CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter is concerned with the literature review on weft-knitted fabrics with reference to some selected areas. Since a voluminous amount of literature is available, this review will be somewhat biased towards certain topics. A considerable amount of work has been carried out on spirality, physical and mechanical properties, handle and pad batch method of dyeing of weft-knitted fabrics. This survey is based upon an intensive search of the journals published on textile technology. Articles from other sources are also included, and the subject is reviewed under different captions.

The concern of previous workers with the above aspects namely, spirality, physical properties of weft-knitted fabrics, handle and mechanical properties is reflected in the following literature review.

2.2 SPIRALITY

The subject of spirality has attracted the attention of many research workers. Table 2.1 shows the summary of research work on the spirality of single-jersey fabrics from 1934 onwards. Davis et al. (1934, 1935) investigated this problem in weft-knitted fabrics produced from wool yarns, and found that the incidence was higher for crossbred yarns than those of botany yarns of the same characteristics. It was possible to correct this
Table 2.1 Summary of research work on the spirality of single-jersey fabrics from 1934 onwards

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Author/s</th>
<th>Year</th>
<th>Types of yarns</th>
<th>Variables used</th>
<th>Conclusions</th>
</tr>
</thead>
</table>
b) Courses per inch  
c) Steam set  
d) Water set  
e) Reverse twist  
f) Two ends of same twist  
g) Doubled yarns | Spirality is prevented by setting and water setting is effective - will not be evident if the single yarns have equal and opposite twists. Suitably balanced two-fold yarns lead to fabric free from spirality. |
| 2.     | Davis and Edwards | 1935 | Cotton : 1/8", 1/16", 1/32"  
Needle : Latch, bearded needle | a) Twist  
b) Courses per inch  
c) Different machines  
d) Yarn mercerisation | Spirality increases with the fineness of the machine gauge; mercerisation is more efficient. |
| 3.     | Centre de Recherches de la Bonneterie | 1969 | Unknown | Steaming or conditioning of yarns | This treatment reduces the angle of spirality, but does not eliminate it. |
R55/2 tex ST  
R55/2 tex ST | Knitting tension varied from 0 to 600 mN | Opines that yarn tension plays a crucial role; spirality can be reduced by increasing the cover factor, reducing the yarn twist or steaming the packages of yarn before knitting. |
| 5.     | Lord, Mohamed and Ajgaonkar | 1974 | P/C yarns : Ring and Rotor  
Ring and Rotor  
Ring and Rotor | Percentage of polyester varying | Increase in polyester percentage increases the spirality of fabrics. Rotor yarns lead to a reduction in spirality. |
| 6.     | Chow                | 1976 | Unknown | Torque and spirality |                                                                        |

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### Table 2.1 Contd....

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<tr>
<td>7.</td>
<td>Harrowfield</td>
<td>1981</td>
<td>Woollen: 37, 74, 111 tex</td>
<td>Twist factor 20-65</td>
<td>Suggests that a reference curve could be provided to predict ply twist required to produce plain knit free from spirality given only the single twist factor.</td>
</tr>
<tr>
<td>8.</td>
<td>Bennett and Postle</td>
<td>1981</td>
<td>Woollen: 37, 74, 111 tex</td>
<td>Twist factor 20-65</td>
<td>Criticise Harrowfield's work that the cover factor of his fabric is 11.7 tex cm⁻¹.</td>
</tr>
</tbody>
</table>
  b) Effect of Coulier region  
  c) Effect of Coulier angle  
  d) Effect of the sinker ring setting  
  e) Effect of knitting direction  
  f) Effect of stitch length  
  g) Effect of fabric take-down  
  h) Effect of yarn twist  
  i) Effect of the snarling tendency  
  j) Effect of yarn doubling  
  k) Effect of using monofilaments  
  l) Effect of twisting of monofilaments  
  m) Use of viscose filament yarn with twist  
  n) Effect of neutral twist in the yarns | 1) Rotating the knitting machine has no effect on the spirality  
  2) Stitch density affects the skew  
  3) Yarn twist has the greatest effect on skew  
  4) Cottons of different classes do not seem to have any effect on the spirality  
  5) Stiffer yarns cause a more pronounced skew  
  6) Steaming the cotton yarns reduce the skew.  
  7) “S” and “Z” twisted yarns are knitted as plated, the skew is zero.  
  8) Opine that neutral twist yarn construction can bring down skew but this is expensive |
Table 2.1 Contd.

<table>
<thead>
<tr>
<th>Sh. No.</th>
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<tr>
<td>10</td>
<td>Alabian</td>
<td>1986</td>
<td>Rotor yarn</td>
<td>1) Effect of gauge 2) Effect of twist</td>
<td>Loop shape, twist liveliness, slackness of construction, openness of machine</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Twist factors</td>
<td>Machine dia: 3.5 in, Gauge: 14, 16, 18, 20</td>
<td>all influence spirality</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rotor, friction, air jet</td>
<td>Yarns were given as: Cotton P/C 50:50, 100% cotton, PVA (polyvinyl alcohol)</td>
<td>Twists lively yarns have to be knitted as tight as possible on a machine of finest possible gauge.</td>
</tr>
<tr>
<td>11</td>
<td>De Araujo and</td>
<td>1989</td>
<td>Cotton yarn</td>
<td>1) Effect of gauge 2) Effect of twist</td>
<td>Loop shape, twist liveliness, slackness of construction, openness of machine</td>
</tr>
<tr>
<td></td>
<td>Smith</td>
<td></td>
<td>Machine dia: 3.5 in</td>
<td>Gauge: 20</td>
<td>all influence spirality</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cotton P/C (18-36%)</td>
<td>Yarns were given as: Cotton P/C 50:50, 100% cotton, PVA (polyvinyl alcohol)</td>
<td>Twists lively yarns have to be knitted as tight as possible on a machine of finest possible gauge.</td>
</tr>
</tbody>
</table>

1) Rotor spun and air jet yams produce fabrics with a low degree of spirality.
2) Friction spun yarn from 100% cotton produced high degree of spirality.
3) P/C 50 : 50 have a lower tendency to produce spirality than 100% cotton.
4) With air jet and rotor 50/50 blend, no spirality was noticed. While ring spun produced maximum spirality.
5) Wet hot treatments reduce spirality.
6) Multifeed circular knitting machines rotating counter clockwise will produce wales inclined to the right and machines rotating clockwise will produce wales inclined to the left.
7) Three-thread fleece fabrics can be knitted with substantially reduced spirality using yarns with different twist directions as the binder and ground yarns.
Conclusions

1) Theoretical investigation confirms the presence of a twisting couple in the yarn leads to spirality.  
2) Spirality can be reduced by using a surface twist or increasing the gauge with a high tightness, preferably with \( d > 0.06\).

Spirality is affected by twist liveliness.

Review on spirality in single jersey fabric:

1) Spirality is found to be high in fabrics knitted from staple core yarn compared to 100% ring spun yarns.  
2) Spirality tends to decrease with wet processing for both the types.  
Spirality of knitted fabric from OE is 3.75° as against 9.25° for ring spun yarn.

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<tr>
<td>12</td>
<td>Hepworth</td>
<td>1991</td>
<td>Spirality - theoretical investigation</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>Primentas</td>
<td>1991</td>
<td>Cotton</td>
<td>Twist liveliness, fabric tightness factor, moisture and washing</td>
<td>Spirality is affected by twist liveliness</td>
</tr>
<tr>
<td>14</td>
<td>Lau, Theo and Dhingra</td>
<td>1995</td>
<td>Spiral Core-yarn and cotton ring spun yarns, 3.5 (88.9 mm) 20 gauge single feed jersey knitted</td>
<td>Direction of twist and processing conditions such as scour, wash</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>Kimmel and Sawhney</td>
<td>1995</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
temporarily by treatment of the fabric in the steam press. Water-setting was found to be more effective than steam-setting. By using two yarns having equal and opposite twists, this effect can be eliminated, and also by suitably balanced two-fold yarns.

They found that the direction of rotation of the cylinder had only a negligible effect on the spirality. The findings of Davis et al. (1934) are interesting but one criticism may be that the knitted fabrics have been produced with a cylinder of 3¾" diameter which means that the fabrics may be suitable for hose; the samples were obviously given dry relaxation treatment, and setting treatments were given to yarns, they being water and steam setting. This work on spirality is a very useful one, and no doubt paved way for many workers to pursue their research in this area. Spirality is a regular deformation of the structure caused by each loop twisting over to approximately the same angle. The angle between the wales and courses is less than 90°, and when the angle is less than about 83° the distorted appearance of the structure is very obvious and the merchandise is likely to bring customer complaints. Spirality is due to 'twist liveliness', the release of torsional potential energy in the yarn. The result of the section of yarn in each loop trying to move to a state of lower strain under the constraint of forces from neighbouring loops is for the loop to twist over. This phenomenon may be seen when the fabric is produced from singles yarns which have not been properly set, or from unset two fold yarns which do not have the balancing ratio of singles twist to folding twist. Structural defects in plain-knitted fabrics consist of "spirality" and "cockling". Cockling is defined as "an irregular surface effect caused by loop distortion".

