CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION

It is a well known fact in the Textile Industry, that the production limits of conventional ring spinning have been reached, and there has been considerable activity in the development of alternative spinning systems. A major part of the work was directed at the short staple spinning sector, since this was where the majority of the ring spindles were concentrated.

This work has resulted in the development of a number of different spinning systems, each having its advantages and disadvantages. The advantages include factors like the elimination of certain of the preparatory processes, higher production rates, reduced power consumption, or simply better working conditions.

Most of these systems exist in special niches they have carved out for themselves. These systems will not be found outside a narrow product or count range. The spinning system that has shown the most promise and has the widest range is "rotor spinning". This is a system that spins yarn on the open end principle.

1.1.1 THE THEORY OF ROTOR SPINNING

The principle of open end spinning has been well known since the fifties and various organisations were working to produce a practical machine working on this principle. A number of different methods of spinning the open end of the yarn were in the process of development at this time. These include 1) Vortex Spinning, 2) Axial Spinning, 3) Discontinuous assembly, 4) Friction spinning and 5) Rotor Spinning.
FIGURE NO. 1.1 SCHEMATIC OF A ROTOR SPINNING HEAD
The rotor method was the first to be developed commercially. In this system after preliminary separation, individual fibres are carried by an air stream into a spinning rotor and laid onto the collecting surface on the inside of the rotor. A continuous strand of fibres is assembled around the circumference of the rotor (Figure 1.1).

A seed yarn end is inserted through the yarn withdrawal tube till it comes in contact with the collecting surface. There the spin of the rotor twists the end into the strand of fibres. Yarn withdrawal then commences so that the strand is peeled off the collecting surface.

As the yarn is withdrawn through the tube, theoretically one twist is inserted for each revolution of the rotor (practically there is some slippage at the open end and the actual twist is always less than that of the theoretical twist).

As the strand is peeled off, it is continuously regenerated by the stream of fibres arriving at the collecting surface. The yarn withdrawal point moves in a circle around the collecting surface (a consequence of this is that one twist is lost or gained for each such rotation, however in practice this is negligible compared to slip at the open end).

The withdrawal point usually moves in the same direction as the rotor is spinning, and the yarn being withdrawn follows a smooth curve to the withdrawal tube mouth. This is normal and produces a yarn with a good appearance.

Sometimes there is a spontaneous change of the direction of the yarn withdrawal point. This 'reverse withdrawal' results in air drag forcing the yarn to form a 'S' shaped curve between the withdrawal point and the tube mouth. The appearance of such yarn is poorer than normal.

The yarn withdrawn from the rotor is passed onto a winding head which usually winds a cheese type of package of up to three kg. weight.
1.1.2 HISTORY OF ROTOR SPINNERS IN INDIA

The first commercial machine, the BD200 was displayed by Investa, a Czechoslovakian company in ITMA at Milan. Production of this machine began in 1967, and over three million rotors were manufactured by 1982.

Investa’s early lead in this field was soon lost to manufacturers in the western countries particularly in the U.S.A. and Germany. The early models of the BD200 worked at rotor speeds of 30000 RPM. However, by 1973 this had been raised to 36000 RPM and to 60000 RPM by 1977. By then, however, American and German second generation rotor machines had taken over the technological lead from Investa, and also a large part of the market share.

Indian mills were slow to take up this new technology. The reason was probably twofold. There was a conservative suspicion of new technology in the case of the majority of the mills. The few innovators were discouraged by government pressure, for the politicians saw rotor spinners as a potential cause of increased unemployment. (Similar pressure existed in the case of chute feed systems also.)

However, BD200 systems were introduced in a few cases here and there, but a lack of understanding of the new technology, improper production techniques and wrong product mixes doomed most of these early efforts.

Rotor spinning frames were seen as magic machines that could take the worst raw material and produce yarn from it. This resulted in the production of markedly inferior yarn, and the yarn quality was blamed on the production method rather than the poor nature of the feed stock. Indians were not unique in this misconception. The production of inferior yarn by Japanese producers in the late seventies gave rotor spinning a very bad reputation in that country from which it was slow to recover. The early users of rotor machines in the U.S.A. had troubles too.

After this debacle, interest in rotor machines almost died out among the Indian mills. Educational and research institutions continued to investigate the
technology, and a few prototype machines were manufactured and tested.

However, it was only in the mid eighties that interest in rotor machines began to revive among the mills. Predictably this revival began with the exporting mills. They were more aware of the foreign textile scene, and of developments in rotor technology.

