in 1965 to offer better protection against bullets.

Further advancements in technology led to the use of composite material for ballistic protection in the recent years. Composites have gained attraction due to its characteristics e.g., light weight, high strength to weight ratio, corrosion resistance, etc. The use of composite materials in ballistic protection has introduced concept of hard and soft body armors, varying in structure and offering different levels of protection accordingly. Concept of composite plates, high-performance synthetic fibers and ceramic backing have been invented for new armors [40].

The ballistic armor is defined to be a protective covering used to avoid damage from being inflicted by a high-speed projectile, usually during combat [42]. Applications of ballistic armors are wide spread and include personal body armor, vehicle armor, ballistic helmets and boots, small arms protective inserts, etc.

The armors being used these days have two major sections, i.e., Soft Armor Panel (SAP) and Hard Armor Plate (HAP). SAP is made up of low-density fiber, e.g., para-aramid, ultra-high molecular weight polyethylene, zylon, nylon, etc. [43]. The para-aramids are the most widely used for body armor, while others have great potential for ballistic protection, but needs to be investigated yet [44–47]. The SAP is flexible in nature and can be tailored to conform to the body contour of the person wearing the body armor. Soft body armor only is manufactured to protect police officer from handgun bullet commonly.

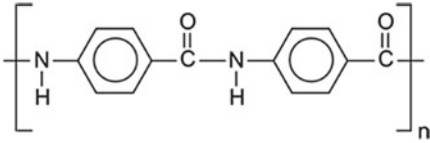
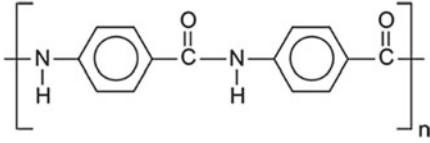
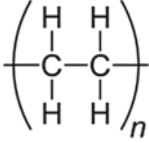
However, for military, hard body armors (HAP) are designed to stop fragments from the explosion as well as a bullet from a rifle and these are normally large and visible. HAP is made from hard ballistic materials like composites, ceramics, and/or metal plates to stop high-energy projectiles. With the advancement of technology,

the metal plates are not being preferred for HAP, and have been replaced by the composite materials.

A number of factors are considered while designing a ballistic helmet. These factors are not limited to ballistic protection but also include its fit, comfort, and weight. With increase in protection level, the helmet weight is increased, and its comfort maybe compromised (owing to burden for wearer and its heat retention). This lack of comfort urges the soldiers to take off the helmets and get themselves into danger. Therefore, the combat helmets are subjected to a series of testing including both the ballistic and non-ballistic tests. The ballistic protection ad bullet penetration are assessed in ballistic testing, while non-ballistic tests assess pad compression durability, helmet compression resistance, and coating adhesion durability.

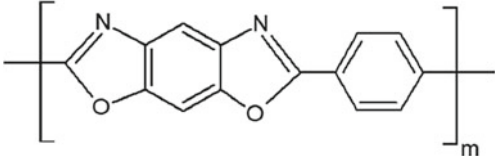
Dupont provided Kevlar fiber and in terms of ballistic helmets, it has been used in the Personnel Armor System (helmets). For just about special application Twaron (soft Aramide) is likewise used as bulletproof fabric. Twaron is a light para-amid fiber. It is really similar to Kevlar having a high impact property. Spectra fiber is likewise applied as reinforcement in existing combat helmets. Compression Molding Technique is applied for combat helmet manufacturing. The international manufacturers of combat helmets include are OPS-core Gentex, United States, Team Wendy, Cleveland, Ohio, and HHV (Hard head veterans) United Kingdom. The fibers used for ballistic protection include p-aramid (Kevlar, Twaron, etc.), Ultra High Molecular Weight Poly Ethylene (Dyneema, Spectra, etc.) and PBO (Zylon, etc.). Table 4.8 gives the properties of commercial fibers that are commonly used for the ballistic protection.

