Chapter 2
Literature Review

2.1 Tencel Fibre

2.1.1 Introduction

Tencel is an eco-friendly regenerated cellulosic fibre and is the brand name of Courtaulds Lyocell fibre used in apparel fabrics and other fashion market. The very different process routes for producing tencel fibre have led to the establishment of the new generic classification for this fibre type viz. ‘Lyocell’. Tencel is the first commercial available lyocell fibre. The establishment of tencel as a completely new fibre type has meant that fibre is not viewed merely as a replacement for cellulosic fibres but as completely separate to them and as a complement to them. It is amongst the strongest and stiffest cellulosic fibres ever produced. It is claimed that lyocell combines the advantages of both natural and synthetic fibre. It has the softness of silk, the strength of polyester, the absorbency of cotton and is fully biodegradable as well as highly durable too. When wet, it retains 85% of its dry tenacity, making it stronger in this state than cotton.

2.1.2 Historical Background

Compared to other synthetic fibre processes, manufacturing of regular viscose is associated with many environmental pollution and economic pitfalls. The environmentalists suggested identifying an alternative cellulosic fibre manufacturing process, which will be free from all sorts of pollution. With this in mind, the researchers developed the NMMO process, which is an entirely new technology for the production of cellulosic fibre without chemical reaction. The attractiveness of the NMMO process is based on the fact that no substances harmful to the environment occur and/or leave the closed production cycles, and that 99.9% of the solvent NMMO can be recycled. In 1987, Lenzing AG and former British company Courtaulds Plc had each obtained a license from Akzo Nobel (NL), a Dutch company for fibre production. The latter has owned the relevant patent since 1980, acquiring than partly from former subsidiary American Enka’s originally worked on the ‘Newcell’ project and as a result of further development carried out at the group’s Obenburg research unit in Germany. Lenzing market its fibre as ‘Lenzing Lyocell’
whereas Courtaulds used two brand names, differentiating between market sectors. For consumer apparel and textile operation, this producer’s fibre is known as Tencel; in industrial textiles and non-woven, it is called Courtaulds Lyocell. Courtaulds fibre built a production plant for 18000 ton/year Lyocell staple fibre (brand name Tencel) in 1993 at Albama/USA and one at Grimshy (UK) in 1997. But in 1998, the Courtaulds found itself in a financial bind and Akzo nobel of Netherlands bought the company. After takeover, Akzo nobel retained only Courtaulds paints division and the fibres side was bought by CVC, a private equity firm that specialized in taking over mature business, improving them and selling them on. On 4 may 2004, the CVC finance group sold its tencel fibre business to the Lenzing AG of Austria which is one of the world leading producers of man-made cellulosic fibres and at present Lenzing markets its lyocell fibres under brand name lyocell by Lenzing.

2.1.3 Spinning of Lyocell Fibre

Tencel is manufactured by a direct dissolving process using N-Methylmorpholine-N-oxide (NMMO) as the solvent.

![Figure 2.1 - N-Methylmorpholine N-oxide](image)

NMMO can be produced from N-methyl-morpholine and hydrogen peroxide in the following manner.
A cyclic tertiary amine oxide, namely NMNO (Fig. 2.1) is used to dissolve the wood pulp cellulose at 90°C-120°C under normal pressure to form stable, concentrated viscous solution of 10% - 15% concentration having a pseudoplastic behaviour. The viscous solution is then filtered so that any particle present can be removed and extruded at temperature of 120°C through spinneret into an aqueous spin bath. The filaments are usually drawn off in an air gap 40 cm long and a greater than draft ratio of 6 is recommended. The spin bath regenerate cellulose in filament form which are washed, dried, crimped and cut to form staple fibres for spinning. The NMNO loaded spin bath is purified, and the surplus water is evaporated off. The remaining concentrated NMNO is recycled into the process. The condensate is used to wash fibre and the reclaim rate of NMNO is greater than 99.5%. Fig. 2.2 shows the production route of tencel.

![Production route of Tencel](image)
2.1.4 Advantages of Solvent Spun Process over Viscose Process [6]

- Most important is that the process used is environmental friendly. Total recycling of solvent leads to a minimum level of non-hazardous waste products.
- A technological evolution shows that cellulose dissolution in NMMO is much simpler than in the viscose process since mercerization, xanthation and ripening are not required.
- The solvent process used for lyocell produces very little atmospheric emission. There are traces of volatile organic compounds associated with the solvent and the soft finish which will leave the plant in the normal course of ventilation. There is no need for any central handling or emission stack. In the viscose process, the air handling and cleaning system employed are costly and most of the emission to atmosphere are collected a discharge through tall stacks.
- The spinning and washing liquors from the viscose process are recycled to allow reuse of the sulphuric acid and zinc sulphate components wherever this is feasible from economic and environment point of view. Same like viscose process NMMO is recycled in solvent process but the viscose process require huge amount of water than solvent process.
- A technological evolution shows that cellulose dissolution in NMMO is much simpler than in the viscose process. The viscose process has a significantly larger process with complex chemistry involving several hazardous materials. The NMMO process is a physical dissolution process only and here no chemical reaction takes place. Total time for NMMO process is less than two hours, while the production cycle for viscose extends beyond 30 hours.

2.1.5 Properties of Tencel Fibre

Tencel is an eco-friendly regenerated cellulosic fibre and has all the natural properties including good moisture absorbency, comfort, luster, biodegradability and excellent coloration characteristics. The cellulose in tencel fibre has a high degree of orientation and crystallinity and a higher molecular weight. As a result, it has high strength both in dry and wet condition and only 15% loss of strength in the wet state. Exceptional wet modulus yields very low fabric shrinkage. Table 2.1 shows the tencel fibre properties in comparison to other fibre properties.
Table 2.1–Properties of tencel fibre and its comparison with properties of other fibres [7]

<table>
<thead>
<tr>
<th>Property</th>
<th>Tencel</th>
<th>Viscose</th>
<th>HWM rayon</th>
<th>Cotton*</th>
<th>Polyester</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denier</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>--</td>
<td>1.5</td>
</tr>
<tr>
<td>Tenacity (g/den)</td>
<td>4.8 - 5.0</td>
<td>2.6 - 3.1</td>
<td>4.1 - 4.3</td>
<td>2.4 - 2.9</td>
<td>4.8 - 6.0</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>14 - 16</td>
<td>20 - 25</td>
<td>13 - 15</td>
<td>7 - 9</td>
<td>44 - 45</td>
</tr>
<tr>
<td>Wet tenacity (g/den)</td>
<td>4.2 - 4.6</td>
<td>1.2 - 1.8</td>
<td>2.3 - 2.5</td>
<td>3.1 - 3.6</td>
<td>4.8 - 6.0</td>
</tr>
<tr>
<td>Wet elongation (%)</td>
<td>16 - 18</td>
<td>25 - 30</td>
<td>13 - 15</td>
<td>12 - 14</td>
<td>44 - 45</td>
</tr>
<tr>
<td>Water imbibition (%)</td>
<td>65</td>
<td>90</td>
<td>75</td>
<td>50</td>
<td>3</td>
</tr>
</tbody>
</table>

2.1.5.1 Structural Characteristics

The structural characteristics of lyocell fibres are responsible for their superior mechanical properties. Lyocell fibres have high degree of crystallinity and orientation, as well as a high average molecular mass and degree of polymerization. This enables lyocell fibres to reach high tensile strength and modulus. The ratio of crystalline to amorphous area is approximately 9:1, while the values for viscose fibre is approximately 6:1. Even in the amorphous area there is still some degree of orientation [8]. The average molecular mass of lyocell fibre is 21% higher than that of modal fibres and 63% higher in comparison to viscose fibres. The degree of crystallinity of lyocell fibre is 16% higher when compared with modal fibres and significantly higher (43%) compared to viscose fibres. Molecular orientation in lyocell fibre is highest and it exceeds the orientation factor of viscose by 18% and modal by 3% [9].

2.1.5.2 Tensile Characteristics

The tensile properties of the fibre are high strength in both the wet and dry states (Table 2.1). The fibre shows very high dry strength compared to other cellulosic, and is similar to polyester. The wet strength is particularly high and showing only a 10-15% drop in strength when wet. This is marked contrast to the other man-made cellulosic, indeed tencel is found to be the first man-made cellulosic to be stronger than cotton in wet state. The fibre has a high modulus, particularly in the wet state, and this leads to a very low shrinkage in water. In fabric terms, this
gives very low finishing losses in dyeing, and low shrinkage on laundering which makes the garments truly launderable.

The stress-strain characteristic of tencel makes it very suitable for blending with other fibre. The shape of stress-strain curve of tencel fibre (Fig. 2.3) is similar to that of cotton and is therefore able to contribute significantly to the strength of cotton blended yarns, even at low blend levels. Tencel also blends well with polyester as the stress-strain curves of both the fibres are compatible that results the yarns of high strength at any blend ratio.

2.1.5.3 Chemical Properties

Tencel degrades hydrolytically when in contact with hot dilute or cold concentrated minerals acids. Alkalis cause swelling at first (maximum at 9% NaOH solution at 25°C) and then ultimately disintegration. It is unaffected by common organic solvent and dry cleaning and can be bleached using peroxide/hypochlorite.

![Stress-strain characteristics of Tencel and other fibres](image)

Fig. 2.3 – Stress-strain characteristics of Tencel and other fibres [10]

2.1.5.4 Thermal Properties

Tencel fibres do not melt and it is stable below 150°C. Above 170°C, the fibre begins to lose strength gradually and starts to decompose more rapidly at 300°C. At 420°C, the fibre will ignite. After 80 hours exposure at 150°C, tencel remains as
strong as the unexposed cotton fibre [11]. As tencel is not thermoplastic at high temperature, this characteristic enables it to be used in many kinds of coated fabrics, from printers’ blankets and abrasive substrate to synthetic suede materials [12].