There is at least one other fabric distortion besides stretching that occurs in knitted fabric and results in spreading difficulties. "Spirality" arises from twist stress in the constituent yarns of plain fabric, causing all loops to distort and throwing the fabric wales and courses into an angular relationship other than 90°. If the fabric is retained as a tube, the spirality
throws the vertical alignment of the fabric awry so that the wales lie at an angle to the edges of the fabric and slowly spiral around the fabric. Garment portions cut from the fabric show obvious distortion and are worthless. If the fabric is slit along the wale line during the knitting process or immediately prior to finishing, the distortion still takes place but appears as a course distortion, with the courses lying at an angle to the cut edges of the fabric. Fabrics with this problem often appear in low cost underwear and tee shirts, angled courses appearing to the consumer to be much less of a fault than angled wales.

Plain-knitted fabrics made from single cotton yarn are more prone to spirality, the degree being related to the number of twists/unit length in the yarn. Such yarn is said to be "twist lively" and, unlike similarly constructed yarns produced from thermoplastic fibres, cannot be heat set in yarn or fabric form to eliminate spirality.

Spirality does not occur in 1x1 rib and interlock fabrics, the loops formed in opposite directions cancelling out the distortions.

Another mild form of spirality occurs in fabrics produced on multifeeder circular machines, because the number of courses knitted in one revolution of the machine distorts the wale/course relationship. For example, a 30 inch diameter machine with 90 feeders of 20 gauge will knit approximately 3 inch of fabric for every revolution. This will produce, if the fabric is finished, 90 inch open width, 2° spirality.

The spirality that has been observed in weft-knitted fabrics has some semblance to skewness in 2/2 twill weave. A paper presented by Snowden (1964) in collaboration with others deals with the subject. The greater part of the paper was devoted to a mathematical analysis, which indicated that weft skew in the direction of the twill was an inherent property of the 2/2 twill weave, but it gave measurements of skew in a
series of cloths woven in various weaves. The Wira report on the skewing of 2/2 twill weave fabrics in the loom state indicated that skew may be minimised by the use of soft compressible yarns and high set (i.e., a closely woven structure, and repeated the fact that skew is an inherent characteristic of a twill weave. The series of reports by Robinson (1970, 1971) of work done by SAWTRI, indicated that:

a) skewing increased with width and tension.
b) the effect on skew of varying the sett differed according to the weave.
c) skew increased with increase in twist factor.
d) fabrics with S-twist in the folded yarn used for both warp and weft gave higher skew than all other twist combinations where the skew was in the same direction as the twill (when the direction of skew opposed the twill, however, the s-warp, s-weft combination gave minimum skew).
e) skew increased with a low weft tension in a 2/2 twill fabric.
f) the use of a full width temple of strong-acting ring temples reduced skew; and
g) the late shed-timing, a low back rest, and minimum tension gave much less skew than other loom settings.

From the above, it is evident that some of the mechanisms which affect skew in woven fabrics are similar to those which affect spirality in plain knitted fabrics.

Knitted fabrics sometimes have an inherent inclination of the courses to the wales (not at right angles to each other) which should not be confused with spirality. The most prominent and fundamental factor contributing to the spirality in a single-jersey fabric is the residual torque of the yarn used. When a twistless yarn is bent by forces and couples to
form a two dimensional loop, a perfectly symmetrical (to the central axis) loop configuration would emerge.

Twisted yarn, which has a tendency to untwist, is said to be twist-lively. If such a yarn is used for knitting, the resultant loop will no longer be symmetrical because of the induced torsional strain in the yarn. The twisted yarn will have a tendency to untwist and release the torsional strain inside it, in order to acquire the natural configuration of a minimum energy state. The yarn will attempt to rotate inside the fabric, thus lifting one side of the loop out of the surface while the other side stays inside the fabric. This distortion of loop symmetry gives rise to spirality - an inclination of loops and a rib like effect on the fabric.

The torque in a twist-lively yarn is generated by bending as well as by torsional stresses in the helical configuration of the fibres or filaments. The relative and absolute contribution of these two groups of forces also depends on the extension of filament helices and thus on the tensile force acting on the fibres or filaments in a yarn. In twisted structures, the couple generated about the yarn axis by the tangential component of tensional stresses in the helical fibres or filaments may also contribute to the total torque.

When plain-knitted fabrics are prepared from twist-lively yarns, a spirality is induced perpendicular to each other. The deviation of the wales from the orthogonal is known as the spirality angle. The spirality direction depends on the twist-liveliness direction of the yarn, an 'S' lively yarn giving a 'Z' spirality on the face of plain knitted fabrics and vice versa. The size of the spirality angle also depends mainly on the twist liveliness of the yarn, although other factors such as fabric structure, yarn linear density, retractive force, and bulkiness may have an influence; but, all other factors being equal, the spirality angle may be considered as an indication of the level of twist liveliness of a yarn.
It has been found that a small amount of fabric spirality can also be observed in a fabric produced from non-twist-lively yarns when knitting on a multi-feed circular machine. This spirality is due to the loop distortion by the unbalanced tension in the two legs of the loop. However, the loop distortion effect in such cases is much smaller than that generated by the residual torque in the yarn.

Direction of fabric spirality depends on the twist geometry of the constituent yarn. A z-twist yarn makes wale line incline to the right and thus produce a z-spiral effect on the fabrics, an s-twist yarn makes wale line incline to the left and thus produce an s-spiral effect on the fabric. Although twist-lively spun yarns are known to yield asymmetric loops, even monofilaments can be knitted to cause asymmetry of loops.

Nutting (1971) reported that a twist lively yarn having z twist would tend to untwist in the s direction and would result in a wale line inclined to the right of its normal position, causing a z-spirality. If, however, the cylinder rotates anti-clockwise or the cam rotates clockwise, when viewed from above the machine, the skewness should get suppressed. Bühler et al. (1985) observed that both rotor and ring spun cotton yarns show increase in spirality with increase in twist multiplier of yarns of the same linear density, whereby the role of tightness factor was to diminish absolute value of spirality and the role of wet relaxation was to enhance spirality compared to that of dry relaxed state. The degree of increase in spirality decreases with increase in tightness factor. Bühler et al. (1985) did not, however, subject the fabric to full relaxation treatment. Decrease in spirality on wet-relaxation treatment was observed for untreated yarns knitted into samples, whereas pretreated yarns (wetted, steamed) display rise in spirality.
2.2.1 Causes of spirality

Fabric spirality is a complex phenomenon arising from many factors influencing the nature and degree of loop distortion in single-jersey knitted fabrics. Residual torque in yarn is believed to be the most important and fundamental factor affecting the degree of fabric spirality. Postle et al. (1964) have demonstrated that the total yarn torque in a twisted yarn not only arises from the stresses due to fibre bending and twisting but is also influenced by the fibre tension in the twisted configuration. These authors derived an equation for the component of yarn torque due to fibre tension.

Accordingly, the following theoretical equation can be used for the estimation of total torque of singles ring-spun yarns as the sum of three components.

\[
\text{Total yarn torque} = \text{yarn torque component due to fibre bending} + \text{yarn torque component due to fibre torsion} + \text{yarn torque component due to fibre tension.}
\]

Yarn torque component due to fibre bending

\[
= [N_f E_t l_f / R_y] f_1 (\theta_s) \quad \ldots \quad (2.1)
\]

where, \[
f_1(\theta_s) = \frac{\log_e \sec^2 \theta_s - \sin^2 \theta_s}{\tan \theta_s} \quad \ldots \quad (2.2)
\]

Yarn torque component due to fibre torsion

\[
= [N_f G_t K_t / R_y] f_2 (\theta_s) \quad \ldots \quad (2.3)
\]

where, \[
f_2 (\theta_s) = \sin \theta_s / \cos \theta_s \quad \ldots \quad (2.3)
\]

Yarn torque component due to fibre tension

\[
= \pi R_y^3 E_t e_f f_3 (\theta_s) \quad \ldots \quad (2.4)
\]

where, \[
\theta_s = \tan \theta_s / 2
\]
\[ N_f = \text{Total number of fibres in the yarn (=yarn denier/fibre denier)} \]
\[ E_f = \text{Fibre tensile modulus} \]
\[ G_f = \text{Fibre torsional (shear) modulus} \]
\[ I_f = \text{Moment of inertia of the fibre cross section with respect to its principal axis of bending (for a homogeneous fibre of circular cross section of radius } r, l_f = \pi r^4/4) \]
\[ K_f = \text{Torsional (polar) moment of inertia of a fibre about the fibre axis (for a homogeneous fibre of circular cross-section of radius, } r, K_f=\pi/2 \]
\[ R_y = \text{Yarn radius} \]
\[ \theta_s = \text{Yarn surface helix angle} \]
\[ e_y = \text{Yarn tensile strain}. \]

The magnitudes of the basic components of yarn torque depend on fibre as well as yarn factors. Fibre factors include: the moduli of fibre (tensile and torsional moduli) and moments of inertia of fibre (which, in turn, depend on fibre cross-section shape and dimension). Yarn factors include: yarn radius, number of fibres in the yarn cross-section, twist and yarn tensile strain.