The real beginning of Rotor Spinning in India can, however, be traced to the decision of the Lakshmi group to manufacture the Rieter open end spinner under license in India. This third generation machine fitted with a modern trash extraction system, and electronic controls is the machine on which this study was done.

The advent of the Rieter M series of machines has not resulted in the elimination of the older systems. The reason for this is economic. The cost of a BD200 system with tandem cards is less than half of that of the more modern machines, and the quality of the yarn produced is adequate for the Indian Market. Many of the older machines have been modified by being fitted with the Dutch rotor which gives an improved production and yarn quality. The exporters and everyone else who can afford them are going in for the new machines.

1.2 SYNOPSIS OF PREVIOUS WORK

1.2.1 INTRODUCTION

There have been many studies on the technology of rotor spinning, and a large number of papers discuss the effects of various parameters like opening roller speed, rotor diameter, rotor speed, twist factor, count etc. on the yarn qualities.

Some papers discuss a number of properties for a single type of yarn or a small group of yarns. Other papers discuss a single property or a small group of related properties for a wide range of fibres.
Numerous workers have done work on different aspects of this problem. Carnaby and Grosberg [1] have studied the relative behaviour of blend components in determining the structure of wool carpet yarns spun on various systems including rotor systems.

Barella et al. [2] have made very useful contributions on the application of computers for the statistical optimization of various parameters using reduced factorial designs that lower the number of discrete experiments that have to be undertaken. Several authors have found inspiration in their work, and a number of papers have appeared applying reduced factorial designs for the study of various parameters in rotor and other types of open end spinning.

That so many papers have been written on the subject is evidence of the growing importance of Rotor Spinning as a means of yarn production. For the sake of convenience, we shall discuss the effects of each parameter under a single heading clubbing together the material from the various sources.

1.2.2 THE EFFECT OF FIBER PROPERTIES

1.2.2.1 FIBER LENGTH

In respect of ring spun yarn, the strength shows an increase with an increase in fibre length, but rotor yarns are insensitive to changes in fibre length. London and Jordan [3] have found that this is the case. Very little change was noted when the fibre length was changed from 32 mm. to 50 mm.

Lunenschloss et al. [4] have stated that in contrast to the strength values of ring spun yarns, the maximum tension curves of rotor yarns display a tendency to decrease as the long fibre content increases. They attributed this to an increasing twist inhomogeneity across the yarn cross section, and an increased formation of 'belly binders' (wrapper fibres). Since these make almost no contribution to yarn strength, the number of fibres carrying load have decreased.
The same workers have said that the elongation values of polyester yams decreased when the long fibre content went up. This was in contrast to cotton yarns spun on the same frame, whose elongation increased as the percentage of long fibres increased. They found that for fine yarns the strength and elongation increase at first with increasing fibre length but that above a fibre length of 35 mm, the negative effect of long fibres predominated leading to increasing twist inhomogeneity and wrapper fibres.

Vaughn and Rhodes [5] found that yarns spun from short staple fibres are stronger and more even and have fewer thin places and neps than yarn spun from medium length fibres. On the other hand, they found that medium length fibres produced yarn with a higher elongation.

From another study, it has been found that opening roller damage of fibres is increased by increasing fibre length. Chattopadhyay [6] has observed that an increase in the fibre length not only increases the total number of broken ends but also increases the number of multisegmental breaks perhaps because of the greater time a longer fibre is exposed to the action of the combing roller. The yarn strength was found to increase with increasing fibre length for cotton.

Another work [7] shows that an increase in mean fibre length causes an increase in the strength of rotor spun yarns. In another paper [8] it is found that beyond a certain fibre length, there is no further increase in yarn strength.

As regards the relationship between fibre length and the incidence of wrapper fibres (belly belts), it has been found that longer fibres lead to an increase in the percentage of wrapper fibres.

Salhotra [9], who investigated the relationship between fibre length and the incidence of wrapper fibres on a Suessen O.E. Spintester using viscose fibres, observed that as the staple length increased, the wrapper fibres shows an increasing trend.

Keller [10] has found that during each revolution of the rotor, the yarn end passes under the fibre feed point once, and any yarn settling there and bridging.
the gap can be spun into the yarn in such a manner that the trailing end of the fibre wraps around the yarn at a very high angle to the yarn axis.