2.1.5.5 Moisture Properties [11]

Fig. 2.4 – Moisture regain comparison of tencel and other fibres [11]

The moisture absorbency of tencel fibre is high, and this means that fabric made from it provides the kind of wearer comfort normally associated with natural fibres such as cotton. The natural moisture regain of tencel is slightly higher than cotton and much greater than for synthetic fibres such as polyester (Fig. 2.4). This helps to ensure static free handling of tencel fibre, yarn and fabrics, both in processing and in use. High strength together with good moisture absorbency is an unusual combination in tencel fibre.

2.1.5.6 Fibrillation

Fibrillation means the detachment of fibrils along the fibre surface of individual fibres swollen in water, caused by mechanical stress. Tencel is composed of microfibrils that are assemblies of cellulose molecule with a very high degree of
orientation and fibrils that are assemblies of the microfibrils. Fig. 2.5 shows various orders of magnitude in structure size for the Lyocell fibre [13].

Fig. 2.5 – Proposed structure at different dimensional levels of lyocell fibres [13]

If the water contained in tencel fibre is about 10%, the fibrils are weakly connected with each other by hydrogen bonds. However, these links will cut off during wetting and the strength vertical to the axis of the fibre will be weakened. In such a condition, machine friction can easily cause fibrillation. On the one hand, fibre manufacture worked intensively to find the solution to this problem, on the other hand the fibrillation makes it possible to achieve special surface effect such as peach skin effect, sand-washed, microvelutino, soft touch, emitterized or simply the used look [14].

Though the fibrillation enables the fibres to be used in special finishes effect, but it prevents their wider use in industry. With lyocell LF, Lenzing has developed a fibre, in which the tendency towards fibrillation is suppressed by chemical cross-linking at the production stage.
2.1.5.6.1 Non Fibrillation Fibre- Lyocell LF [15]

The production process for Lyocell LF is based on the principle of cross-linking during production that result in a non fibrillated fibre (Fig. 2.6) and finisher requires no additional finishing steps to suppress fibrillation. As a result of cross-linking, we now have a Lyocell LF fibre with which it is possible to conduct processing on the machinery normally used for cellulose fibres without the occurrence of the problems we associate with fibre fibrillation. No fibrillation effects are observed on a fabric finished in an optimum manner even after repeated washing (Fig. 2.7).

Table 2.2 shows the comparative results of the fibre test of lyocell LF and standard Lyocell in which the high relative wet strength characteristics of lyocell, the high transverse strength (loop and knot strength) or the high wet modulus are documented. As a result of cross-linking, the tenacity and the elongation of the fibre are reduced.
Table 2.2 – Comparison of properties of lyocell LF and standard lyocell [15]

<table>
<thead>
<tr>
<th>Properties</th>
<th>Lyocell LF</th>
<th>Standard Lyocell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenacity cond. [cN/tex]</td>
<td>35-37</td>
<td>40-42</td>
</tr>
<tr>
<td>Elongation cond. [%]</td>
<td>9-11</td>
<td>15-17</td>
</tr>
<tr>
<td>Wet tenacity [cN/tex]</td>
<td>27-29</td>
<td>34-36</td>
</tr>
<tr>
<td>Wet elongation [%]</td>
<td>11-13</td>
<td>17-19</td>
</tr>
<tr>
<td>Bisfa wet modulus [cN/tex 5% ext]</td>
<td>9.5-10.5</td>
<td>9-10</td>
</tr>
<tr>
<td>Loop strength cond. [cN/tex]</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>Loop elongation [%]</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Knot strength cond. [cN/tex]</td>
<td>28</td>
<td></td>
</tr>
</tbody>
</table>

Fang et al. [16] also studied that cross linking treatment with polycarboxylic acids form ester bond that can effectively reduce the fibrillation tendency of lyocell fibres. Lyocell fibres treated with 5-6% 1,2,3,4-butanetetra-carboxylic acid or 13-14% polymaleic acid exhibit satisfactory fibrillation resistance properties and acceptable breaking strength loss.

2.1.5.7 Functional Properties [17]

The ability to absorb water into the fibre structure is a common feature of all cellulosic fibres and is the basis of some very important physiological properties. All cellulosic fibres show the following physiological properties to a certain extent:

- High absorbency
- Warm and dry (as an insulation layer)
- High heat capacity
- Cool and dry to touch
- Can actively reduce temperature
- Neutral electric properties
- Strongly retard bacterial growth
- Gentle to the skin

Tencel has a very high absorption capacity, a unique nano-fibril structure and a very smooth surface. As a result, all these physiological functions are much more pronounced for tencel than for other cellulosic fibres.
2.1.6 Application of Tencel Fibres

1. Apparel Fabrics: Tencel fibre exhibit unique combination of physical properties and exploitation of these properties in fabric finishing has allowed a wide variety of truly unique aesthetics to be created for high fashion apparel [18]. It has beautiful drape and is quite like silk in both appearance and feel. This versatile fiber lends itself to a broad range of men's and women's clothing styles, as well as to upholstery fabrics and home-fashions in sheets and towels. In blends, the natural qualities of Tencel complement those of wool, cotton, linen, silk, polyester, elastane and nylon, and enhance their inherent properties. Blended with wool, tencel introduces new softness and drape; blended with cotton and linen, it increases suppleness and luster. With stretchy fabrics, it leads a quality of softness and shape retention. Garments made from Tencel include pants, shirts, suits, skirts and leggings. New garment applications are being introduced with advances in fiber enhancements and blends.

2. Nonwovens: The lyocell fibres are used in a wide range of nonwovens products that require absorbency, purity, softness, strength and biodegradability. Key areas of application are wipes, medical and hygiene as well as filtration application. Within these sectors, the strong growth of the spun-laced wipes market has built but the development of short staple length fibre (below 20mm). Specifically tailored these fibres for air-laid and wet laid have also been an important area for business growth [19].

3. Carpets: For carpets manufacturing, coarse long staple tencel fibre are suited upto a titer of 15 dtex and cut length upto 150 mm. and are processed into semi worsted or woolen yarns either alone or in combination with other fibres. Tencel exhibits excellent moisture management properties that bring positive effects for room climate as well as beneficial hygiene and low static properties. Tencel fibres are inherently antiallergic, antistatic and moth proof. The cellulosic tencel fibre derives from the natural raw material wood, is produced by a sustainable process and to 100% biodegradable, thus offering a new range of ecologically friendly carpets [20].

4. Filling: The new tencel lyocell filling fibre has a star shaped cross-section which provides higher rigidity and bulkiness to the fibre along with higher fibre surface and increased moisture absorption. The new tencel fibre has perfect symbiosis with polyester and both fibres in filling allow a range of irresistible properties to
blossom. Tencel fibres retain their volume longer and lose none of their bulkiness [21].

2.2 Yarn Spinning Technology

The ring-spun yarn production method has been in use for over “150 years and is still the most widely used spinning machine all over the world at present. It seems that it will continue to dominate the long and short-staple spinning industries. The popularity of ring spinning comes from its flexibility with respect to type of material and count range, and particularly its optimal yarn structure, which results in outstanding yarn strength [22, 23]. At present ring spun yarn sets the standard against which all other yarn types are judged. Up to a few years ago, ring spun yarns were thought to have reached the ultimate perfection in the art of making yarns from staple fibers but now, rotor spinning and air-jet spinning are other spun yarn preparation systems. These spinning systems are not quite as popular as ring spinning due to the yarns being weaker, but they produces yarn at a much faster speed. Where rotor spinning is produces yarn at about 120,000 rpm, air-jet spinning produces at approximately twice the speed of rotor spinning, and is approximately fifteen times faster than the ring spinning.

The flow chart of the operations involved for converting fiber into yarn for various spinning system is shown in Fig. 2.8. Ring spun yarns can be made from either carded or combed fibers. Ring spinning is a comparatively expensive process because of its slower production speeds and the additional processes required for producing the yarns. Most of the processes for rotor spinning are the same as for ring spinning and the main difference is that rotor spinning does not require the roving and winding process. Instead, the machine spins the yarn directly from the sliver. For this reason, rotor spinning normally produces coarser count yarns than does ring. Also, as rotor spinning does not requires two additional processes when compared to ring spinning it makes rotor spun yarn less expensive to produce. Similar to rotor spinning, air jet spun yarn is a lot cheaper as it also uses fewer production stages and produces yarn with very high speed but due to the sensitivity of the air-jet machine, the sliver must be drawn three times in order to ensure uniformity.
2.2.1 Principle of Ring Spinning

In ring spinning, the roving is attenuated by means of a drafting arrangement until the required fineness is achieved, then the twist is imparted to the fine fiber strand emerging from the front rollers by the traveler, and the resulting yarn is wound onto a bobbin tube. Each revolution of the traveler inserts one turn of twist to the fiber strand. The traveler, a tiny C-shaped metal piece, slides on the inside flange of a ring encircling the spindle. It is carried along the ring by the yarn it is threaded with. Due to the friction between the traveler and the ring, and air drag on the yarn balloon generated between the thread guide and the traveler, the speed of the traveler is less than that of spindle, and this speed difference enables winding of the yarn onto the package [22, 25]. Fig. 2.9 shows the principle of ring spinning operation. The major drawbacks of this system are the relatively low production
speed, additional processes (roving and winding) required for producing yarns and difficulty of automation. In fact, the ring spinning machine accounts for 60% of total production cost in a spinning mill. The production speed of the ring spinning frame depends on the traveler and spindle speeds. In most cases the source of low production speed is the excessive heat generated between the ring and traveler due to high contact pressure during winding and the temperature of the traveler might reach more than 400 °C.

The real problem is not generation of heat, but its dissipation. Due to very small mass of the traveler, it cannot transmit the heat to the air or the ring in the time available [22, 27]. Currently, the traveler speed is limited to about 50m/s but most machines seldom exceed 40m/s [27]. Ring spun yarns are of high quality and are mainly produced in the fine (60 Ne, 10 tex) to medium count (30 Ne, 20 tex) range, with a small amount produced in the coarse count (10 Ne, 60 tex) range. End-uses include high quality underwear, shirting, towels.