The effects of viscoelasticity on residual yarn torque have not been investigated. Fabric spirality is strongly influenced by several factors arising from fibre type, fibre cross-sectional shape, spinning system and the yarn geometry. In addition, many factors, which affect the level of residual torsional stresses in the yarn and/or the relative freedom of loop movement within the knitted structure, will influence the spirality in finished material. These factors include: knit structure, knitting machine settings and fabric setting due to finishing.
2.2.1.1 Fibre factors

Differences in the values of tensile modulus of different fibres affect the magnitude of yarn torque arising from the yarn stretch during subsequent processing of yarn and knitted materials.

Lord et al (1974) have found that an increase in percentage of polyester in the cotton/polyester blended yarns increased the twist liveliness in both ring and open end spun yarns and consequently enhanced spirality distortion in the single jersey knitted fabrics produced from the yarn. Bühler et al's (1986) observations were, however, more uniform than those of Lord et al (1974), the latter having recorded both increase and decrease in spirality on wet relaxation. Studies by de Araujo and Smith (1989) have also revealed that a higher polyester content in a 30 tex cotton/polyester ring spun yarn increased the tendency for the yarn to snarl. Reasons for the increased spirality in a single-jersey knitted fabric, arising from higher polyester content in a cotton/polyester yarn of the same linear yarn density, are probably the higher rigidities and the difference in cross sectional shape between these fibre types.

2.2.1.2 Yarn structure

The theoretical derivations by Platt et al (1958, 1959) and Postle et al (1964) have assumed that fibres in the yarn follow a perfect concentrical helical path, that is, each fibre has a constant curvature along the yarn axial length. It is, however, known that even in ring spun yarns, fibre migration, arising from equalisation of the radial stress in yarn, changes the curvatures of the fibre along the yarn axial length. This situation contradicts the basic assumption made by the researchers in deriving the theoretical equations stated above. Platt et al (1958) have made the following comments:
The results for the idealized geometry offer, at the very least, the approximate torque magnitude due to fibre curvature as well as its sensitivity to changes in yarn construction.

Twist increases the twist liveliness and loop spirality of cotton as well as cotton/polyester blends, and a considerable amount of experimental data is available.

Unconventional spinning techniques produce yarns with different yarn structures, and hence they will have different fibre arrangement; this will give rise to different levels of yarn torque. Experimental investigations concerning changes in angle of spirality have been made by several research workers. de Araujo and Smith (1989) have experimentally demonstrated that friction spun yarns produced the largest angle of spirality followed by ring spun, rotor spun and air jet spun yarns in that order, keeping all other variables constant. Similar observations have also been recorded by these authors in the case of single jersey fabrics knitted from 50% cotton 50% polyester yarn produced by ring spun, rotor spun and air jet system.

In an interesting paper, Carnaby (1973) has discussed spirality effects in single-jersey fabrics knitted from self-twist yarns. When knitting was done using R55/2 Tex ST yarn by varying the input tension from 0-600 mN, it was found that the fabric knitted with 600 mN had a very marked distortion, including three dimensional puckering of the fabric. But when a fabric was produced with no feed-in tension (hand-fed), stitch distortion due to torsional effects had almost been completely eliminated. In general, the fabrics produced indicated that loop distortion was caused by twist redistribution in the yarn before its entry to the feed-in guide and that the loop distortion was enhanced by using lower cover factor. Thus the problem is essentially similar to the familiar problem of spirality which is caused by knitting with an unset or unbalanced yarn. The difference is, however, that
with the ST yarn, the torque created by tension varies in both magnitude, and direction along the yarn, depending on the cycle of the ply twist, so that the resultant spirality also varies in direction. Where there is a fixed ratio between the yarn-twist cycle length and the yarn path length in successive courses, textural effects such as stripes and bars can arise from reinforced reflection from adjacent distorted loops. These textural effects disappear when there is no loop distortion, so that it seems that they do not arise from reflection off the twisted threads themselves.

Thus it follows that acceptable single-jersey fabrics can be knitted from ST yarns provided that twist redistribution in the yarn is minimal before knitting takes place. This is possible to do so in circular knitting machine by simply reducing the input tension. Further reductions in spirality, he says, can be obtained by increasing the cover factor, reducing the yarn twist or by steaming the packages of yarn before knitting. Reducing the yarn twist and steaming the yarn while it is under tension both reduce the amount of twist redistribution that can occur when the yarn is stretched on the knitting machine. Carnaby’s work on the spirality of knitted fabrics is a worthwhile study, as it unfolds for the first time, the mechanical methods of controlling or eliminating it.

Harrowfield (1981) has carried out studies on the relationship between the ratio of ply twist to single twist that is required to give zero spirality in single-jersey knit wear constructed from two-fold yarns. He took single yarns of 37, 74 and 111 tex which were produced with twist factors (turns/cm x tex$^{0.5}$) in the range of 20-65. From each yarn of a particular linear density and twist levels, four two-fold yarns were made that had folding twists that would bracket the folding twist expected for balance; these yarns were steamed at 70°C and wound onto cones, and subsequently knitted. These fabrics, after wet relaxation treatment, were tested for spirality, and a plot of the angle of spirality against the ply twist yielded the ply twist required to give zero spirality. The observed $T_f/T_s$ so obtained was
plotted against singles twist factor. It was noticed by him that, although at twist factors commonly used for singles botany and woollen knitting yarns, the ratio is about two-thirds, at higher singles twist factor, the ratio required falls to about one-half. Harrowfield feels that from his data, for a given set of production conditions, a reference curve could be provided to predict the ply twist required to produce plain knitting free from spirality given only the singles twist factor.

According to Bennett and Postle (1981) knitted-fabric spirality, as measured by the complement of the angle between the courses and wales in the fabric, is not the only manifestation of loop asymmetry due to the interaction of yarn torque and yarn stresses induced by the formation of the knitted-loop shape. Since plain knitted loop tends to rotate about an axis parallel to the line of the wales to produce an apparently asymmetric loop structure, this factor has to be taken into account.

2.2.1.3 Fabric tightness factor

The tightness factor (tex^3/loop length) for a knitted fabric indicates the relative looseness or tightness of a knitted loop in the space. Therefore it indirectly affects the fabric spirality by controlling the loop rotation in the knitted structure. If a twist-lively yarn is knitted very tightly (higher tightness factor) the high level of inter yarn friction in the loop will reduce the tendency of loop rotation and thus reduce the spirality in single-jersey fabrics. Thus if the tightness of the fabric is not sufficient to restrain the rotation of the torsionally strained loop, it will generate spirality. There is sufficient experimental evidence that a higher degree of freedom for the yarn loop results in a higher spirality angle. Alternatively, the extent of spirality decreases, with increase in tightness factor, where changes in tightness factor could be obtained by varying the stitch length or yarn linear density.
In a multi-feed circular knitting machine, fabrics are produced under a helical condition which may distort the loop shape by introducing an unbalanced tension in the two legs of the loop. Unbalanced tension in a loop inclines the wale lines and leads to spirality in the knitted fabrics. A clockwise rotating machine produces fabrics with left-inclined wales thus resulting in an S-spiralled fabric and anticlockwise rotating machine produces fabrics with right-inclined wales, thus resulting in a Z-spiralled fabric. However, spirality in a knitted fabric arising from the effects of machine rotation and number of feeders is normally much smaller than that caused by the yarn residual torque. Invariably, spirality in a knitted fabric can be largely eliminated by knitting with a yarn which induces a spirality (arising from its twist-liveliness) of a somewhat similar magnitude but in the opposite direction to that arising from the direction of machine rotation in a multi-feed circular knitting machine.

A large number of papers discuss the effect of tightness factor on the spirality. Alaiban (1986) has found that spirality in fully relaxed fabrics can be kept down by knitting loops to tightness factor value greater than or equal to 14.

2.2.1.4 Moisture and washing

Fabric relaxation process favours the growth of twist liveliness/spirality in a single-jersey knitted structure. According to Nutting's (1961) explanation, the relaxation process changes the intermolecular structure inside the fibre and helps to relieve the torque stored inside the fibre.