When long fibres are being spun, such places can be so tightly wrapped that they look like a thin place though in fact their linear density is much greater than average because of the fibre wrapped around them. In fact such places show up as thick places and neps when the yarn is scanned in an Uster Tester.

In the case of short staple fibres, the belts can be so slack that they can work free and move independently over the yarn surface. Such loops are a source of trouble for further processing.

It has been pointed out that the number of wrapper fibres and incompletely bound in fibres is related to the length of the tie in zone, the fibre length to rotor diameter ratio, the number of fibres in the yarn cross section and the fibre linear density. Further it has been said that the yarn properties deteriorated rapidly with increasing wrapper fibre formation.

According to Heap [11] longer fibres produced more wrapper fibres than shorter fibres and such fibres contribute very little to the yarn strength.

Coll Tortosa [12] found that the twist in zone should be made as small as possible to minimise wrappers as well as incompletely bound in fibres.

Long staple rotor spun yarns are much weaker and slightly less extensible than corresponding ring spun yarns. Grosberg and Abou Zeid [13] and Frey [14] concluded that ring spun yarns have better evenness and elongation than rotor spun yarns for fibre lengths greater than 30 mm. The difference in strength between rotor and ring spun yarn was found to decrease as the yarns became coarser. Landwehrkamp [15] observed that the difference in tenacity between rotor and ring spun yarns is minimum for yarns spun from short fibres. In terms of regularity and elongation, however yarns spun from longer fibres were closer to each other.
Landwehrkamp [15] has presented the following equation for calculating the ratio of wrapper fibres (p).

\[ p = \frac{l}{\left(\pi \times D\right)} \]  (1.1)

where \( l \) is the staple length and \( D \) the rotor diameter.

Alaiban [16] has found that the optimum fibre length for getting maximum tenacity from viscose fibre seems to be around 30 mm. irrespective of the rotor diameter.

1.2.2.2 FIBER CROSS SECTION

Sengupta, Chattopadhyay and Majumdar [17] have carried out a study on the effect of cross sectional shape of polyester and acrylic fibres on the structure and properties of rotor and ring spun yams. It has been found that the cross sectional shape of the fibre affects the tensile behaviour of rotor spun yams significantly. This has been attributed to the changes in interfibre cohesion due to changes in shape. The strength of ring spun yams is governed by fibre strength, while that of rotor yarn is largely influenced by interfibre cohesion and packing density.

1.2.3 THE EFFECT OF MACHINE VARIABLES

A great deal of work has been done on the effect of draft, opening roller speed, rotor diameter and rotor speed on the yarn properties. Rotor diameter and profile have a significant influence on the rate of production, yarn quality and power consumption.

1.2.3.1 ROTOR SPEED

Grosberg and Mansour, [18] in their study with a 46 mm rotor and using cotton of 32 mm. staple length, have demonstrated that yarn strength improves slightly with increasing rotor speeds (up to 90,000 RPM). The twist factor for
maximum yarn strength appears to be independent of rotor speed, and is around 57 for a 37 tex yarn. At normal twist factors, the rotor speed has little effect on variation in yarn strength. Yarn irregularity (CV) increased significantly with increasing rotor speed, whereas the yarn extension at break decreased considerably, as the rotor speed increased. The yarn also became less bulky and more compact.

1.2.3.2 ROTOR DIAMETER

A number of authors have reported work on the effects of rotor diameter. Barella et al. [2] using two rotor diameters in a Suessen rotor frame (46 mm. and 56 mm.) for spinning cotton of staple length 30.5 mm have found that increase in rotor diameter generally improves the yarn regularity, particularly at low speeds and low twist, but not when low speeds occur in connection with high twist. The tenacity drops significantly when the rotor diameter increases whereas the elongation at break is only slightly affected by the rotor diameter at low speed but is very much affected when the rotor speed is above 40,000 RPM. The 56 mm. rotor produced an appreciable drop in elongation at break over the whole twist range. Finally Barella et al. [2] report that the 46 mm. rotor seems to be more suitable than the 56 mm. rotor.

In a separate study, they confirmed that an increase in rotor diameter had led to an improvement in yarn evenness and a deterioration in strength and elongation. However they reviewed some work on the influence of rotor diameter on yarn properties and explained the improvement in regularity as being due to the improved fibre separation and doubling that occur when the rotor diameter increases.