2.2 Principle of Rotor Spinning

Open-end or rotor-spun yarns are created through a process that is fundamentally different from ring spinning. An illustration of this process is shown in Fig. 2.10. The sliver is completely disassembled into individual fibers, which are fed
into a rotating chamber. The fibers are individualized “by means of a small feed roller to a rapidly rotating opening roller that is covered with wire points. This opening roller detaches fibers individually from the sliver and projects them into the airstream flowing down the delivery duct. The fibers are deposited in a V shaped groove along the sides of a rotor and further these fibers are “peeled off” to join the “open-end” of a previously formed yarn. As the fibers join the yarn, twist is conveyed to the fibers from the movement of the rotor. A constant stream of individual fibers enters the rotor, is distributed in the groove, and is removed after becoming part of the yarn itself” [28]. A much thinner strand of fibers collect in the perimeter of the chamber via centrifugal force. One end of the strand of fibers is pulled from the rotating chamber, which imparts twist into the strand of fibers, creating the yarn.

Fig. 2.10 – Operating principle of rotor spinning machine [29]
As the yarn is pulled from the chamber, more fibers are randomly laid in the perimeter of the chamber. A percentage of these fibers become trapped in the yarn as it is pulled from the chamber. Because these fibers are added to the yarn after it has been partially twisted, fibers on the surface of the yarn contain less twist than those in the center of the yarn. As the yarn is pulled through the navel of the rotor, there is a great potential for the loose fiber to wrap circumferentially around the yarn. The result is a highly-twisted yarn core covered with fibers of widely varying twist angles which are partially covered by tightly bound “wrapper” fibers.

2.2.3 Principle of Air-Jet Spinning

Air-jet spinning produces yarn at approximately twice the speed of rotor spinning, and approximately fifteen times faster than ring spinning. At the time the MJS 801 was introduced, its delivery speed was 160 m/min, ten times faster than that of ring spinning [25]. Besides, it was able to spin finer yarns than the rotor system. As a result of these advantages, the MJS 801 system captured great commercial success quickly in spinning pure synthetic fibers, blends of synthetic fibers, or rich blends of synthetic with cotton fibers. However, it is not suitable for pure cotton fibers or rich blends of cotton fibers. In the late 80’s Murata introduced a new version of this system, the MJS 802 [30]. The MJS 802 contains a 4-line drafting unit and a modified nozzle which provides better fibre control and a speed up to 210 m/min was possible. The spinning process used by Murata Jet Spinner 802 is depicted in Fig. 2.11.

First a drawframe sliver passes through the drafting unit which reduces the sliver weight of approximately 200 to 1. Then the delivered fibre strand, as it leaves the nip line, passed to twin air-nozzles located directly after the drafting unit. The first nozzle imparts twist to the leading ends of the fibre while their trailing ends are still being held by the front roller. The second nozzle imparts false twist to the whole fibre bundle in opposite direction to that of the first nozzle. Because of the higher air pressure used in the second nozzle, the false twist to the fiber bundle travels back to the front rollers of the drafting unit. As the yarn comes through the second nozzle, the false twist is removed and the core fibers no longer exhibit any twist. They are arranged in parallel form and at that point the surface fibres which were twisted by the first nozzle are caused to further increase their twist by the untwisting action [23, 25].
2.3 Structural Characteristics of Ring, Rotor and Air-Jet Yarns

Yarns spun on different spinning systems have their own distinct structural characteristics and properties. The structure of yarn spun with different spinning technologies depends on the different conditions of fibres in the feed during drafting and twisting mechanism employed to manufacture the respective yarn. As these aspects of yarn manufacturing vary from one spinning technology to other, the resultant yarn spun out of different spinning systems exhibits different structures accordingly (Fig. 2.12). The structural characteristics of a yarn include fibre extent and orientation, twist structure, fibre migration and packing density of fibres which basically govern various yarn properties.
2.3.1 Ring Spun Yarn

In ring spun yarn, the twist that provides the final entanglement is built up from the outside to the inside and the twist is same across the yarn cross section. If twist is removed by untwisting on a twist tester, one may observe a parallel bundle of fibres at some part of time, indicating complete removal of twist [32]. The packing coefficient of ring spun yarns generally ranges between 0.5-0.6. The close packing is caused by the high level of tension acting on the fibres at the yarn format point. The fibre in the yarn shows a regular tendency to migrate from core to surface and surface to core. Table 2.3 shows the value of different migration parameters for ring spun yarns. The value of mean fibre positions ranging between 0.35-0.38 implying greater density of packing near the centre of yarn. Ishtiaque [33] reported that the fibre packing density across the yarn cross section is not uniform and that is not highest at yarn core. Depending upon level of twist, the mean migration intensity value, which indicate the mean rate of change of radial position, range between 0.12 and 0.49 [34].
Table 2.3 – Migration parameters in a spun rayon yarn [34]

<table>
<thead>
<tr>
<th></th>
<th>Twist factor</th>
<th>Value for complete ideal migration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.1</td>
<td>3.0</td>
</tr>
<tr>
<td>Mean fibre position</td>
<td>0.33</td>
<td>0.36</td>
</tr>
<tr>
<td>CV%</td>
<td>39</td>
<td>32</td>
</tr>
<tr>
<td>RSM deviation</td>
<td>0.17</td>
<td>0.16</td>
</tr>
<tr>
<td>CV%</td>
<td>28</td>
<td>20</td>
</tr>
<tr>
<td>Mean migration intensity (cm⁻¹)</td>
<td>0.12</td>
<td>0.17</td>
</tr>
<tr>
<td>CV%</td>
<td>32</td>
<td>24</td>
</tr>
<tr>
<td>Equivalent migration frequency (cm⁻¹)</td>
<td>0.10</td>
<td>0.16</td>
</tr>
<tr>
<td>CV%</td>
<td>25</td>
<td>23</td>
</tr>
</tbody>
</table>

2.3.2 Rotor Spun Yarn

Rotor spun yarns are well known for their peculiar three part structure namely, a densely packed core of fibres that are substantially aligned with the axis of the yarn and somewhat resembles to ring spun yarn structure, a sheath of loosely packed non migrating surface fibres which occurs irregularly along the core length, and the wrapper or belts that are wrapped around the outside of the yarn at very small inclination [35]. Lawrence and Finikopulos [36] gave a detailed study of the surface structure of rotor spun yarns and classified the yarn structure into seven classes as shown in Fig. 2.13 and Table 2.4. The effective fibre length utilized in yarn structure or the fibre spinning-in coefficient is minimum for carded rotor yarn and maximum for combed ring spun yarn [37]. The lower spinning-in coefficient for rotor yarn is also observed by Ghosh et al. [38]. They observed that the spinning-in coefficient for rotor yarn is 0.46 against a value of 0.69 for ring yarn. Further, the rotor spun yarns exhibit minima for all migration parameters as the twist level is increased whereas in ring spun yarn, all the migration parameters increases with increase in twist [39]. The packing density of the rotor yarns is generally less than the ring spun yarn and it is more near the yarn axis and less towards the outer surface of yarn. The packing is maximum at a point approximately one quarter to one third of yarn radius from the yarn axis and it increase with increase in twist [33].
<table>
<thead>
<tr>
<th>Class of surface structure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I - Ordered</td>
<td>There are no wrapper fibres; has the appearance of uniformly twisted core fibre.</td>
</tr>
<tr>
<td>Class II – Loosely wrapped</td>
<td>Loose wrapping of fibres around the core. Wrapping angles differ from the twist angle of core fibres.</td>
</tr>
<tr>
<td>Class III – Hairy</td>
<td>Surface fibres are loosely attached to the yarn and appear entangled.</td>
</tr>
<tr>
<td>Class IV – Multiple wraps</td>
<td>Part of the wrapping fibres bind the core with a high wrap angle, and part at a lower angle having direction opposite to that of the core twist.</td>
</tr>
<tr>
<td>Class V – Opposingly wrapped</td>
<td>Wrapper fibres have a warp helix in opposite direction to the core twist.</td>
</tr>
<tr>
<td>Class VI – Tightly wrapped</td>
<td>These sections of yarn appear uniformly wrapped and have few protruding fibre ends or loops. The angle of wrap is approximately 90°.</td>
</tr>
<tr>
<td>Class VII – Belts</td>
<td>Fibers are wrapped very tightly around the core at 90° in a narrow length on the order of 1mm.</td>
</tr>
</tbody>
</table>
Fig. 2.13 – Scanning electron micrographs of rotor spun yarn surface structures
[I-Ordered; II-loosely wrapped; III-Hairy; IV-Multiple wrapped; V- Opposingly wrapped; VI-Tightly wrapped; and VII-Belt wrapped] [36]
2.3.2 Air-Jet Spun Yarn

The air-jet spun is also called fasciated yarn where the central core of fibers has no twist and is wrapped by an outer zone of wrapper fibers. Lawrence and Baqui [40] classified the yarn structure into three groups, as orderly wrapped, randomly wrapped and unwrapped section (Fig. 2.14 and Table 2.5).