Stress in a torsionally strained fibre is generally held by the system of forces or bonds which link up the long chain molecules. Release of torque arises from the breaking and reforming of the relatively weak intermolecular bonds (such as hydrogen bond) of the fibre structure in the presence of moisture. The extent and rate of breakage of these bonds in the
presence of moisture depend both on the magnitude and condition of the torsional energy stored in the yarn. According to Alaiban (1981), the effect of relaxation (due to moisture) on the spirality in a single-jersey fabric depends not only on the reconstruction of the intermolecular bonds inside the yarn, but also on the swelling behaviour of the fibre and yarn. In effect, the former (reconstruction of intermolecular bonds) promotes higher spirality; the latter (swelling) limits the space available for the yarn to rotate within the interlocked structure. Whether the spirality in a single-jersey knitted fabric increases or decreases as a result of the moisture relaxation phenomenon will thus depend on the predominance of one factor over the other.

Several methods can be adopted to eliminate or alleviate problems associated with spirality in fabrics knitted from twisted single yarns. Based on their principles, these methods can be divided into two main categories:

a) Setting of yarn to reduce its residual torque and
b) balancing the yarn torque by various means.

Setting of yarn under stress introduces new intermolecular bonds within fibre structure after breaking the previous ones. It is known that the higher the amount of permanent setting introduced within a fibre, the lesser the degree of spirality due to yarn residual torque. The process makes fibres more stable in their deformed state. Therefore this results in less residual torque and consequently smaller fabric spirality.

Steaming, setting in hot water and chemical treatments such as mercerisation in the case of cotton fibres and treatment with sodium bisulphate in the case of wool yarn are some of the setting treatments. In respect of synthetic fibres, heat treatment is given to the yarn or fabric under stress.
Following the setting process, the much reduced residual stresses left inside the fibre will become dormant from the inter yarn friction developed during knitting. This has a direct effect on controlling the yarn twist-liveliness and hence spirality in the single-jersey knitted fabrics produced from set yarns.

Balancing the yarn torque: This can be done by various methods. Some of the techniques adopted are:

1. Plying two identical single yarns with a twist in the opposite direction to that in the single yarn.
2. Feeding two single yarns with twist of the same magnitude but in the opposite direction onto the same feeder; or simply
3. Knitted with plaited yarns of the same number of twist but in the opposite direction. In practice the approaches are limited by the use of two yarns.

Spirality due to yarn residual torque can be minimised by knitting it on a multi-feeder circular knitting machine with the direction of rotation selected in such a manner that the effect of direction of rotation is counterbalanced by the effect of yarn residual torque.

On the other hand, spirality due to machine factors can also be eliminated by knitting with yarns that give the same angle of spirality as the machine factors but in the opposite direction. However, there are practical constraints arising from the difficulty of incorporating the mechanical/electronic devices on knitting machines.

Spirality in a single-jersey knitted fabric, arising from the residual yarn torque, can also be indirectly controlled by changing fabric construction. For example, knitting with yarns which induce spirality of equal magnitude but in the opposite direction in alternative courses will
reduce spirality. However, this technique will give rise to a zig-zag effect on the fabric.

Spirality can be eliminated by knitting fabrics in a balanced construction. e.g. interlock and the balanced rib structures. During the formation of these balanced construction fabrics, two sets of needles are used with the loops formed on the front and back needles in alternate wales. In these circumstances, torque in yarn affects the two faces of the fabric in opposite manner such that the spiral effect on one side of the fabric is counterbalanced by that on the other side resulting in a spirality - free fabric.

Bühler and Häussler (1985) have carried out an extensive study on the spirality of single jersey fabrics and they have coined the term "skew" for it. The effects of cam setting, number of feeders, cam angle, sinker ring setting, direction of rotation of knitting machine, stitch length, and fabric take-down have been studied. Further, the effect of yarn twist in ring and rotor has been studied, and also using viscose filament yarns with varying twist density, the formation of skewness/spirality has been investigated. Also, effect of yarn snarling and yarn doubling on spirality of weft knitted fabrics has been investigated. The work done by these authors is a comprehensive and a useful study, and prima facie establishes the various factors responsible for spirality. Recently, spirality in weft-knitted fabric produced from new types of core yarns has been reported. It has been found that the spirality of fabrics knitted from staple core yarns has been found to be high and that the wet processing treatments have reduced it.

Kimmal and Sawhney (1995) have reported that the weft knitted fabrics produced from stable core yarns display greater spirality than that of all cotton yarns, and it is eliminated by substituting S-for Z-twist staple core yarn. Another point is that relaxed S-twist staple core fabrics are also dense and greatly more abrasion resistant than comparable Z-twist knits.
2.2.2 Method of determination of spirality

The measurement of spirality in knitted fabrics is quite simple. By placing a protractor on the flat smooth fabric surface with its base line along the course, and reading the angle between the wale line and a line 90° perpendicular to the course line, this parameter can be measured. Bühler and Haüssler (1985) have introduced a coloured yarn every 500 revolutions of the knitting machine to enable the angle to be measured. Catsatos (1984) has described a method which is more or less similar to Bühler and Haüssler's one; the same method was used by Alaiban (1986). Chow (1976) has also carried out studies on the torsional behaviour of false twist textured yarns, by a simple twist-liveliness test and the spirality of knitted fabrics knitted from them. The spirality followed the expected trends with an increase of spirality as torque increased and a decrease of spirality as retraction power increased. A decrease in spirality with both increasing heat temperature and twist is observed. For fixed values of torque, increase of crimp rigidity gives a rapid decrease of spirality although at high values of torque, a relatively small increase in torque is necessary to restore the original spirality.

Primentas (1991) has examined twist liveliness of acrylic yarns and the spirality of the knitted fabrics produced from them. An interesting observation that there is a dramatic reduction of the yarn liveliness during the first five days of storage has been made. With reference to the spirality, as time passes, the angle of spirality reduces. The effect of time on the relation between the yarn snarliness and the fabric spirality shows that snarliness value is high on the 5th day, and the corresponding angle of spirality of the fabric made of that yarn is also high.

By reducing the tension of the feed yarn in knitting, and by introducing false-twist in the yarn (filament) before feeding to the needles, the spirality may be eliminated. These observations can be made from the
work of Carnaby (1973) who experimented with the ST yarns. Development of mechanical methods to control or eliminate the spirality of weft knitted fabrics will go a long way in solving the problem, and this will form a separate study. Hepworth (1991) has presented a theoretical investigation on spirality in knitted fabrics caused by twist-lively yarns. The angle of spirality not only increases with the yarn twisting couple but also decreases with fabric tightness confirming experimental observations. The role of jamming is to reduce the spirality in tighter fabrics. She has concluded that in order to minimise spirality, it is desirable to design and treat the yarn in such a way as to avoid a residual twisting couple and to knit the fabric to a sufficiently high tightness.

2.3 MECHANICAL PROPERTIES OF WEFT KNITTED FABRICS

A large number of papers discuss the mechanical properties of weft knitted fabrics, and with the introduction of Kawabata Evaluation System for fabrics (KES-F), the measurement of these properties can be easily accomplished with some modifications. There are a number of papers which are concerned with the loop shape, the structural mechanics and the prediction of the tensile properties. Knitted structures represent the most general application of the energy equations because of their inherently three-dimensional loop configuration. On the basis of quarter-loop symmetry, Shanahan and Postle (1974) considered that the loop was held in equilibrium under the action of a force \( P \) and a couple \( M \), where \( M \) lies in the plane of the fabric and is normal to the yarn axis. (Fig 2.1) and \( M \) were taken to be statically equivalent to the real inter-yarn forces in a fabric. It was assumed that the yarn was in continuous constant from points \( l \) to \( l' \) and subsequently the displacements between the yarns at \( l \) and \( l' \) in the direction normal to the fabric plane were assumed to be equal. The magnitudes of the force \( P \) and couple \( M \) were then varied to generate different inter-yarn distances and loop lengths. The position of the point force and couple was derived from a minimum-energy condition which was
Figure 2.1 Forces and couples acting within the plain-knitted structure
a) after Shanahan and Postle (1974a),
b) after Hepworth and Leaf (1970).
later shown to be in error because movement of the point forces and couples was not included in the energy condition.

A more rigorous, but also more limiting assumption was made by Hepworth and Leaf (1970). In this case, it was assumed that the inter-yarn contact in the plain-knitted structure was approximated by a two point contact system, in which the yams were considered frictionless and consequently the forces acted normal to the yarn axis. From the assumed quarter-loop symmetry, the point forces $P$ and $P'$ (acting at the point contacts) were derived. The magnitude of the dimensionless quantity $PL^2/B$, where $L$ is the quarter loop length and $B$ is the yarn bending rigidity, was then varied under prescribed boundary conditions at the ends of each of the three quarter-loop segments to generate different inter-yarn distances.