Table 4.8 Properties of fiber commonly used for ballistic protection

Commercial name	Chemical name	Properties
Kevlar by Dupont	p-aramid	 <p data-bbox="495 412 1020 566"> Low density and high tensile strength Flame retardant with self-extinguishing properties Low thermal shrinkage and excellent dimensional stability High modulus due to low elongation High toughness (work-to-break) Excellent cut resistance </p>
Twaron by Teijin	p-aramid	 <p data-bbox="495 735 991 864"> Low flammability High decomposition temperature (500 °C) Neither burns nor melts Highly crystalline and offers good chemical resistance Excellent energy dissipation properties </p>
Spectra by Honeywell	UHMWPE	 <p data-bbox="495 1033 903 1162"> Low density (less than 1 g/cm³) Specific strength 40% greater than aramid Very high initial modulus Excellent vibration damping and flex fatigue Enhanced tear and abrasion resistance </p>

(continued)

Table 4.8 (continued)

Commercial name	Chemical name	Properties
Dyneema by DSM	UHMWPE	$\left(\begin{array}{cc} \text{H} & \text{H} \\ & \\ -\text{C} & -\text{C}- \\ & \\ \text{H} & \text{H} \end{array} \right)_n$ <p>Low density (less than 1 g/cm³) High strength to weight ratio Flame retardant and self-extinguishing Faster dissipation of shock waves, and high energy absorption characteristics Biologically inert</p>
Zylon by Toyobo	PBO	 <p>Excellent strength-to-weight ratio (better than aramid) Excellent heat resistance and dimensional stability Good chemical resistance Exceptional ballistic properties</p>

References

1. E.A. Campo, Selection of polymeric materials : how to select design properties from different standards. William Andrew (2008)
2. R. Mishra J. Militky, Nanotechnology in textiles : theory and application
3. M. Matusiak, W. Sybilska, Thermal resistance of fabrics vs. thermal insulation of clothing made of the fabrics. *J. Text. Inst.* **107**(7), 842–848 (2016)
4. M. Fan, F. (Structural Engineer) Fu, Advanced high strength natural fibre composites in construction. (Woodhead Publishing, 2017)
5. A. Shrivastava, Introduction to Plastics Engineering. (Elsevier, 2018)
6. C. Lautenberger, J. Torero, C. Fernandez-Pello, Understanding materials flammability, in *Flammability Testing of Materials Used in Construction, Transport and Mining*. (Woodhead Publishing, 2006), pp. 1–21
7. J. Ernsting, Crash Impact, Encyclopedia.com. <https://www.encyclopedia.com/medicine/encyclopedias-almanacs-transcripts-and-maps/crash-impact>. Accessed 17 Aug 2019
8. D. Dubois, P. Silverthorne, E. Markiewicz, Assessment of seat belt webbing bunching phenomena. *Int. J. Impact Eng* **38**(5), 339–357 (2011)
9. D. Dubois, H. Zellmer, E. Markiewicz, Experimental and numerical analysis of seat belt bunching phenomenon. *Int. J. Impact Eng* **36**(6), 763–774 (2009)
10. AS 1753 Webbing for restraining devices for occupants of motor vehicles. (Standards Australia, 1990)
11. R.G. Vaughan, Seat belts-some aspects of compulsory wearing in New South Wales, Australia, in *Institution of Mechanical Engineers* (1977)
12. K. Singha, Strategies for in Automobile: Strategies for using automotive textiles manufacturing techniques and applications. *J. Saf. Eng.* **1**(1), 7–16 (2012)
13. D. Carr, G. Starling, T. de Wilton, I. Horsfall, Tensile properties of military chin-strap webbing. *Text. Res. J.* **84**(6), 655–661 (2013)
14. W. Fung, M. Hardcastle, Textiles in automotive engineering (2001)
15. A. Zulifqar, K. Shaker, Y. Nawab, M. Umair, D.M. Baitab, M. Maqsood, Investigation of multi-layered woven car seatbelts with optimum performance. *Ind. Textila* **68**(2), 77–82 (2017)
16. Mars Exploration Rover Mission: The Mission. https://mars.nasa.gov/mer/mission/spacecraft_edl_airbags.html. Accessed 17 Aug 2019
17. J. Stein, C. Sandy, Recent developments in inflatable airbag impact attenuation systems for Mars Exploration, in 44th AIAA/ASME/ASCE/AHS/ASC Struct. Struct. Dyn. Mater. Conf. (2003)
18. Vectran, Grasp the world of tomorrow, Kurary. <http://www.imattec.com/linked/vectran-technicaldata.pdf>. Accessed 19 Aug 2019
19. R. Nayak, R. Padhye, K. Sinnappoo, L. Arnold, B.K. Behera, Airbags. *Text. Prog.* **45**(4), 209–301 (2013)
20. Y. Nawab (ed.), *Textile Engineering: An Introduction* (De Gruyter, Berlin, 2016)
21. S.G. Kulkarni, Ballistic helmets: Their Design, materials, and performance against traumatic brain injury. *Comp. Struct.* **101**, 313–331 (2013)
22. F. Çitoğlu, B. Esi, Parachute fabric and its manufacturing process. *Int. J. Sci. Environ.* **6**(5), 3214–3224 (2017)
23. J.W.S. Hearle (ed.), *High Performance Fibers* (CRC Press, Cambridge, 2001)
24. J.G. Cook, *Handbook of Textile Fibre*, 4th edn. (Woodhead Publishing, Cambridge, 2001)
25. S.J. Eichhorn, J.W.S. Hearle, M. Jaffe, T. Kikutani (eds.), *Handbook of Textile Fibre Structure. (vol 2)* (CRC Press, Cambridge, 2009)
26. G. Song, S. Mandal, R. Rossi, *Thermal Protective Clothing for Firefighters* (Woodhead Publishing, Cambridge, 2016)
27. J. McLoughlin, T. Sabir (eds.), *High-Performance Apparel* (Woodhead Publishing, Cambridge, 2018)