![Air-jet spun yarn surface structure](image)

**Fig. 2.14 – Air-jet spun yarn surface structure [40]**

**Table 2.5 – Classification of air-jet spun yarn surface structure [40]**

<table>
<thead>
<tr>
<th>Class of surface structure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I – Ribbon wrapped</td>
<td>A thin ribbon of fibers uniformly wrapped around the twistless core; the angle of wrap ranges from 40(^\circ) to 45(^\circ).</td>
</tr>
<tr>
<td>Class II – Randomly wrapped</td>
<td>Fibers wrapping the twistless core at varying angles; although most wrappers have the same helix direction, some are in the opposing direction. The class II substructure may be further divided into four groups.</td>
</tr>
<tr>
<td>Class III – Unwrapped</td>
<td>Section of yarn with no apparent wrapper fibers, in which the core appears twisted or twistless.</td>
</tr>
</tbody>
</table>

Chasmawala *et al.* [41] described the yarn structure as a comparatively straight central core of fibres held together by taught surface fibres wound helically onto the central core. They reported five different configurations of fibres in the yarn, namely core, wrappers, wild, core–wild and wrapper–wild. The fibre packing density is non-uniform throughout the yarn cross-section, with fibres mostly packed nearer the yarn
core in air-jet yarns [42]. However, the total packing coefficient, calculated as the ratio of the total area of the fibres in the cross section to the yarn cross section is maximum for air-jet yarn followed by ring and rotor yarns. Alteration in yarn structural properties occurs with changes in fibre type, and therefore with composition of the fibre blends and production speed [43]. They reported that under all experimental conditions, polyester–viscose yarns exhibited more wrappers and wraps per centimeter, larger helix angles and larger helix diameters than polyester–cotton yarns. For both blends, each of these parameters showed an ascending relationship when both the polyester content and the spinning speed increased.

2.4 Blended Yarns

Fibre blending has been a common practice in the textile industry for a long time, stimulated to a great degree by the availability of an ever increasing number of man-made fibres. Fibre blending can achieve quality product that cannot be realized using one fibre type alone. Since individual natural and synthetic fibres will vary in characteristic and quality, blending fibres of the same type from different source can be used to produce a more uniform and consistent product. It is also possible to blend different types of fibre to achieve particular yarn properties, though the blending process may be more complicated as a result [44]. Blending different fibre types can improve particular aesthetic or functional properties such as colour, feel, strength or insulation. In polyester-cotton blends, the crease resistance of polyester helps to retain fabric shape without losing the comfort characteristics provided by the cotton [45]. Clothes using such a blend are more easily laundered, dry quickly and can be ironed using a lower temperature than pure cotton. The blending of nylon and wool makes the resulting fabric stronger and more durable whilst retaining the soft feel, insulating and absorbent qualities of wool. Blending different fibre of varying price may also be important in balancing quality with cost.

2.4.1 Ring Spun Blended Yarns

Majumdar et al. [46] studied the properties of ring-spun yarns made from cotton and regenerated bamboo cellulosic fibres and their blends (50:50). They observed that the yarn tenacity initially reduces and then increases as the proportion of bamboo fibre increases whereas breaking elongation increases continuously as the proportion of bamboo fibre is increased. The yarn unevenness is found to be
maximum for 50:50 cotton-bamboo yarns and yarn diameter reduces as the proportion of bamboo fibre increases. The hairiness of bamboo yarn is much lower than that of equivalent cotton yarns and mean hair length also reduces as the proportion of bamboo increases in the yarn. The addition of bamboo fibre increases the percentage of hair in the shorter length group (3mm) and reduces the percentage of hair in longer length groups (4mm and 5mm).

Sekerden [47] also investigated the unevenness, tenacity and breaking extension of bamboo/cotton blended yarns and found that as the ratio of bamboo fibre increases in the blend, yarn unevenness decreases. However, no apparent significant effect of the percentage of bamboo on the yarn tenacity and elongation is observed. It is also noticed that there is no significant difference between the tenacity of 100% bamboo yarn and 100% cotton yarn.

In a study on the properties of acrylic-polyester blended yarn by Tyagi and Dhamija [48], it was observed that yarns spun with higher polyester content are considerably stronger and more extensible than acrylic majority yarn. Also, polyester majority yarns are more regular, have fewer imperfections, less hairy and rigid and have better abrasion resistance as compared to acrylic majority yarns but neps are more in polyester majority yarn.

Bargeron et al. [49] studied the spinning performance and yarn properties of different carded and combed cotton blended with polyester fibre. They found that longer cotton produces better results. The number of ends down decreased with increasing the proportion and length of polyester in blend with cotton. The longer polyester produced a superior yarn quality for 50% cotton-50% polyester blend but not for 75% cotton- 25% polyester blend. Yarn strength was lower for 75C-25P blends than for the corresponding 100% cotton. For 50C-50P blends, as compared to the corresponding 100% cotton, yarn strength were higher for the blends containing long polyester and equal or lower for the blends containing the short polyester.

Canoglu and Tanvir [50] investigated the yarn hairiness and other properties of polyester/cotton blended ring spun yarn for five blend ratios. They observed that a higher proportion of polyester fibre in the blend generally decreases the hairiness value (class N3) which reaches its minimum value at a polyester/cotton blend ratio of 83/17. The best hairiness value in class S3 has been reached for a polyester/cotton blend ratio of 33/67. Also, the breaking tenacity, elongation and evenness improve with increase in polyester content in the blend.
In a study on the properties of cotton-tencel and cotton-promodal blended yarns spun on ring, compact and vortex spinning system [51], it was observed that increasing ratio of regenerated cellulosic fibre content with cotton decreases unevenness, imperfection, diameter and roughness value, whereas an increase in breaking force, elongation, density and shape value is noticed.

Zurec et al. [52] studied the recovery properties of yarns made of viscose, acetate and polyamide fibre and their blends at various levels of strains and proposed the mechanics of elastic recovery of the blended yarn.

El-Shiekh [53] reported a very slow increase in elongation with small increase in polyester content, and a sudden rise when polyester content increases to more than 50% in polyester-viscose rayon blends. In very low polyester content, the tenacity and elongation were independent of blend ratio. Balasubramanian and Nerurkar [54] have reported an increase in blended yarn strength and elongation with increase in polyester content. Simpson and Fiori [55] have found that the blended yarn strength and elongation increase continuously with increase in polyester content. However, the same trend is not observed for yarn grade and imperfections, the latter decreases only when polyester content increases to more than 65%.

### 2.4.2 Rotor Spun Blended Yarn

Tyagi [56] has studied the response of acrylic-viscose blends to rotor spinning and observed that 80% acrylic-20% viscose yarns are slightly weaker and more extensible than 20% acrylic-80% viscose yarn. Also, acrylic majority yarns have lower stiffness, bigger diameter, less hairy and register higher yarn-to-metal friction. Kaushik et al. [57] during their study on acrylic-viscose rotor spun yarn observed that yarns spun with higher proportion of viscose fibre possess a marginally higher strength but have more twist loss and lower breaking extension with lower yarn irregularity.

Sett et al. [58] reported the tensile characteristics of jute blended yarn of lower count. The tensile characteristics of rotor spun blended yarn are affected by the amount of less extensible jute fibre present in the blend. In case of time-dependent viscoelastic characteristics, increasing the percentage of more rigid and less extensible jute reduce creep or stress relaxation in rotor yarn but helps to exhibits better elasticity.
Tyagi et al. [59, 60] investigated the properties of acrylic-cotton blended yarn. In comparison with cotton- majority yarns, acrylic-cotton (70:30) yarns have higher strength, breaking extension, flexural rigidity and abrasion resistance. Further, more than 50% acrylic is required for improvement in tenacity [59]. In an another study by Tyagi et al. [60], it was observed that knittability of acrylic- majority yarns is superior to that of cotton- majority yarns, although the acrylic- majority yarns are more stiffer. The knot strength ratio and loop strength ratio increases with the increase in acrylic content and additional advantage of acrylic- majority yarns are their lower twist liveliness, higher elongation, higher bulk and lower hairiness.

Barella and Manich [61] studied the relation between twist and abrasion resistance of polyester, polyester-cotton (50/50) and polyester-viscose (50/50) open end spun yarn. The abrasion resistance increases as the twist increases. Further, at low twist, there are not great difference between resistance of yarns spun with component fibres and that of blended spun yarn. But when twist is increases to $\alpha =150$-$170$, there is a clear difference between resistance of yarn spun with component of blend and that of blended yarn. The resistance of blended spun yarn is than lesser than the average calculated from resistance of yarns with the component fibres in the blend.

In a study by Sett and Sur [62] for jute-viscose blended yarns with blend ratio of 50/50 and 25/75, it was observed that the increased percentage of jute in rotor spun jute-viscose yarn results in a decrease in both its tensile strength and breaking elongation while it help to obtain an improved initial modulus. Kaushik et al. [63] found in their study on influence of twist and repeated extension of acrylic-viscose rotor spun yarn that there is a decrease in breaking strength and extension due to repeated extension of acrylic-viscose yarns. The decrease in breaking strength and breaking extension increases with an increase either in the amplitude of extension or the number of cycles, however the decreases is less marked in low-twist yarn.

The recovery properties of acrylic-cotton OE rotor-spun yarn were studied by Tyagi and Goyal [64]. They observed that immediate elastic recovery and delayed recovery decrease considerably with increase in cotton content and twist factor whereas reasonably lower cotton content and twist factor is needed to reduce permanent set.
2.4.3 Air-Jet Spun Blended Yarn

Rajamanickam et al. [65-67] carried out a very exhaustive study on fibre-process-structure-property relationship in air-jet spinning of polyester-cotton blended yarns. Apart from the different process parameters, the blend ratio used were 50:50 P/C, 67:33 P/C, 80:20 P/C and 100% polyester fibre. It was observed that as the cotton component in the blended yarn increases, the proportion of wrapper fibres decreases for both polyester and cotton fibres. Also, with the increase in the cotton component in the blend, the proportion of class I structure decreases, whereas that of the class II and class III structures increases [65]. The tenacity and breaking extension of the yarns increase with increase in the percentage of micro denier polyester fibre. The Uster value and the number of imperfections also decrease as the percentage of polyester fibre increases in the yarn [66]. Further, yarn hairiness decreases with increasing proportion of polyester fibre in the yarn and this trend is generally true for all three length of hairs studied (1, 2 and 3 mm) [67].

Regenerated cellulosic fibre (bamboo) offers significant advantage in air-jet spinning [68]. The yarns produced with high content of bamboo fibres, in general, are substantially stronger, more extensible, more regular, more hairy and have lower rigidity than the equivalent yarns produced with cotton-majority blend. Tyagi and Salhotra [69] studied the influence of process parameters and blend ratio of polyester-viscose MJS yarns and found that with the increase in polyester content in the blend, the tensile strength, breaking extension, evenness and imperfection and elastic recovery of the yarn improve but yarn become more rigid. In an another study by Tyagi et al. [70] on acrylic-cotton MJS yarns, it was observed that acrylic rich MJS yarns are considerably stronger, more extensible, more even, more rigid and yield higher abrasion resistance than the yarn with higher cotton content.