Despite the different assumptions made in these two analyses, it was shown that the two force systems were statically equivalent and yielded essentially the same results (Shanahan and Postle, 1971). However the analysis yielded differences in jamming conditions, where jamming is defined as an extra (unassumed) contact between adjacent yams in neighbouring loops. Hepworth (1971) found that jamming occurred first in the length direction and then also in the width direction, with increasing yarn diameter, a result which was in contradiction to that found by Shanahan and Postle (1970) who calculated the effect of jamming to be negligible for fabrics of normal tightness of construction. Because of the different assumptions by Hepworth and by Shanahan and Postle, it was stated that slight differences in loop shapes could lead to jamming in one of the analyses and not in the other (Shanahan and Postle, 1971). Hepworth (1971) analysed the jamming conditions further and found that the jamming forces so generated were relatively small.

The load-extension properties of knitted fabrics have been investigated theoretically by several workers, Shanahan and Postle (1974)
Popper (1966), Whitney and Epüng (1966), MacRory, McCraith and McNamara (1975). Using a three dimensional model and assuming the shape of the yarn in the contacting region of the plain knitting as a helix, the load-extension properties were investigated by MacRory, McCraith and McNamara (1977).

Theoretical load extension curves for plain-knitted fabric have been derived by three of the force methods. Except for the course-way extension by Shanahan and Postle (1974a, 1974b), all the predicted tensile moduli were higher than the experimentally observed values. Only two methods of analysis have been capable of including both length and width jamming in the determination of the tensile properties of plain-knitted fabric. Using the Hepworth and Leaf force model, Hepworth (1978) predicted the load extension behaviour of plain knitted fabrics under uniaxial and biaxial tension. De Jong (1976) determined the effects of very small uniaxial loads (PL/B = 2) on the plain knitted loop using the energy model. The energy analysis includes yarn compression which is omitted from the Hepworth and Leaf force model.

Konopasek (1970) has predicted the stress strain behaviour of plain weft knitted fabrics by three dimensional bending curve model, which he has successfully used for all the structures. He has included bending rigidity and friction in his work, and the same results have been obtained by Hepworth and Leaf (1970). The mathematical models in course-way and wale-way directions consist of a set of differential equations of the planar bending curve and of a set of parameters and initial and boundary conditions. Thus there is some agreement between the two methods although the approaches made are different.
2.3.1 Bending Properties of Plain-Knitted Structures

The force model of Hepworth and Leaf (1970) has been used by Hepworth (1982) to evaluate the bending behaviour of knitted fabrics about the course direction. An almost linear bending moment - angle relationship resulted; this has been predicted by energy method also. The advantage of this analysis is the inclusion of yarn compression. Experimental data on bending of weft-knitted fabrics are provided by Hamilton and Postle (1974), Gibson and Postle (1978), Paulin Chen (1992) and Elder and Somashekar (1975).

2.3.2 Shear Behaviour

Experimental results of plain weft knitted fabrics are provided by Carnaby, (1974), Hamilton and Postle (1975), Gibson and Postle (1978) and Akhtar Begum (1995). It should be mentioned that a rigorous mathematical analysis has been carried out on weft knitted fabrics by force and energy methods with a view to predicting their mechanical properties. The extent to which work has been done on woven fabrics to predict their shear behaviour is considerable when compared to plain weft-knitted structures.

With the introduction of KES-F, it is possible to measure the various mechanical properties quite precisely. However, to what use these properties can be put remains to be seen. Also, it has been found that the use of shearing behaviour of weft knitted fabrics in trying to have an idea whether or not the fabrics have reached stable configuration is limited than in bending. Bending hysteresis curves of unrelaxed knitted fabrics and relaxed knitted fabrics have been used to predict the curling couple which gives an indication of the curliness of the knitted fabrics.
Wei-hiang Wu (1994) has recently developed a method for predicting the deformation behaviour and the related mechanical properties of weft-knitted structures. A two-dimensional hexagonal mechanical model based on the plain-knitted fabric structure has been used to simulate the deformation and mechanical properties with acceptable accuracy; this model incorporates the slippage effect onto the cross-over region of the unit model. The analytical method used to determine the tensile properties was proved to be effective after the experimental data was converted to the tensile parameters of the model. The mechanical model also successfully predicted the deformation and related mechanical quantities even in the case of a three-dimensional deformation.

2.4 DIMENSIONAL STABILITY OF WEFT-KNITTED FABRICS

A great deal of attention has been paid by research workers to dimensional properties of weft-knitted fabrics since Chamberlain (1949) deduced some very simple relationships between linear-dimensions of fabric, loop length and diameter of yarn. His analysis is concerned with that of a jammed loop and did not account for (a) three-dimensional nature of the loop and (b) bulk as well as surface properties of the yarn. Peirce (1947) improved Chamberlain's treatment by (a) incorporating suitable changes in course-sparing necessitated by a constant curvature of the body of loop across the fabric thickness and (b) generalising the geometry so as to encompass non-jammed structures as well. Both these pioneering efforts were based on assumed configuration of loop underlining the supposition that the role of yarn in governing fabric dimension is determined by its dimensional properties.

Doyle (1952) demonstrated with the help of a very simple model, the forces of elastic recovery active within a loop which lead to curling of edges of single jersey fabrics which is encountered very commonly and hence Doyle's analysis proved that yarns composing a loop would generate and
retain stress when subjected to a strain. Hence elastic properties of yarn would have to be taken into account while making a three-dimensional loop of given length. Love's (1952) treatment of elastica in determining path of the yarn axis can be taken if the yarn is considered to be perfectly elastic. Such an approach reveals that a given length of yarn, bent and twisted into a loop governed by the knit construction employed, would necessarily follow a unique path. Such a state corresponds to that of static equilibrium peculiar to the construction employed, and the strain energy associated with this state is the minimum energy level of the yarn element in the loop. Additional forces and couples have to be brought into play in order to change this unique path of yarn axis (or the shape of the corresponding loop). The loop would naturally tend to its unique shape, determined by nature of knit construction, once these additional forces and couples are withdrawn. Knitted fabrics, taken immediately from the knitting machines, display loops having diverse shapes due to varying degree of strains. Subsequently, however, the loops should tend to shapes, corresponding to that of static equilibrium governed by knit construction employed, as strains imposed by machines would not exist any more.

There have been studies on loop shapes, which are theoretical and experimental in nature. The theoretical treatments have been along two lines. In the earlier studies, the author assumed before-hand, shape of the different portions of the loop and adjusted lengths in each such segment so as to achieve a degree of correspondence with the established experimental findings. The other approach has been to locate nature of forces and couples acting on loop segments from free-body diagram as well as from nature of interlacement and derive resulting relationships governing loop-shape.

Leaf and Glaskin (1955) after underlining of Peirce's (1947) three-dimensional model of loop, assumed a loop geometry composed of arcs of circle when projected on a fabric plane, whereby the shape in the third dimension is determined by considerations arising out of nature of
interlacement. Evaluation of this model demonstrated over-estimation of the actual loop length. Moreover, the model predicts dependency of dimensions on tightness of construction which violated the results of Munden's (1959) elastic work. In view of the inadequacies in this model, Leaf (1960) designed models of loop based on joining of bent elasticas, whereby, for adjusting the form along the third dimension, Peirce's (1947) method was taken recourse to forming one model, whereas the other model was formed by assuming sinusoidal nature of the same. It was claimed that the first and simpler model fitted to wet - relaxed loops only whereas the second and more completed one fitted to both dry and wet relaxed loops. These models were so designed as to fit the values of dimensional parameters suggested by Munden (1959). Leaf (1961) in an attempt to determine nature and magnitude of forces and couples acting on the dry relaxed loop, used the second model of loop, as described, but did suggest an outline of a better approach for finding equilibrium configuration of yarn which was taken up in his later works, (Hepworth and Leaf (1970), Hepworth (1982)).