The process is also influenced by the degree of fibre parallelisation, which is greater for the larger diameter rotor (this is due to the fact that the greater centrifugal force in a bigger rotor extends the fibres to a greater extent).
The influence of rotor diameter on wrapper fibres was also investigated. It was found that belts were more frequent and more tightly wound in the case of smaller rotors. It follows that if belts are considered as yarn defects they will influence irregularity values and imperfection counts. Also the greater number of wrappers in the case of yarn from smaller rotors could explain the greater strength of these yarns, though the exact contribution of belts to this parameter has not been determined.

Barella et al. [2] have observed that the average number of belts in 25 mm. of yarn as 3.5 and 2.7 for 46 mm. and 56 mm. rotors respectively. They consider this sufficient to explain the improved evenness by the argument stated above.

It is a well known fact that the maximum fibre length must not exceed the rotor diameter. Gayler and Schuren [19] have reported that the most common ratios of staple length to rotor diameter are found in the range from $1 : 1.15$ to $1 : 1.5$.

The rotor size is normally chosen so that the fibre staple length is between the rotor radius and the rotor diameter and rotors with a radius of 90 mm. are reported to have spun fibres of staple lengths of up to 63.5 mm. Shah [18a] has shown for viscose yarns that a large diameter has produced a very even yarn which is contradictory to the findings of Grosberg and Abou Zeid [13] who have demonstrated that large diameters do not give a more uniform yarn. According to Gayler and Schuren [19] for extremely short fibres a staple length to rotor diameter ratio of up to $1 : 3$ may be necessary for successful spinning whereas for extremely long fibres a ratio of $1 : 1$ may be sufficient. In another paper, they show that rotor diameters which are too large in comparison with fibre length result in unnecessary high yarn tension whereas too small a diameter impairs the yarn formation and results in a higher irregularity and more end breaks. Radhakrishnaiah [20] has concluded that an increase in the length of viscose fibre from 27 mm. to 38 mm. increases the strength of the yarn due to improvement in
the length of the belts and when the fibre length is further increased, no further beneficial effect is observed. He also stated that in a yarn composed of long and short fibres the longer fibres predominate as belts. Balasubramanian [21], while studying the effect of rotor diameter on yarn characteristics, concluded that yarn spun from a larger rotor has higher uniformity but possess lower strength, breaking elongation and yarn quality index. He attributed the decrease in yarn tenacity to a lower spinning in coefficient and that of breaking elongation to the higher spinning tension. Stalder [22] has found a deterioration in yarn properties with an increase in rotor speed.

1.2.3.3 OPENING ROLLER SPEED

Many workers have investigated the effect of opening roller speed on the characteristics of rotor spun yarn. Vaughn and Rhodes [5] reported that at too high a opening roller speed the fibre damage increases and yarn strength deteriorates.

Chattopadhyay [6] has carried out an extensive study on this aspect. Siersch [23] has found that the opening roller speed in the range of 6000 to 9000 RPM does not effect the evenness, tenacity and friction for polyester and polyester / cotton yams. Too low a speed results in inadequate fibre separation, and too high a speed level to extensive fibre breakage and a drop in yarn strength. Opening roller speeds are somewhat higher for synthetic fibres than for cotton but excessively high speeds can damage the fibres.

Barella et al. [24] have found in respect of 30 Tex 67/33 polyester / cotton blended yarn, that there is a deterioration in yarn characteristics chiefly due to the breakage of fibres by the card.

For cotton yams, Barella and Vigo [24] have found that the optimum opening roller speed depends on whether the regularity or the tenacity is considered the more important parameter. If the regularity is to be improved, the
speed of the opening roller must be increased till the tenacity is at the lowest acceptable value.

Balasubramanian [21] has found that an increase in the opening roller speed results in an improvement in the yarn quality index.

Singh, Grosberg and Oxenham [25], while working on the effects of opening roller speed on polyester cotton yarn, have found that there is a deterioration in yarn strength when the speed increases. They report that there is not much difference in the elongation and unevenness. Their general conclusions are that at any fibre feed level for optimum yarn properties, an opener speed capable of individualising and straightening the fibres to a maximum extent without rupture is required. At this speed, most of the yarn properties achieve their optimum values. Below this optimum speed, although the fibres are not damaged, the lack of fibre individualisation and orientation results in a deterioration of yarn qualities. Opener speeds higher than the optimum tend to rupture the fibres and the straightening effect is lost.