Punj et al. [71] investigated the effect of blend ratio on structure and properties of polyester-viscose blended MJS yarns. They found that with the increase of polyester fibre percentage in the mix, the breaking tenacity, breaking elongation, flexural rigidity, elastic recovery and abrasion resistance increase significantly but unevenness and imperfection have no fixed trend. Also, the results show that as the polyester proportion increases from 48% to 80%, the diameter of yarn for both wrapped and unwrapped portion increases significantly and packing diminishes owing to lack of efficient wrapping. In a study by Tyagi and Dhamija [72] for acrylic-cotton jet spun yarns, it was observed that yarns produced with high acrylic fibre content
show substantially higher bulk, abrasion resistance, flexural rigidity, tenacity and breaking extension than the yarns spun with higher cotton fibre content.

The response of polyester-viscose jet spun yarns to the repeated extension has been studied by Tyagi and Dhamija [73] by varying fibre composition and other process variables. The observation revealed that repeated extension of polyester-viscose MJS yarns causes significant losses in tenacity and breaking extension but the loss can be minimized by increasing polyester content in the fibre mix. The tenacity and breaking extension register further drop when both amplitude of extension and number of extension cycles increased.

2.5 Role of Twist in Blended Ring Spun Yarn

In general, strength initially increases with increase in twist up to a maximum and the corresponding twist being the optimal twist. This is attributed to the inter fiber frictional resistance to fiber slippage and is called the ‘coherence region’. Yarn breaks are usually the result of a combination of a proportion of the constituent fibers breaking and the rest slipping; the greater the amount of fibres breaking, the stronger the yarn. At low twist, yarn failure is mainly the result of fiber slippage. With increasing twist, yarn diameter decreases, while fiber packing and frictional contact increase, thereby enabling an increasing number of fibers to be extended to break. It is reported that about 60\% of fibers break at the peak yarn strength [74]. Beyond the optimal twist, the strength decreases with twist, resulting from a reducing contribution of the fiber modulus to the yarn modulus as the fiber helix angle becomes more oblique. Physically, this means that more of the yarn extension is being used to extend the helical shape of the fiber rather than the fiber itself. Therefore, the contribution of fiber modulus to yarn modulus decreases [75]. This latter part of the curve is termed the ‘obliquity region’.

2.5.1 Tenacity

Many researchers have carried out investigation of the influence of twist on the tensile strength of ring spun yarns. Tyagi et al. [76] investigated the influence of twist on the acrylic-polyester yarns and found that the tenacity of all yarns initially increases and then decreases with increasing the twist factor. They also find that an increase in proportion of polyester fibre raises the yarn strength owing to high tenacity of this fibre. In an another study by Tyagi et al. [77] on acrylic-polypropylene
blended yarn, it is also confirmed that there is an optimum value of twist for all yarn samples beyond which there is a fall in tensile strength. Besides, optimum twist multiplier also changes with change in proportion of different fibres in the blend. They also reported that a majority of polypropylene fibre possess a high breaking strength due to high tenacity of polypropylene fibre as compared to acrylic fibre. A very exhaustive study on the influence of twist factor on terylene-polynosic blend characteristics was carried out by Balasubramanian and Nerurkar [54]. They found that strength-twist curve are markedly different for different blended yarn with different proportion of the fibres and significantly higher strength realization is obtained with terylene. The breaking strength of the blend is lower than the weighted average at all blend proportion but the difference were slightly more pronounced at low twist indicating that the contribution from lesser extensible component improve with twist. Sreenivasan and Shankaranarayana [74] also studied the role of twist and tension on yarn characteristics and confirmed that lea strength of yarn rapidly increases with increase in twist, attaining a maximum at twist multiplier of about 5 and then decreases with further increase in twist multiplier. It was confirmed in many more studies [78-80] that there is an optimum twist factor where ring spun yarn have maximum strength followed by reduction in strength with further increase in the twist level.

2.5.2 Breaking Extension

For ring spun yarn, the breaking elongation increases continually with increase in twist. Initially the rate of increase in breaking elongation is rapid until the optimum twist is not reached and after that the increase is at much reduced rate (Fig. 2.15). Like the coherence-obliquity curves, the initial rise in extension is the result of increased inter fibre friction; as slippage between fibres decreases and more and more fibres undergo extension. But at optimum twist, as fibre breakages is maximum the corresponding reduction in radial pressures lead to increased fibre slippage and, consequently, the rate of increase in yarn extension become much lower. In case of acrylic-polypropylene blended yarn [77], the breaking extension follows the same trend as strength with yarn composition and it is low in yarns spun from higher proportion of polypropylene fibre. At low level of twist, the breaking extension increases with increase in twist.
In a study of ring and compact yarns by Tyagi et al. [81], it was found that yarns spun with 38.56 twist factor are more extensible than the yarns twisted with 33.36 twist factor.

2.5.3 Unevenness and Imperfection

The effect of yarn twist on unevenness of viscose-cotton blended yarn was studied by Ratnam et al. [82]. They found that as the viscose in the blend increases the evenness of the yarn improves. With the addition of 33% and 50% viscose in cotton, the blended yarn are 10% and 15% more uniform while all viscose yarn are 22% more uniform than all-cotton yarns. On the other hand, unevenness of all the yarns increases with increase in twist level. When the twist is low, the thick places on the yarn after leaving the front roller nip may get themselves slightly drafted because of spinning tension. But when the twist is high, it flows to the nip of the front roller at quicker rate and the tendency of the thicker place to get extended will be less and that result higher unevenness at higher twist multiplier. Simpson and Fiori [55] also conducted twist experiment on the unevenness and imperfection of cotton/polyester blended yarn and found that yarn uniformity decreases and imperfection increases as twist is increased in the yarn. The decrease in uniformity was not evident for the
35/65 cotton/polyester blend. In a study, Sreenivasan and Shankaranarayana [74] found that Uster tends to increase as the twist is increased in the yarn, whereas the variation in diameter of the yarn decreases with increase in twist. Tyagi et al. [76, 77, 78, 81] also reported in different studies that evenness of the yarn deteriorates significantly with increase in twist factor. They also reported that with increase in polyester fibre content the yarn evenness increases and imperfections decrease in polyester/silk blends [78] whereas unevenness and imperfections increase in polyester-acrylic blend [76].

### 2.5.4 Hairiness

A study by Barella et al. [83] for 70/30 and 50/50 polyester/cotton blended ring-spun yarns showed that, in general, as twist multiple increases, hairiness decreases. The “hairs” were further separated into two categories of greater or less than 3 mm and it was observed that when the twist increases, the number of hairs longer than 3 mm decreases rapidly. The number of hairs shorter than 3 mm are also affected by the twist increase, but the change is more gradual and depends on the degree of order existing in the yarn. In another study, Barella et al. [84] confirmed that hairiness decreases when twist increases and cotton have maximum hairiness whereas polyester the least. In that work, however, the hairiness of 50/50 polyester cotton blend was not situated in an intermediate position, but instead they were very close to 100% polyester yarns. In yet another studies by Tyagi et al. [76,77,85] on different blended yarns, the hairiness decreases with the increase in twist factor because high twist enables the fibres to move towards the yarn axis, resulting in firm embedment of the fibres in the main body of yarn. For acrylic-polypropylene blended yarn [77], yarns spun from higher proportion of polypropylene fibre are more hairy, whereas the yarns spun with trilobal polyester fibre are less hairy than circular polyester fibre blended with cotton and viscose fibre [85]. It was also found out by Tyagi et al. [76] that yarns spun from higher proportion of acrylic fibre in acrylic-polyester blended yarn exhibit more hairiness owing to higher bending stiffness and larger diameter of acrylic fibre. Kothari et al. [86] studied the influence of blend ratio on hairiness measured by different instrument of polyester cotton blended yarn. They observed that cotton yarn shows the maximum hairiness and polyester yarn shows the least hairiness, whereas the hairiness of blended yarns is intermediate between the two extremes set by individually fibres.
2.5.5 Flexural Rigidity

Tyagi et al. [76] studied the influence of blend ratio and twist on flexural rigidity of acrylic-polyester blended yarn and found that yarn flexural rigidity increases with increase in polyester fibre content owing to high modulus and lower bulk of polyester with respect to acrylic which give close packing and restrict fibre movement during bending. With the increase in twist the flexural rigidity of all the yarns increases owing to high inter fibre cohesion though the increase is very marginal. Kaushik et al. [87] investigated the influence of twist and fibre profile on flexural rigidity of yarn. They found that an increase in twist factor leads to a significant increase in flexural rigidity; however the increase is less for yarns spun from trilobal fibres due to lesser freedom of fibre movement. They also confirmed that yarns spun from trilobal fibre exhibit slightly higher flexural rigidity than the yarn spun from circular polyester fibres. The same result was also confirmed by Tyagi et al. [85] in a study of blended yarns containing trilobal and circular polyester fibres with cotton and viscose fibre. The presence of trilobal fibre gives more rigidity of yarn as compared to circular fiber. Increase in twist further increases the flexural rigidity of all the blended yarns. In a study, Thierron [88] reported that twist has no significant influence on the flexural rigidity of polyester-cotton ring spun yarns because a higher twist causes a lower degree of freedom of fibre movement owing to the higher radial forces in the yarn but also reduces flexural rigidity owing to higher helix angle.