Munden (1959), while seeking a dimensionally reliable and accurate parameter that is least affected by distortion of fabric, observed that stitch density and hence, following Doyle's (1953) work, the loop length could form the unit of measurement provided that the fabric is in zero strain state. He stated that the geometry of the knitted fabric, therefore, is basically a study of the geometry of the single knitted loop because the configuration of a loop in its minimum energy level is unique implying thereby that the constants of proportionality relating dimensions with loopp length at minimum energy level of the loop are also unique, which he established theoretically, although in a very simplified manner. In a further attempt to justify that the stitch length would uniquely determine dimension, Munden (1962) took resort to analogy between square plain - woven fabrics and plain knitted fabrics. Kemp and Pollitt (1956) had established that count of yarn (N) of a square fabric would completely specify the dimensions, weight and properties of cloth for a given value of
cover factor (K). Defining cover factor of a plain knitted fabric, Munden went on to state that "dimensions, weight and properties of knitted fabrics will be related to stitch length" omitting thereby, which the analogy demanded, this relation would depend on cover factor. All his postulations were, moreover, based on the underlying assumption that a knitted loop could be brought to its minimum energy level through the process of relaxation. The experiment that he conducted in support of his theory yielded, however, contradictory results in the sense that fabrics knitted from yarns spun from different raw materials exhibited different Ks values indicating thereby that either the different fabrics could not be brought to their respective minimum energy levels or that there is a dependence of loop configuration on yarn and/or structural parameters. Hence, a closer look at the relaxation process accompanied with fabric shrinkage was undertaken by Munden (1960) and he defined three states of shrinkages namely, wet - relaxation, consolidation, and felting whereby the states of wet relaxation and dry relaxation were still considered to be two unique equilibrium states of the loop made of hydrophilic fibres other than wool. Nutting (1961), continuing this line of investigation, established that a wet - relaxed fabric exhibits reversible dimensional changes with changes in moisture regain, whereas a dry relaxed fabric does not. This is explained by proposed shrinkage mechanisms according to which the dry - relaxed loop made of hydrophilic yarn would suffer physico - chemical changes when exposed to moisture as a result of which the loop configuration changes. But then this argument would necessarily mean that the configuration of loop depends on yarn properties as well. These problems are aptly highlighted in Nutting and Leaf's (1964) work in which they observed dependency of the shape of a knitted loop on state of relaxation, type of raw material, construction of fabric and ratio of flexural to torsional rigidity of yarn (B/G). In fact they proposed that the ratio of rigidities should necessarily be same for different loops to have same configuration and is directly related to the value of Ks. However, the sufficient condition for similarity of configuration was not spelt out. Confusion also prevailed because of employment of such terms as
configuration and shape without specifying a parameter which would characterise the same although the ratio of number of courses and wales in unit space was suggested by Munden (1959) arbitrarily. This was in contrast to conclusion of Leaf and Glaskin (1955) that the ratio of course to wale spacing would be a function of tightness of construction.

Attention was thus focused on deducing theoretically shape and configuration of the loop in undeformed state i.e., only when such forces and couples act on the loop, and determined by the nature of interlacement with a view to establishing factors governing configuration of a loop in the undeformed shape. Intra and inter yarn friction, compressibility, set as well as symmetry of the loops were beyond the purview of such treatments.

Postle and Munden (1967) in their analysis of dry relaxed knitted loop configuration included that the geometry of a plain - knitted structure was completely specified by the loop angle ($\alpha$) and the interlocking angle ($\beta$); the value of loop angle determining the shape of the loop and the interlocking angle determining the point on the loop at which interlocking occurred.

Munden (1959) stated that the yarn going to the fabric was subjected to high strains during the knitting operation and if the fabrics were allowed to dry-relax after knitting the yarns relaxed to a considerable extent and relaxed further on wetting. Accordingly, he defined two states of relaxation of plain - knitted fabrics viz., 'dry-relaxed' and 'wet-relaxed' state. A reaction force as well as a couple of vector, caused by intertwining of yarn element over the interlacement region, were assumed to be acting at the interlocking points and disposed parallel to the plane of symmetry of fabric. The results indicated that although the loop shape, characterised by the value of loop angle, do not change much over the range of fabric tightness factors between 13.5 and 17, the dimensional properties $K_c$, $K_w$ and $K_s$ exhibit significant dependence on fabric tightness and loop shape. The
completely jammed structure was predicted to occur at a tightness factor of 17, whereas depending on the loop shape and interlocking angles, any value of tightness factor below 17 may cause either widthwise or coursewise jamming. Apparently, factors other than that of tightness, which govern values of loop angle and interlocking angle, play decisive roles in determining dimension. In this analysis, effect of torsion was generally ignored, although the authors mentioned that for large values of ratio of torsional energy to flexural strain energy of loop, yarn torsion becomes an important factor in the determination of loop shape.

Shanahan and Postle's (1970) work was an extension of that of Postle and Munden (1967) in the sense that the three-dimensional shape of loop caused by reaction forces and couples outlined in were investigated more systematically and dependence of the linear dimensional parameters on fabric tightness factor at the lowest energy levels are clearly difficult to achieve in practice. The energy level was minimised by suitably changing the loop angle in conjunction with the interlocking angle and hence importance of factors other than that of fabric tightness, which govern values of loop angle and interlocking angle, is inherent. The manner of minimising energy and contradiction in assumptions made in this analysis have been criticised elsewhere. A peculiar result was obtained with respect to conditions of jamming and it was stated that for a value of tightness factor above 17, wale wise jamming would occur, but no jamming would be encountered for values of tightness factor below 17.

The free-body diagram of the interlacement region, as conceived by Hepworth and Leaf (1970, 1976), is different from that of Postle et al (1967), in that the reaction forces act at two contact points instead of one and they act along common normals to the contact points while passing through the yarn axis. Similarly, the reaction couples act not at an assumed point along the yarn axis but are dispositioned based on logical deductions. Otherwise the treatment is very similar although no parameter has been identified to
Table 2.2  Dimensional parameters corresponding to a completely dry relaxed loop (approx)

<table>
<thead>
<tr>
<th>Tightness factor (Tex ° Cm⁻¹)</th>
<th>$K_e$</th>
<th>$K_w$</th>
<th>$K_e/K_w$</th>
<th>$K_s$</th>
<th>t/d</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>12.33</td>
<td>1.92</td>
<td>6.42</td>
<td>23.67</td>
<td>4.27</td>
</tr>
<tr>
<td>5.4</td>
<td>7.56</td>
<td>2.39</td>
<td>3.16</td>
<td>18.07</td>
<td>2.91</td>
</tr>
<tr>
<td>9.0</td>
<td>6.38</td>
<td>2.85</td>
<td>2.24</td>
<td>18.18</td>
<td>2.55</td>
</tr>
<tr>
<td>14.0</td>
<td>5.44</td>
<td>3.66</td>
<td>1.49</td>
<td>19.91</td>
<td>2.28</td>
</tr>
<tr>
<td>16.1</td>
<td>5.29</td>
<td>4.16</td>
<td>1.27</td>
<td>22.01</td>
<td>2.23</td>
</tr>
</tbody>
</table>
represent loop shape. The results indicate that coursewise and walewise jammings would occur for values of tightness factor whereby $K_r$ decreases and $K_w$ increases with increasing value of tightness factors but the trend is reversed after complete jamming has taken place. It has been mentioned that if a twisting couple is introduced in the idealised system either by the presence of friction or by an asymmetry of cross-section of yarn, then the ratio of torsional to flexural rigidities ($G/B$) becomes another factor in determining dimension. From the data furnished by Hepworth and Leaf (1976), it is possible to deduce dimensional parameters, corresponding to a completely dry-relaxed loop (Table 2.2).

Summarising results of the theoretical work, based on force analysis of plain knitted loop, it could be concluded that the dimensional properties of a plain knitted loop in the dry relaxed state would definitely depend on tightness factor and possibly also on the ratio of torsional to flexural rigidity of yarn ($G/B$). This, of course, applies to yarns perfectly elastic and incompressible in nature deformed into a symmetrical three-dimensional loop shape of corresponding minimum energy level. Yarns spun from natural fibres would deviate approximately from the yarn model used in these theoretical studies.

Doyle (1953) established relationship between stitch density and loop length for a wide range of plain-knitted fabrics but only in dry-relaxed state. Munden's (1959) experimental data was related to dry relaxed and an arbitrarily defined wet-relaxed state. The nature of relationships between relevant parameters was observed to be same in both these states, although the coefficients differed in absolute values. The graphs plotted depicting relations between stitch density and inverse of square of loop length show intercepts with ordinate and abscissa respectively for cotton and nylon in the dry-relaxed as well as in the wet-relaxed states but no intercept for wools in dry as well as in wet-relaxed states, whereas plots of CPI and WPI (courses per inch and wales per inch) against inverse of loop length for wool
show intercepts with the abscissa even in wet-relaxed state. The corresponding data for cotton and nylon were not reported. This, however, points to insufficiency of the model in which loop length alone governs the dimension. It might be noted in this context that a loop in the dry-relaxed state is normally not in its shape corresponding to minimum energy level and hence the value of \( K_s = 3.8 \), as found by Munden (1959) for wool fabrics in the dry-relaxed state, must be a result of additional strains imposed during knitting from which the loops partly recover during wet-relaxation treatment. This state of dry relaxation is apparently quite different from the one described by Postle and Munden (1967) although the \( K_s \) value of 3.8 has been freely used by the latter, owing to the belief that dry relaxed state is an equilibrium state.