28. S. Bourbigot, X. Flambard, Heat resistance and flammability of high performance fibres: A review. *Fire Mater.* **26**(4–5), 155–168 (2002)
29. Our high tech fibre. <http://www.kermel.com/en/our-high-tech-fibre/>. Accessed 28 Aug 2019
30. PBI Fiber PBI <https://pbiproducts.com/international/product/pbi-fiber/>. Accessed 28 Aug 2019
31. P. Bajaj, Flame retardant materials. *Bull. Mater. Sci.* **15**(1), 67–76 (1992)
32. TEIJIN|News/Teijin to Launch Denim-like Fireproof Aramid Fabric. https://www.teijin.com/news/2016/ebd161214_18.html. Accessed 05 Dec 2019
33. P.J. Wakelyn, Environmentally friendly flame resistant textiles, in *Advances in Fire Retardant Materials* (Elsevier Ltd, 2008), pp. 188–212
34. S. Ahmad et al., Preparation of conductive polyethylene terephthalate yarns by deposition of silver & copper nanoparticles. *Fibres Text. East. Eur.* **25**(5), 25–30 (2017)
35. C. Kallmayer, E. Simon, Large area sensor integration in textiles, in *International Multi-Conference on Systems, Signals and Devices* (2012), pp. 1–5
36. W.D. Schindler, P.J. Hauser, Antistatic finishes, in *Chemical Finishing of Textiles* (Elsevier, 2004), pp. 121–128
37. M. Stoppa, A. Chiolerio, Testing and evaluation of wearable electronic textiles and assessment thereof, in *Performance Testing of Textiles: Methods, Technology and Applications* (Elsevier Inc., 2016), pp. 65–101
38. J.H. Gibbons, Police body armor standards and testing. *United States Am Congr. Off. Technol. Assess.* **1**, 32 (1992)
39. C. Chu, Y. Chen, Ballistic-proof effects of various woven constructions. *Fibres Text. East. Eur.* **18**(6), 63–67 (2010)
40. Wilkinson (Frederick), *Battle Dress* (Doubleday & Co. Inc., Garden city, NY, 1969), pp. 64–71
41. D. Dimeski, V. Srebrenkoska, N. Mirceska, Ballistic impact resistance mechanism of woven fabrics and their composites. *Int. J. Eng. Res. Technol.* **4**(14), 107–111 (2015)
42. P. Bajaj, Sriram, B. Requirements, Ballistic protective clothing: An overview, *Indian J. Fibre Text. Res.* **22**(12), 274–291 (1997)
43. X. Chen, Textile for protection, in *Elsevier*, ed. by R.A. Scott (Woodhead publishing in Textiles, 2005), p. 531
44. P. Blank et al., Point blank introduces lightest weight body armor based on Dyneema force multiplier technology, in *Defense Update, Qadima* (2014), pp. 2013–2015
45. G. Gopinath, J.Q. Zheng, R.C. Batra, Effect of matrix on ballistic performance of soft body armor. *Compos. Struct.* **94**(9), 2690–2696 (2012)
46. G. Nilakantan, S. Nutt, State of the art in the deterministic and probabilistic ballistic impact modeling of soft body armor : filaments to fabrics, in *American Society for Composites 29th Technical Conference* (2014)
47. J. Singletary, A. Bogdanovich, 3-D orthogonal woven soft body armor. *J. Ind. Text.* **29**(4), 287 (2000)