2.6 Comparison of Blended Yarn Properties Spun on Different Spinning System

2.6.1 Ring and Rotor Spun Blended Yarns

Kaushik and Tyagi [80] studied the properties of polyester-viscose ring- and rotor- spun yarns and observed that tenacity and breaking extension of rotor- spun yarns are considerably lower than the ring- spun yarns, which further increase with the increase in polyester fibre content in the mix. Also, polyester-viscose rotor- spun yarns are more regular and have fewer imperfections than their ring- spun counterparts. For both types of yarns, uster % and imperfections are slightly higher for polyester- majority yarns and a decrease in polyester fibre content decreases the nep content of rotor- spun yarns. Further, polyester-viscose rotor- spun yarns possess larger diameter as compare to ring- spun yarns, which further increases with increase in polyester content. The flexural rigidity and elastic recovery of polyester-viscose
rotor yarns are considerably higher than the corresponding ring yarns [89]. In a study by Tyagi et al. [90] on acrylic-cotton blended ring and rotor spun yarns, it was found that acrylic-cotton rotor spun yarns are substantially weaker, more extensible and even, possess more optical diameter and have lower abrasion resistance than the equivalent ring spun yarns. All the properties get improved with increase in acrylic content in the fibre mix, the acrylic content in the fibre mix should be more than 50% for improvement in yarn characteristics. In a study on polyester-viscose and polyester-cotton blended ring- and rotor- spin yarns [79], it was found that for both mixes, rotor- spin yarns are slightly weaker, more extensible and have fewer imperfection and high quality index than their ring spun counterparts but yarn irregularity of polyester-viscose and polyester-cotton blended yarns show opposite trends for ring- and rotor- spin yarns. In case of polyester-viscose yarns, ring yarns are more regular whereas in case polyester-cotton mix yarns, rotor spun yarns are found more regular than their counterparts. With increase in polyester content in both fibre mix, the breaking extension and yarn quality index increase. Further, with increase in polyester content, the unevenness and imperfection of ring and rotor spin polyester-viscose and polyester-cotton blended yarn increase except the ring spun polyester-cotton yarn where decrease in unevenness and imperfection with increase in polyester content is observed.

In another study by Tyagi et al. [85], it was observed that fibre profile also plays an important role in determining the mechanical and surface properties of all-polyester, polyester-viscose and polyester-cotton yarns as evidenced by the fact that both ring and rotor yarns spun with trilobal polyester fibres have lower tenacity, high breaking extension, more twist liveliness, lower work of rupture and higher flexural rigidity. Further, lesser yarn-to-metal friction, higher dye pick-up and low hairiness are obtained for blended yarn having trilobal polyester fibre as compared to circular fibre. Also, rotor yarns are found less hairy, more rigid, less twist lively with lower frictional coefficient and absorb more dye than the equivalent ring spun yarns. However, an addition of cotton in the polyester fibre mix results in an increase in snarling propensity but decrease in dye uptake and flexural rigidity. Barella et al. [84] compared the diameter and hairiness of 100% cotton, 100% polyester and 50%-50% polyester-cotton blended yarns spun on ring and rotor spinning machines. They found that in case of ring yarns, cotton yarn is more bulky than polyester yarn but in case of rotor yarn, polyester yarn has higher diameter than cotton yarn while blends are in a
intermediate position. For both types of yarns, hairiness of 100% cotton yarn is
greater than 100% polyester and polyester-cotton blended yarns. Mohamed et al. [91]
also studied the hairiness and diameter of ring and rotor spun polyester-cotton blended
yarns and found that ring yarns have lesser diameter and more hairy as compared to
rotor spun yarn. Also, yarn becomes more bulky as percentage of cotton is increased
but slight drop at 100% cotton for both types of spun yarns. Hairiness is found to be
increase with increase in polyester content. The flexural rigidity of rotor- spun yarn is
30% higher than that of ring yarn spun from 70/30 polyester-cotton blend [88].

2.6.2 Ring and Air-Jet Spun Blended Yarns

Kaushik et al. [92] investigated the properties of polyester-viscose blended
air-jet and ring- spun yarns. In their study, they observed that MJS yarns are slightly
weaker, more even, have fewer imperfections and have higher extension, flexural
rigidity and elastic recovery. Also, the tenacity and breaking extension of all the yarns
increase with increase in polyester fibre content in the mix. In a study on properties of
polyester-viscose and polyester-cotton blended MJS and ring- spun yarns, Tyagi and
Doshi [43] observed that MJS yarns displays considerably lower tenacity, low
extension, poor abrasion resistance, higher rigidity and low elastic recovery than their
ring- spun counterparts. Further, high polyester content in the mix lead to a marked
increase in these properties, however increase is less marked in polyester-cotton than
polyester-viscose yarns. In few more studies [93, 94], it was observed that MJS yarns
are about 10 to 26% weaker, more extensible and regular as compared to their ring
counter parts, depending upon fibre composition, yarn linear density and nozzle
pressures. Thermal treatment of polyester-viscose ring and MJS yarns increases
breaking extension and yarn linear density but adversely affects tenacity, evenness
and imperfection. The decrease in tenacity is higher for MJS yarn than those of ring
yarns, and it decreases with decreasing polyester fibre content. Residual shrinkage for
MJS yarns is considerable higher than the corresponding ring- spun yarns. Also, jet-
spun yarns are more rigid than ring yarns, and yarns spun with higher viscose content
show consistent reduction in flexural rigidity. Thermal treatment under relaxed
condition results in a significant reduction in flexural rigidity [93], which is more in
jet-spun yarn than equivalent ring yarns. The response of heat treatment under relaxed
condition for polyester-viscose ring and MJS yarns was also assessed in another study
by Tyagi et al. [95] and found that heat treatment markedly decreases the rigidity of both ring and MJS yarns, but the loss in tensile strength is considerably higher.

Tyagi et al. [96] studied the performance characteristics of polyester-viscose and polyester-cotton ring and MJS yarns and observed that MJS yarns display better structural integrity, lower compressional energy, higher compressional resiliency, lower abrasion resistance and have fewer hairs than do the ring yarns. However, polyester-cotton mix with higher cotton content and trilobal polyester fibre may limit structural integrity and compressional resistance. Also, for all yarns samples, MJS yarns spun from polyester-cotton mix are more hairy as compared to the yarn made from polyester-viscose mix. The hairiness markedly reduces with increase in polyester content and use of trilobal fibre in the mix.

2.6.3 Rotor and Air-Jet Spun Blended Yarns

Bamboo-cotton air-jet spun yarns are weaker, less extensible and have better abrasion resistance than bamboo-cotton OE rotor spun yarns [97]. Each of these characteristics increases with increase in proportion of bamboo fibres in the mix. Further, bamboo-cotton air-jet spun yarns are found to be more even and contain fewer imperfections than the OE rotor spun yarns, and the yarn produced with high cotton content exhibit more unevenness and imperfection. Also, in comparison with OE rotor spun yarns, bamboo-cotton air-jet yarns are considerable more hairy and rigid, and both type of spun yarns become less hairy and rigid with increase in bamboo content in the mix. Both these properties improve with increase in bamboo content in the mix.

Acrylic-cotton MJS yarns are weaker by 20-30%, less extensible by 36-43%, less even by 20-40%, more rigid by 15-20% and having 30-42% lower abrasion resistance than the corresponding OE rotor spun yarns [98].

2.6.4 Ring, Rotor and Air-Jet Spun Blended Yarns

Ishtiaque and Khare [42] studied the structure and properties of polyester-cotton (50/50) blended ring-, rotor- and air-jet spun yarns. They observed that packing density of air-jet yarn is maximum followed by ring and rotor yarn. Yarn tenacity is found to be maximum for ring yarn followed by air-jet and rotor yarn, whereas breaking elongation is maximum for air-jet yarn followed by rotor and ring yarn.
Also, polyester tends to induce inward migration and cotton induces outward migration.

Nikolic et al. [99] compared quality parameters of polyester-cotton blended ring-, rotor- and air-jet spun yarns (Fig. 2.16). The highest value of the quality parameter is located at the circular line and it diminishes as it approaches the centre of circle. The comparison of eight quality parameters shows that the air-jet spun yarn line approaches the circle line the most and therefore indicating that it has the best overall performance of the three yarn types. The values in figure are not absolute, but relative to the sequence of decreasing values.

![Fig. 2.16 – Comparison of ring, rotor and air-jet spun yarns [99]](image)

2.7 Structure–Property Relationships of Staple Spun Yarns

The properties of staple spun yarns are strongly related to their structural characteristics. This can be best understood by comparing the distinctive structural differences of the yarns produced by the four staple spinning systems of most commercial importance: ring, rotor, friction and air-jet spinning [100]. Ring yarns
provide a unique combination of structural features that contribute to a consistently higher yarn tenacity that is not possible with any other yarn structure. This unique combination of structural features is made up of the greatest proportion of straight and parallel fibres a high level of migration, and a reasonably high packing density. These structural features permit the greatest translation of fibre-to-yarn strength (i.e. fibre strength utilization). Rotor and friction spun yarn strengths range from weaker to much weaker than that of ring spun yarn, depending on the fibre and processing parameters used. The yarn structural features responsible for lower yarn strength are as follows: in the case of rotor spun yarns, disoriented and folded fibres in the core, lower fibre packing, non-load-sharing wrapper fibres, and a low level of migration; and in the case of friction spun yarns, the presence of highly disoriented and folded sheath fibres as well as a low degree of fibre packing in the yarn core. As described earlier, air-jet yarns have surface fibres tightly wrapped around a core of parallel and straight fibres which generate sufficient radial pressure on the core fibres to give a better translation of fibre-to-yarn strength than in rotor or friction spun yarns. Changes in yarn properties with various process parameters have therefore been explained by the changes in the structural parameters [40]. Rajamanickam et al. [101] formulated a computer simulation model for the prediction of yarn strength from various parameters, including the number of wrapper fibres, the wrapping angle and the length of structural classes. Basu [102] observed that the physical properties of air-jet yarns are correlated with structural parameters. Chasmawala et al. [41] derived equations for air-jet spun yarns in which the yarn structure has been related to yarn properties.