Rakshit and Balasubramaniam [26] have reported on the effect of opening roller speed on 14 Ne and 24 Ne yams. They have shown that both the medium and long term irregularity of the yarn are higher at low opening roller speed. As far as the single thread strength is concerned, it has been found that yarn strength improves with increase in opening roller speed up to 6500 RPM, and then drops as the opening roller speed increases further. In the case of 24 Ne yarn, single thread strength remains more or less the same till an opening roller speed of 6500 RPM, and then drops slightly, while the CSP shows a continuous drop from 4000 to 6000 RPM.
1.2.4 YARN PARAMETERS

1.2.4.1 YARN TWIST

Barella et al. [24] have found that for 30 Ne yarn, twist factor significantly influences the elongation but not the regularity and tenacity.

Alaiban [16] has demonstrated that yarn unevenness and imperfections of 40 and 60 Tex yarn increase with yarn twist.

The increase in twist loss and in yarn unevenness with increasing twist factor for a given count appears to be an associated phenomenon.

A higher twist factor produces a yarn with a higher coefficient of friction, though the magnitude of the increase is small, and a decrease in yarn count also shows an increase in the coefficient of friction.

A similar finding has been reported by Castatos [27] which he attributed to increase in twist variability at higher factors. He has demonstrated that at higher twist levels, the wrapper fibres are coiled more tightly around the yarn thus creating tight spots and increasing the bulk variation of the yarn. This changes the area of contact and results in a change in the frictional properties of the yarn.

On the effect of twist on the bending behaviour of rotor spun yarn of 30 Tex, Hari [28] has given data which demonstrate that there is a marginal difference in the coercive couple, initial elastic flexural rigidity and flexural rigidity. Interfibre friction as represented by the coercive couple is greater for rotor yarns than ring yarns.

Subramaniam et al. [29] have demonstrated that twist increases the coercive couple presumably due to the wrapper fibres. Bending rigidity shows a marginal increase with an increase in twist factor, and bending recovery shows a deterioration.

Thierron [30] has reported that values of flexural rigidity for rotor spun yarns are about thirty percent higher than those for ring spun yarns.
Ly and Denby [31] working on wool have reported that the bending hysteresis (the coercive couple) increases as the maximum curvature attained in a cyclic bending test increases. This has been attributed to the viscoelasticity of wool fibres, and it is thought the frictional couple has a viscoelastic component as well.

Dhingra and Postle [32] and Elder and El-Tawashi [33] have also made useful contributions to the bending behaviour of various types of yams.

1.2.5 BENDING

1.2.5.1 THEORETICAL INVESTIGATIONS

The bending properties of yams strongly determine many fabric properties like stiffness, handle, drape and crease recovery. Livesey and Owen [34] were able to obtain the bending hysteresis curve which characterizes the bending properties of yams and fabrics. Two important parameters in bending behaviour were established, the bending or flexural rigidity, represented by the slope of the hysteresis loop and the coercive couple, which is the width of the hysteresis loop at zero curvature. The bending rigidity was attributed to the elastic properties of the fibre material and the coercive couple was thought to arise from interfibre friction. Chapman [35] has shown that wool and nylon fibres at low bending strains (usually < 1%) are linearly viscoelastic and that fabric composed of linearly viscoelastic fibres behaves as an anisotropic linear viscoelastic sheet with an internal frictional element. Thus viscoelasticity and fibre friction both contribute to the width of the hysteresis loop in bending.

Since fabrics are woven from yams that are in turn composed of twisted fibres, an understanding of the bending properties of single fibres and yams is necessary to formulate the mechanics of fabric bending. Most work on bending has concentrated on fabric bending however, and little work has been reported on yarn and even less on single fibre bending.
The Bernoulli - Euler law describes the pure bending of a solid prismatic beam of uniform crosssection. It states that the applied bending moment under suitable conditions of crosssectional symmetry is proportional to the resulting change in the center line curvature \( K \). That is:

\[
m = A \times (\delta K) = A \times (K - K_0)
\]

(1.2)

where \( K \) and \( K_0 \) are the values of the new and original curvatures respectively and \( A \) is the bending rigidity of the beam. The bending rigidity \( A \) is the product of the elastic modulus \( E \) and the crosssectional moment of Inertia \( I \) about the neutral axis perpendicular to the plain of bending. The bending of yarns however differs from that of solid beams. It is strongly influenced by the degree of ease or restraint with which the fibres can move with respect to each other in order to accommodate the total deformation due to bending. The nature and the degree of the constraint are governed by the level of twist in the yarn and the surface properties of the fibres. In yarns in which the freedom of relative fibre movement is high, the fibres are assumed to bend more or less independently of each other. Consequently the yarn bending rigidity is effectively equal to the sum of the bending rigidities of individual fibres. Thus the bending rigidity of such a yarn is proportional to the number of fibres in its cross section.