Postle (1968) knitted various yarns of unspecified properties but of varying raw materials such as silk, wool, rayon, acetate, nylon, terylene, acrilan etc. into plain knitted fabrics of a range of tightness of construction and experimented with various relaxation methods so as to establish a standard complete relaxation treatment that would bring loops to their dimensionally stable states. It was concluded that wetting a fabric with gentle agitation for 30 minutes at 100°C followed by tumble drying at 80°C for 15 minutes should bring all loops to states in which they do not exhibit tendency to further change in shape and display similar shapes irrespective of yarn properties and fabric tightness factor. However, it is observed from the data presented that, the range of values of loop shape factor varied between a minimum of 1.26 (silk) and a maximum of 1.47 (double ply wool) whereas \( K_s \) values varied between a minimum of 20.7 (silk) and 25.8 (worsted). Hence, the resulting loops should be varying significantly in their spatial configurations. However, inspite of the questionable inference, the effort at establishing standard complete relaxation treatment for the full relaxation treatment has contributed appreciably towards bringing fabrics to their reference states.
Knapton et al (1968), in their study on the effect of loop length and yarn count on relaxed dimensions of plain-knitted woollen fabrics, demonstrated that states of minimum internal energy of fully relaxed states are achieved neither through dry nor through wet relaxation but only through a full-relaxation treatment, which meant a wet relaxation followed by tumble drying over 60 minutes. Their data on the effect of take-down tension and tumble drying time on dimensional parameters showed progressive increase in values of loop shape factor $K_s$ and $K_e$ and decrease in $K_w$ with continued relaxation, although beyond a tumble drying period of 45 minutes, all the parameters show a marginal drop. It is not clear, therefore, that the loops had reached their minimum energy levels after 60 minutes of tumble drying. However, from another set of data presented in the course of the work, they infer that a thorough wetting for 24 hours, a brief hydroextraction and 60 minutes of tumble drying should bring plain knitted fabrics to fully relaxed states. Notwithstanding their assertions, the data show changes in values of dimensional parameters even beyond a tumble drying period of 60 minutes. However, these changes with progressive relaxation time do not follow a definite trend although the corresponding values at fully relaxed states are higher than those at dry relaxed. Knapton et al (1968) concluded on the basis of measurements conducted on fabrics knitted over a range of tightness factors for worsted yarns of different raw materials, counts, twist factors and resin finishes that, for all relaxation states, $K_o$ is dependent on count of yarn, $K_c$ and $K_e$ depend on loop length, count of yarn and tightness factor of fabric, loop shape factor depends on tightness factor, fabric thickness depends on count of yarn and fabric bulk density - defined as ratio of fabric thickness to its area density - depends on loop length. The dependence of loop shape on yarn properties was not studied although it was noted that these were indications of dimensional changes due to differences in yarn physical properties.

In order to find out the effect of fibre properties on the dimensional parameters at fully relaxed state, Knapton et al (1975) conducted similar
tests on cotton fabrics knitted over a range of tightness factors from ring spun yams of different counts, ply and twist factors made of fibres of varying fineness. It was observed that about ten cycles of laundering and tumble drying bring the fabrics to a state beyond which $K_s$ values do not change on further relaxation. The $K_s$ values at such dimensionally stable states show an appreciable spread and it was concluded that some factors, so far unidentified, must be influencing the stable state. Values of $K_i$ and $K_m$ were found to depend on tightness factor such that with increasing tightness factor, $K_i$ increased and $K_m$ decreased marginally. It might be noted that this contradicts the theoretical deductions for non-jammed structures but agrees with for jammed ones. Yarn quality and fibre quality affect $K_s$ but yarn twist was observed to be of no effect at stable state. Thickness and bulk densities were also observed being affected by fabric tightness.

The average dimensional parameters at stable state are somewhat similar for cotton and wool pointing to a similarity of configuration of stable loop shapes. An important observation regarding stabilisation of loop shape during repeated relaxation was that the bulking of yarn causes the loops to touch each other to form a jammed loop configuration, irrespective of the original fabric tightness. A specific loop shape, and therefore, the dimensional stability of the fabric, appears to be reached when yarn bulking is restricted by yarn jamming. Munden's values of $K_i$ and $K_m$ on plain - knitted wool fabrics are often quoted because they represent the values for fully relaxed fabrics. However, it is noticed from the literature that more severe relaxation conditions are required to obtain fully relaxed fabrics, and hence truly constant values of $K_i$ and $K_m$. The reason why so much of work on the dimensions of weft knitted fabrics has been carried out is because of the fact that this stable loop configuration governs the properties of these fabrics, and there is some meaning in the testing of them for various physical and mechanical properties. Since the determination of fabric dimensional constants involves loop length, it is quite obvious that, in
practice, the stable fabric dimensions are easily predictable if one knows the loop length. An inherent assumption in such statements is that an undefined spread of dimensional properties due to variation in fibre and yarn properties as well as in tightness factor would be commercially acceptable.

In view of the findings of Knapton et al (1968, 1975), it has been found that data on dimensional parameters given by Burnip et al (1973) are unreliable. So also, the data provided by Lord et al (1974) are unreliable as the relaxation treatments given by them are also inadequate. Gowers et al (1978) produced acrylic, worsted and cotton yarns of different counts but of negligible twist liveliness and converted them into plain-knitted fabrics of a range of tightness factors. They have reported that soaking samples for 24 hours at 50°C followed by hydroextraction and tumble drying at 45°C for 30 minutes succeeded by a 24 hour dry relaxation brings the dimensional parameters to a stable value which does not change significantly on further relaxation. This full relaxation treatment is very similar to one suggested by Knapton (1968) for wool but is not in agreement with the findings reached for cotton. The dimensional parameters of so relaxed material when calculated according to equations given by Munden (1959) would yield values of 21.5, 5.26, 4.19 and 1.25 for $K_g$, $K_c$, $K_a$ and $K/K_a$ respectively for all the materials considered together. Appreciable deviation of experimental points from the regression lines through origin prompted the authors to try regression equation for which the corresponding straight lines show intercepts. As a result, it was observed that the intercepts exhibit some dependence on yarn diameters whereas the corresponding slopes, representing linear dimensional parameters, vary with tightness factor in the manner predicted by Knapton (1975), but opposite to that observed by Shanahan and Postle (1970), Hepworth and Leaf (1970), Hepworth and Leaf (1976) and Hepworth (1982). It was suggested that the effect of yarn diameter on fabric dimension is caused by yarn torsional to flexural rigidities, as well as by yarn twist and fibre diameter.
Starfish project, which is an integrated approach to shrinkage control in cotton knits initiated by International Institute for Cotton, provides very useful information on the reference state of weft knitted fabrics. The reference state is as under:

1. Wash in automatic domestic washer at 60°C.
2. Tumble dry to constant weight.
3. Wetout in washing machine (Rinse cycle).
4. Tumble dry to constant weight.
5. Repeat steps (3) and (4) three more times.

The primary reason for the selection of the procedure shown above was its reproducibility. The method used to bring the fabric into this state must be precise, accurate and reproducible. At this state, the linear dimensions would depend on count of yarn, stitch length as well as coefficients embodying effects of yarn properties, finishing routes, structural features etc. The linear equations proposed in starfish project for the reference state are given below.

\[
\begin{align*}
\text{a. Reference courses/Cm} &= C_m + C_s/L + C_5 \sqrt{T} \quad \ldots (2.5) \\
\text{b. Reference Wales/Cm} &= C_6 + C_7/L + C_8 \sqrt{T} \quad \ldots (2.6) \\
\text{c. Reference Stitches/Cm}^2 &= C_9 + C_{10}/L^2 + C_{11} \sqrt{T} \quad \ldots (2.7) \\
\text{d. Reference weight/m}^2 &= C_{12} + C_{13} T/L \quad \ldots (2.8)
\end{align*}
\]

Where \(L\) is the reference loop length, \(T\) the reference tex, \(C_3, C_{13}\), the regression coefficients. The reference loop length and the reference tex are found from the average loop length as knitted and the tex as knitted by separate regression equations.

Thus,

\[
\begin{align*}
L &= C_1 \text{ loop length} \\
T &= C_2 \text{ Tex}
\end{align*}
\]
For purposes of comparison, the corresponding equations proposed by Munden (1959), Nutting and Leaf (1964) and Gowers and Hurt (1978) are given below:

a. Munden (1959) Courses per unit length = $K_{y_1} \div W_{y_1}$
   Wales per unit length = $K_{y_1}/L$

b. Nutting and Leaf (1964) Courses per unit length = $1$
   Wales per unit length = $\frac{AL + D \sqrt{\text{tex}}}{a_2L + b_2}$

c. Gowers and Hurt (1978) Courses per unit length = $1$
   Wales per unit length = $\frac{1}{a_1L + b_1}$

The corresponding values of $K_1$, $K_2$, $K_3$ and $K/K_n$ proposed by several authors are given in Table 2.3 for purposes of comparison.