Air-jet yarns are least extensible due to an untwisted core of straight and parallel fibres comprising 90% of the population. In comparison with ring spun yarns, rotor spun yarns have a higher breaking elongation, though it is lower than that of friction spun yarns. The large proportion of hooked and disordered fibres in the sheath and the low tension used during friction spinning tend to make the structure less dense and more extensible. The unique combination of yarn structural features responsible for the higher breaking elongation of rotor spun yarns is a higher incidence of hooked and disoriented fibres in the structure and a low level of spinning tension.

Abrasion resistance is often considerably higher for rotor spun yarns than for ring spun yarns, presumably due to surface fibre configurations. However, comparing air-jet and ring spun yarns, the former is inferior in terms of abrasion resistance. The
reason is that with air-jet yarns, the wrapper fibres do not adequately shield the yarn core, and consequently this leads to its early exposure to abrasion. Ring spun yarns, on the other hand, are spun under the highest level of spinning tension, and there are no hooked fibres in the structure, but the helical arrangement of fibres is a highly significant factor in determining yarn breaking elongation during abrasion.

It is generally recognized that air-jet spun yarns display higher bending rigidity (i.e. specific rigidity) than the equivalent yarns spun on other spinning systems. The clustering effect of core fibres due to the parallel arrangement and tightly wound binding fibres restricts the freedom of fibre movement during bending. Rotor spun and friction spun yarns are more rigid structures than ring spun yarns because of their compact core and large diameters. In the case of ring spun yarns, the helical fibre arrangement is a contributing factor to the lower bending rigidity. Park and Oh [103] reported that the yarn bending rigidity depends upon the bending and torsional rigidity of its constituent fibres, the arrangement due to twist and the geometrical parameters such as helix angle.

2.8 Prediction of Blended Yarn Quality

Various researchers have studied the properties of blended yarn and have observed that, in general, the strength of blended yarns is considerably lower than one might expect from strength of the components fibres. The first theoretical work published which concern the mechanics of blended yarn was given by Hamburger [104]. He was concerned with the fact that the blended yarns have breaking strengths lower than those expected from the summation of the proportioned constituent fiber component strengths. Considering the two components A and B (with A representing viscose and B representing polyester), having independent load elongation curves and to be under tension in parallel, he predicted the behaviour of the blended yarn from the tensile behaviour of its components. The tensile behaviour of the viscose and polyester fiber used in his study is shown in Fig. 2.17.

For a blended yarn, the tensile resistance will correspond to the weighted average of the tensile resistance of the two components of blend up to the limit of strain, at which the less extensible component A failed. At strains beyond this point, yarn resistance is corresponds to the resistance of the unbroken component. Thus a blended yarn was expected to have two breaking points - one for its less extensible
component and the other for its more extensible one. The breaking strength of the blend was reported as the higher of these two values.

Fig. 2.17 – Stress-strain curves of viscose and polyester fibers [104]

The first rupture level would be maximum for a yarn made of 100% of fiber A, and its minimum would occur in a yarn containing no portion of fiber A. The first rupture point would never fall to zero in the absence of component A. Similarly, the second rupture level will be maximum for a yarn containing 100% of fiber B and would be minimum for yarns containing less or no portion of fiber B. The solid lines of Fig. 2.18 reflect the generally reported variations of breaking strength with blend levels. In general the first and second ruptures are as given below Eq. (2.1) and Eq. (2.2):

\[
P_1 = \frac{bD}{100} (aS_A + bS_B) \tag{2.1}
\]

\[
P_2 = \frac{bD}{100} S_B \tag{2.2}
\]

Where, \( P_1 \) = first rupture; \( P_2 \) = second rupture; \( D \) = total yarn denier; \( S_A \) = breaking tenacity of fiber A; \( S_B \) = breaking tenacity of fiber B; and \( a \) and \( b \) are weighted ratios of fiber A and B in the yarn [104].
Kemp and Owen [105] investigated the stress-strain characteristics and cotton fiber breakage during tensile failure of a series of nylon/cotton blended yarns. At strains above the breaking strain of all cotton, the stress-strain curve of the 60/40 and 80/20 nylon/cotton blended yarns did not follow the predictions of Hamburger, nor did the plot of yarn tenacity versus blend ratio produce a linear relationship as predicted by Hamburger [104]. They developed a similar equation in the form Eq. (2.3):

\[ \sigma_y = \left( \frac{y}{100} \right) \sigma_n + \left( 1 - \frac{y}{100} \right) \sigma_c \]  

(2.3)

Where, \( \sigma_n \), \( \sigma_c \) and \( \sigma_y \) are the stresses in the nylon, cotton, and nylon/cotton blended yarns containing ‘y’ percent of nylon. The predicted values fit the experimental values up to 7.5% strain level. The cotton fibers contribute to an amount of \( \sigma_{cf} \) to the blended yarn stress over the rupture strain of the all cotton yarn, so the cotton contribution \( \sigma_{cf} \) estimated by modifying the above equation to the form Eq. (2.4):

\[ \sigma_{cf} = \left[ \sigma_y - \left( \frac{y}{100} \right) \sigma_n \right] / \left( 1 - \frac{y}{100} \right) \]  

(2.4)
The cotton fibers in the blended yarns sustain a high stress at strains above which all cotton yarns break. This stress, in fact rises considerably above the breaking stress of all cotton yarns. They have found that at high strains, the cotton fibers often broke more than once [105]. Owen presented a scheme for predicting the tensile properties of blends. The scheme requires; the single-fiber stress-strain curves for each component & the stress-strain curves for yarns spun from 100% of each component of lower breaking strain. The methodology used was primarily graphic, but it produced predictions that agreed reasonably well with the experimental results [106].

Monego and Backer [107] investigated the mechanics of rupture of cotton-polyester blended yarn to explore the reinforcing mechanism of fibre blending and the effect of twist-generated interactions of the different constituent fibres. They have made a fair comment on the prediction of early rupture, multiple rupture, partial rupture and catastrophic rupture in different cotton-polyester blended yarn with variable twist.

Machida [108] carried out the most extensive experimental investigation on the mechanics of rupture of blended yarns. His investigation was concerned with the transfer of stresses from low elongation fiber component to the high elongation fiber component. He produced gross-model yarns consisting of ninety-one component yarns twisted, without migration, in five helical layers about a central core yarn. In many models the occurrence of a break in one cotton element was accompanied by breaks in adjacent cotton element across a narrow zone of rupture. This occurrence was dependent on the direct contact between elements and sufficient lateral pressure to transmit the forces on the first element to the other elements. If the cotton elements were sufficiently congregated, propagation of element rupture across a narrow zone caused failure of the entire model at strains lower than those sustained by uniformly blended models. His observation also claims that at low twist level, the low elongation components “dropped out” (slipped) after they started to rupture. As a result, at strains above the breaking strain of the low elongation component, the yarn properties became highly dependent on the properties of the high elongation component.

Shiekh [53] studied the various properties like tenacity, elongation, initial modulus, dynamic modulus of polyester/viscose blended yarns by using different blend proportions. He compared the experimentally observed tenacity values with the values predicted from the mixture theory proposed by Hamburger. Here the
agreement appears to be fairly good at the extreme points, but appreciable differences are present at the transition regions, as shown in Fig. 2.19. The reason for this discrepancy was explained by Kemp and Owen [105] and later by Machida [108], to be due to the multi-breakage of the low elongation components. The effect of twist is to lower the percentage of high tenacity fiber (polyester) in the yarn, at which the blended yarn strength starts to increase. At this critical percentage the yarn has its lowest tenacity. The effect of blend levels on elongation follows the prediction of Hamburger at high twist levels. At low twist level, however, the elongation at break is independent of the blend level, where the yarn elongation is mainly due to the fiber slippage rather than fiber extension. The modulus of blended yarn has been thought to follow the mixture theory as given below Eq. (2.5):

\[
E_b = \frac{a E_A + b E_B}{a + b}
\] (2.5)

Where, \(E_b\) is the modulus of the blended yarn; \(E_A\), modulus of yarn made of 100% fiber \(A\); \(E_B\), modulus of yarn made of 100% fiber \(B\); \(a\), fraction of fiber \(A\) in the blend; \(b\), fraction of fiber \(B\) in the blend.

![Fig. 2.19 – Effect of blend level on yarn tenacity; comparison of theoretical and experimental results [53]](image-url)
The experimental result showed an abnormal trend, where the modulus has a consistent maximum value at the 10% level of polyester (low modulus fiber). This could be due to a sudden increase in the drafting forces at this level, but the relative measurements of the drafting forces of the ten blends were made on a cohesion tester proved that the drafting forces increased with increasing the percentage of polyester component. The increase of modulus at 10% polyester probably could be due to fiber clustering in the yarn cross-section [53].

Pan and Postle [1] gave a theoretical analysis of interfibre interactions and their effect on the strength of blended yarns. They explained that the blended yarn strength $\sigma_y$ is a statistical variable with a normal distribution function as $\sigma_{y1}$. Its distribution parameters i.e. $\bar{\sigma}_y$, the average strength of blended yarn and $\theta_{y}^2$, the variance of yarn strength can be calculated as Eq.(2.6) and Eq.(2.7):

$$\bar{\sigma}_y = \eta_q \left( V_1 + V_2 \frac{E_{f2}}{E_{f1}} \right) \left( l_{c1} \alpha_1 \beta_1 \right) \frac{1}{\bar{\beta}_1} \exp\left(-\frac{1}{\bar{\beta}_1}\right)$$  \hspace{1cm} (2.6)

$$\theta_{y}^2 = \eta_q^2 \left( V_1 + V_2 \frac{E_{f2}}{E_{f1}} \right) \left( l_{c1} \alpha_1 \beta_1 \right) \frac{2}{\bar{\beta}_1} \left[ \exp\left(-\frac{1}{\bar{\beta}_1}\right) \right] \left[ 1 - \exp\left(-\frac{1}{\bar{\beta}_1}\right) \right] \cdot (a_1 N)^{-1}$$  \hspace{1cm} (2.7)

Where, $\eta_q$ is called the orientation efficiency factor; $V_1$ & $V_2$, fiber volume fractions of type 1 & 2; $E_{f1}$ and $E_{f2}$ are the tensile modulus of type 1 & 2 fibers; $l_{c1}$ is the fiber length; $\alpha_1$ and $\beta_1$ are the scale & shape parameters of fibers respectively; $a_1$ and $N$ are the number proportion of fiber 1 and total number of fibers respectively. So the density function of the blended yarn strength can be expressed as Eq. (2.8):

$$H(\sigma_y) = \frac{1}{\sqrt{2\pi\theta_y}} \exp \left[ -\frac{(\sigma_y - \bar{\sigma}_y)^2}{2\theta_y^2} \right]$$  \hspace{1cm} (2.8)

If we accept the hypothesis on estimating the maximum range of statistical distribution, based on this normality of the strength distribution, there is a 99% chance that the actual blended yarn strength will fall in to the range of $\bar{\sigma}_y \pm 3\theta_y$, i.e.

$$\sigma_y = \bar{\sigma}_y \pm 3\theta_y$$  \hspace{1cm} (2.9)
He also quantified the strength hybrid effect by a new parameter $\vartheta_y$, which predicts the deviation of the actual yarn strength from the strength predicted by the Rule of Mixture. This can be expressed as Eq. (2.10):

$$\vartheta_y = \left( \frac{l_{c1}}{l_f} \right)^{-\frac{1}{\varphi_1}} \quad \text{(2.10)}$$

Where, $l_{c1}$ is the critical fiber length and $l_f$ is original fiber length [1].

Three major variables, i.e. the blend ratio $a_1$, the yarn strain $\varepsilon_y$ and the fiber modulus ratio $\frac{E_{f2}}{E_{f1}}$, are found to be the most important ones which, along with the yarn twist level, determine the value of the parameter $\vartheta_y$ when the fiber types are given. Fig. 2.20 shows the effect of the blend ratio $a_1$ at a given yarn strain and four yarn twist levels.

As the blend ratio $a_1$ increases, the hybrid effect coefficient $\vartheta_y$ increases monotonically. This means that increment of fiber with low breaking extension will enhance the hybrid effect. It is also interesting to see that although there is also an optimal yarn twist level at which the hybrid effect $\vartheta_y$ will get its maximum value, this optimal twist level is not the same as the optimal value for yarn strength, i.e., the two optimal levels do not coincide. The twist level which leads to the highest yarn strength does not yield the highest hybrid effect.

Fig. 2.20 – Relationship between the parameter $\vartheta_y$ and the blend ratio $a_1$ at four yarn twist levels
Furthermore, Fig. 2.20 also shows that the $\theta_y$ value is higher in the unblended yarn made of low extensible fibers than of high extensible fibers, indicating that the protection function due to the lateral interaction between fibers works more efficiently for low extensible fibers.

Fig. 2.21 provides the effect of the yarn strain at a fixed blend ratio $a_1 = 0.5$ and four twist levels. Not surprisingly, $\theta_y$ is 1, meaning no 'hybrid effect', when there is no strain on the yarn, a further evidence that this 'hybrid effect' is due to the lateral interaction induced by extensional strain. As the yarn strain rises however, the $\theta_y$ value increases as well. Naturally, twist plays an important role in this process since as expected the 'hybrid effect' will also disappear when there is no twist in the yarn. Again, the existence of an optimal twist level is shown in the Fig. 2.21.

![Graph showing the relationship between $\theta_y$ and $\varepsilon_y$ at different twist levels.]

Fig. 2.21 – Relationship between the parameter $\theta_y$ and the yarn strain $\varepsilon_y$ at four yarn twist levels

Fig. 2.22 is constructed taking the fiber modulus ratio $\frac{E_{f2}}{E_{f1}}$ against the $\theta_y$ value. When the modulus ratio is small, meaning small dispersion between the fiber tensile moduli, the hybrid effect is small. Increasing $\frac{E_{f2}}{E_{f1}}$ leads to a greater $\theta_y$ value. This is not difficult to understand since for fiber types of given strengths; a larger value corresponds to a bigger difference between the breaking strains of two fiber types, and consequently a more significant hybrid effect.
Pan and Chen [2] explained that, in a blended system or mixture, the overall properties of the system are related to the proportion and corresponding properties of each component. If the mixture is not uniform, the distribution or local concentration of each constituent plays an important role in determining some aspects of the system’s behaviour. The remaining factor has to do with the interactions of the components themselves, which complicate an otherwise much simpler relationship between the blend system and its component properties.

Fig. 2.22 – Relationship between the parameter \( \vartheta_y \) and the fiber modulus ratio \( \frac{E_{f2}}{E_{f1}} \) at four yam twist levels

Many properties of a material mixed or blended from two or more different components can be calculated using the simple rule of mixture (ROM); such properties include the elastic moduli, electrical and thermal conductivities, dialectical constant and thermal expansion coefficients. However, there are other properties of a material, like its overall strength or elastic lifetime, which are influenced by the interaction of the different components in the system and therefore, cannot be accurately predicted by the simple ROM. If we have a mixture of two different constituents, type 1 and 2 in general, the system property \( X_s \) can be calculated by a general ROM as Eq. (2.11):

\[
X_s = X_1 W_1 + X_2 W_2
\]  

(2.11)
Where, $X_i$ and $W_i$ are the corresponding property and the volume fraction respectively. If the interaction between components is proposed, the simple model (ROM) can be written as

$$X_S = X_1W_1 + X_2W_2 + IW_1W_2$$

$$= X_1W_1 + X_2(1 - W_1) + IW_1(1 - W_1),$$

(2.12)

and $I$ is a coefficient representing the intensity of interactions of the two constituents. There are three cases based on the value of $I$: for $I > 0$, the interactions of the constituents 1 and 2 will enhance the overall system property and lead to a synergetic effect; $I < 0$ represents a case where the interactions actually reduce system property and $I = 0$ means that the interaction does not exist, so that the Eq. (2.12) degenerates into the simple ROM. The expression for $I$ can be written as:

$$I = 4X_{50\%} - 2(X_1 + X_2) = 4[X_{50\%} - 0.5(X_1 + X_2)]$$

$$= 4[X_{50\%} - \langle x \rangle] = 4\Delta X$$

(2.13)

Where, $X_{50\%}$ is the actual system property $X_S$, when the $W_1 = W_2 = 0.5$ and $\langle x \rangle = 0.5 X_1 + 0.5 X_2$ are the arithmetic mean of the property for homogeneous constituents composed of $X_1$ and $X_2$ alone. If there are no interactions of the two constituents, there will be $X_{50\%} = \langle x \rangle$, so that $\Delta X = 0$ and $I = 0$.

Marom et al. [3] explained that the alteration of the system’s overall properties caused by the interaction of the different constituents can be specified by using the concept of hybrid effect which is defined as the deviation of behavior of hybrid structure from the ROM. A positive hybrid effect means the synergetic case, and the actual property is above the ROM prediction, whereas a negative hybrid effect means the property is below the prediction. Therefore, numerically the value of $\Delta X$ can be used to indicate the hybrid effect and can be written from Eq. (2.13) as:

$$\Delta X = X_{50\%} - \langle x \rangle = X_{50\%} - (0.5X_1 + 0.5X_2)$$

(2.14)

The Eq. (2.12) can be normalized to eliminate the effect of twist as follows Eq. (2.15):
The more efficient way of normalizing the Eq. (2.12) to eliminate the effect of twist to develop the relationship between relative tenacity and blend ratio is as follows Eq. (2.16):

\[
X_{sn} = \frac{X_5}{X_2} = \frac{X_1}{X_2} W_1 + \frac{I}{X_2} W_1 (1 - W_1) + \frac{I}{X_2} W_1 (1 - W_1)
\]

\[
X_{50\%} = \frac{X_5}{X_{50\%}} = \frac{X_1}{X_{50\%}} W_1 + \frac{X_2}{X_{50\%}} (1 - W_1) + \frac{I}{X_{50\%}} W_1 (1 - W_1)
\]

\[X_{50\%}\] includes the effect of both twist and interactions, the model indicated good correlation with the practical observations. The nature and results of the interactions of different fiber types are determined by their properties, such as the tensile modulus. The increase in modulus ratio leads to increase in interaction effect [1].

Aghasian et al. [109] investigated the interaction between blended rotor-spun yarns of cotton and polyester fibre using the hybrid model. The value of interaction coefficient is show in Table 2.6.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Elongation</th>
<th>Tenacity</th>
<th>Work of rupture</th>
<th>Elastic modulus</th>
<th>Thick place</th>
<th>Thin place</th>
<th>Nep</th>
<th>Hairiness</th>
<th>Uniformity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mm)</td>
<td>(cN/tex)</td>
<td>(N mm)</td>
<td>(cN/tex)</td>
<td>(km⁻¹)</td>
<td>(km⁻¹)</td>
<td>Nep</td>
<td></td>
<td>U %</td>
</tr>
<tr>
<td>(I)</td>
<td>4.84</td>
<td>-0.34</td>
<td>-30.427</td>
<td>-25.805</td>
<td>0.366</td>
<td>-0.061</td>
<td>3.27</td>
<td>-0.088</td>
<td>0.008</td>
</tr>
<tr>
<td>(\langle x \rangle)</td>
<td>19.64</td>
<td>2.384</td>
<td>41.15</td>
<td>366.6</td>
<td>3.68</td>
<td>2.45</td>
<td>1.78</td>
<td>1.506</td>
<td>2.425</td>
</tr>
</tbody>
</table>

It can be clearly observed from the Table 2.6 that \(I\) is positive for elongation, thick places, nep and uniformity and negative for tenacity, work of rupture, elastic modulus, thin places and hairiness. It is further concluded that interaction between cotton and polyester fibres have no significant effect on elongation and thin place and hence these parameters can be calculated from the ROM model. But for other properties there are significant negative or positive interaction and these properties cannot be accurately predicted from simple ROM.