2.5 COMPRESSIONAL PROPERTIES OF WEFT-KNITTED FABRICS

On the compressional properties of weft-knitted fabrics, two papers by Postle (1971a) and Akhthar Begum and Subramaniam (1994) deserve mention. One way of measuring compressibility of fabrics is by monitoring thickness at various pressures. Thickness decides bending of a loop across the fabric plane; it is also a contributing factor towards bulk density. Knapton et al. (1968) formulated a relationship between thickness of fabric and yarn diameter based on Peirce's (1947) geometry of loop. Experimental results showed that $K_1$, the constant of proportionality between thickness of fabric and yarn diameter which was theoretically worked out to be equal to 5.17, varied for different yarn linear densities in the fully relaxed states of fabric. This variation was explained as being due to different degrees of swelling of different yarns during relaxation. However, for any particular
Table 2.3 Values of $K_e$, $K_w$, $K$, and $K_e/K_w$ reported by several authors for different materials and relaxation treatments

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>$K_e$</th>
<th>$K_w$</th>
<th>$K$</th>
<th>$K_e/K_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.3(WR)</td>
<td>4.1(WR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cotton: 19.0±0.3(DR)</td>
<td>22.6±0.5(WR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nylon: 18.5±1.0(DR)</td>
<td>18.5±1.0(WR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Orlon: 18.5±1.0(DR)</td>
<td>18.5±1.0(WR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Silk: 21.0±0.3(FR)</td>
<td>25.2±0.6(FR)</td>
<td>Silk: 1.29±0.3(FR)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Worsted: 5.8±0.2(FR)</td>
<td>4.3±0.1(FR)</td>
<td>Worsted: 1.32±0.4(FR)</td>
<td></td>
</tr>
<tr>
<td>Postle (1968)</td>
<td>Silk: 5.2±0.1(FR)</td>
<td>4.0±0.1(FR)</td>
<td>Silk: 21.0±0.3(FR)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Worsted: 5.8±0.2(FR)</td>
<td>4.3±0.1(FR)</td>
<td>Worsted: 25.2±0.6(FR)</td>
<td></td>
</tr>
<tr>
<td>Knapton et al (1968)</td>
<td>Wool: 5.54±0.2(FR)</td>
<td>4.23±0.1(FR)</td>
<td>Wool: 23.5±1.4(FR)</td>
<td>Wool: 1.31±0.3(FR)</td>
</tr>
</tbody>
</table>

contd
<table>
<thead>
<tr>
<th>Table 2.3 Contd.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton : 5.77±0.1(FR)</td>
</tr>
<tr>
<td>Cotton : 4.15±0.04(FR)</td>
</tr>
<tr>
<td>Cotton : 23.9±0.3(FR)</td>
</tr>
<tr>
<td>Cotton : 1.27(WR)</td>
</tr>
<tr>
<td>Cotton : 1.22(WR)</td>
</tr>
</tbody>
</table>
yarn, thickness of fabric was independent of loop length and related directly to the yarn diameter in fully-relaxed state of fabric.

Postle (1971a, 1974) has dealt with the lateral compression of weft knitted fabrics and its mechanisms. The thickness of the knitted structure is related to the curvature of the loops out of the fabric plane. He carried out a study on plain knit fabrics produced from a variety of yams, and found the pressure vs thickness (or stress vs strain) relationship to be highly nonlinear. He did not formulate any functional relationship between these two parameters. Instead, he proposed a model for each to estimate the fabric thickness and its bulk density in terms of the fabric construction and the fabric tightness factor. He found that the absolute value of fabric thickness is determined by fibre specific gravity and yarn linear density, and appears to depend only very slightly on the fabric loop length. Leaf (1971), who studied Postle’s work somewhat critically, pointed out that in respect of silk fabric, a relationship between loop length and thickness was observed and suggested some modifications in his model. Postle (1971) also suggested that there was a need to do much more work on compression of plain knit fabrics using different types of yams, and methods of measuring compressibility.

It may be noted that when the work on compressional properties of plain knitted fabrics was carried out by Postle (1971a), commercial instruments such as KES-F compression tester were not available. Also, parameters for quantifying the compressional parameters were not formulated. In fact, Postle used a technique developed by Brown (1966) in his work on the characterization of bulk. In a very interesting paper, Williams and Leaf (1974) have described an ingenious device, in Marsh thickness tester which is generally used for measuring thickness, for determining the thickness under zero load. The object is to obtain a compression thickness curve in the same form as that of stress-strain curve. A hysteresis curve has been obtained with compression and recovery. The relationship between thickness and stitch length has been studied for soft
cotton, mercerised cotton and continuous filament viscose rayon fabrics. The most important finding is that there is a tendency for the thickness to decrease as the stitch length is increased thus proving Leaf's (1971) views on the relationship between loop length and thickness. The lateral compression of double jersey fabrics produced from polyester yarns has been investigated by Hallos et al (1990) using the compression cell of Instron; the parameters studied are fabric hardness and compression recovery. Hardness of fabrics varies between 270.5 g/cm² to 1666.7 g/cm² and compression recovery ranges between 61.2% to 85.7%.

Pau-Lin-chen et al (1992) have demonstrated that the single jersey fabrics are characterised by lower WC and RC compared to triple cross tuck. Recently, an extensive work on the compression of weft - knitted fabrics has been reported by Akhther Begum (1994).

Kawabata (1981) has studied the compression of woven fabrics and found the non-linear relationship between pressure and thickness. He has defined several parameters to characterise this compressional behaviour; they include work done per unit volume (undeformed) during compression (WC) work done (per unit volume) during the recovery (WC), and resilience as the percentage ratio of WC and WC. Initial thickness of the sample (t₀) was defined as the thickness measured at 0.5 gf/Cm² (0.05 Kpa) pressure; tₘ designated the thickness at maximum pressure Pₘ. Kawabata proposed a linearity measure, LC defined by

\[ LC = \frac{WC}{(t₀ - tₘ) Pₘ/2} \]  \hspace{1cm} \text{(2.8)}

as one means of characterizing the compressional behaviour. In the extreme case, when the compressional curve is completely linear, the value of LC would be unity. These parameters, however, do not give any information about the fabric stiffness when subjected to compressional force.
The subject of geometrical thickness of knitted fabrics has been dealt with by Postle (1974) who has suggested a geometrical model for computing thickness, bulk density and specific volume; this model is, of course, based on the assumption that fully relaxed shape of the unit cell is similar for all knitted fabrics of the same type of construction. Thickness was found to be related to yarn diameter by the factor 2.6 and to loop length by a factor 0.147 for plain knitted fabrics. The proposed linear relation between thickness and loop length was, however, disputed by Knapton et al (1975).

Williams and Leaf (1974) have used a very low pressure namely [0-0.15 g/Cm², (0.015 KPa)] in their work; they are wrong in quoting the pressures used by Postle (1971) (85 KPa). Postle (1971) has used pressures ranging from 0-0.61 KPa for silk and nylon continuous filament fabrics while for all the staple fibre fabrics, a pressure range of 0-76 KPa has been used. Also, all the compression recovery curves for all the fabrics start from 0 in his paper (1971) and thesis (1965).

2.6 HANDLE, BAGGINESS AND PAD-BATCH METHOD OF DYEING OF WEFT-KNITTED FABRICS

A number of papers have dealt with the handle of weft knitted fabrics. A paper by Gong (1995) deals with the subjective and objective measurements of the weft-knitted fabrics. His views are that it will suffice if the shear and bending rigidities are tested to have an idea of fullness of garments. An excellent study covers the effect of design of doffing tube on yarn characteristics and, the quality of knitted goods. Lawrence and Finikopulos (1992) have studied the surface appearance of yarns made from various doffing tube types microscopically, and classified the structure. Changes in the doffing tube effected changes in the frequency of certain classes of wrapped structure, and in a number of the measured parameters defining the handle of the knitted fabrics. It has been found that smooth
doffing tubes have led to the lowest frequency of wrapper fibres and resulted in the best measured values for the softness of hand of a single jersey fabric. Thus this work represents an important contribution to knitted fabrics in particular on their appearance and handle.

In the subject of bagginess of weft-knitted fabrics, two types of testers which are used for measuring it have been discussed.

Pad batch method of dyeing cotton weft-knitted goods has been discussed by Janakiraman (1994). In order to avoid edge marks, some modifications have been made to the padding mangle design in that, the shore hardness of the rubber bowls has been reduced. Jaeckel, Jones and Potts (1982) have presented some interesting results on costs of reactive dyeing of cotton using winch, Jet or Pad-steam equipment. Their analysis has shown that pad-steam dyeing is worth consideration if the amount of material to be processed is sufficiently large. A survey of the dyeing of knitted cotton fabric in the U.K. showed a complete absence of semicontinuous or continuous dyeing, unlike the situation for woven fabrics and for knitted fabric. Most dyehouses used batch processing in winch or jet equipment and justified this choice on the grounds of expediency since the equipment was readily available. Murfet (1985) feels that there is a great determination to succeed in the pad-batch dyeing of circular weft knitted fabrics. Pad batch system of dyeing requires less alkali, less chemicals and water, thereby reducing the energy required. There are many pad-batch systems, which have been commercially produced for dyeing knitted fabrics, namely, AB calator, Beau-Tech, Goller, Jawatex, Kleinwefers, Jaeggli.
2.7 SUMMARY

A survey of literature, as above, shows that, although a considerable amount of work has been done on many areas related to weft-knitted fabrics, there are gaps which exist in them. The motivation for this thesis was thus to explore this less intensely investigated area, and to develop an understanding of the interaction between knitted fabric structure and properties.