The bending or flexural rigidity \( A_y \) of a yarn is usually defined by the relation between the bending moment \( m \) and the curvature \( K \) (the reciprocal of the radius of curvature \( l \)). If that relation is linear then

\[
A_y = \frac{m}{K}
\]

(1.3)

If not it is defined locally by the rate of change of the bending moment with respect to the curvature, ie.

\[
A_y = \frac{\delta m}{\delta K}
\]

(1.4)

Analysis of the bending behaviour of yarns therefore consists in relating \( A_y \) to the fibre properties and the parameters of the yarn structure. It is almost always
based on the idealizing assumption that fibres in a yarn follow right circular helical paths of constant pitch.

It was Backer [36] who carried out a purely geometric analysis of a yarn bent into a torus of constant radius. He calculated the total fibre strain for the two extreme cases of deformation, one with complete freedom of movement for the fibres relative to each other, and the other with complete lack of movement. He concluded that if the fibres in the yarn were completely free to change their paths, no fibre strain would develop during bending of the yarn. On the other hand, if complete restriction of fibre movement was imposed, maximum strain would occur in the fibres lying on the outside (tensile) and inside (compressive) of the torus.

Platt et al. [37] developed this analysis further and developed moment/curvature relations for the two extreme cases postulated by Backer. They showed that the yarn bending rigidity can be expressed as:

$$A_y \text{ (complete freedom)} = N \times A_f \times f_1(\theta)$$  \hspace{1cm} (1.5)

$$A_y \text{ (no freedom)} = \frac{4 \times N^2 \times A_f \times f_2(\theta)}{P_y}$$  \hspace{1cm} (1.6)

where $N$ is the number of fibres in yarn cross section, $A_f$ is the bending rigidity of a single fibre, $f_1(\theta)$ and $f_2(\theta)$ are structure related modifying functions defined by the surface helix angles $\theta$ of the unbent yarn configuration and $P_y$ is the yarn packing factor defined as the ratio of the area occupied by fibres to the total area in the yarn cross section. The values of the ratio of $f_2(\theta)$ to $f_1(\theta)$ is approximately constant and ranges from 0.2 to 0.25 over a range of twist angles from 0° to 35°. Yarn bending rigidity in the ‘no freedom’ case therefore is approximately $N/P_y$ times that in the ‘complete freedom’ case. In both cases it decreases with an increase in twist and more so in the ‘no freedom’ case.

Livesey and Owen [34], on the other hand considered the yarn to be a collection of independent noninteracting helixes and determined its bending rigidity under the assumption of infinitesimal elastic deformation. They determined the
minimum fabric rigidity from the equation:

\[ A_y = N A_f \times \frac{2}{\left[1 + \left(\frac{A_f}{C_f}\right) \times \tan^2 \theta\right]} \times \ln\left\{1 + \tan^2 \theta \times \frac{\left(1 + \frac{A_f}{C_f}\right)}{2}\right\} \]  

where \( C_f \) is the fibre torsional rigidity.

Grosberg [38] has shown that for low twist angles the two solutions (by Platt et al. and Livesey and Owen) give similar values when the bending and torsional rigidities of the fibres are equal.

Leaf [39] calculated the large deformation of a helical spring by numerical integration and found that even for large deformations Livesey and Owen's equation is accurate to about 2%. According to Livesey and Owen [34] and Platt et al. [37] in an analysis that assume 'complete freedom', yarn flexural rigidity decreases by about 20-30% for an increase in helix angle from 0° to 35°. However in practice as noted by Grosberg [38] yarn flexural rigidity is observed to increase by 200-300% for such an increase in helix angle. Leaf [39] and Grosberg [38] point out that the position of the neutral axis moves towards the center of curvature as the curvature of the helix increases. Furthermore as a helix is bent and its curvature increases its length below the neutral plane decreases whereas that above the neutral plane increases. Thus multiple concentric helixes in contact with each other cannot bend without interfering with each other. Work must be expended to overcome friction during displacement of neighboring helixes in contact with each other under transverse pressure.

Platt et al. [37] in their 'clustering' analysis recognised the existence of this interference phenomenon. They defined clustering as the case when a group of fibres act together as one owing to 'infinite friction'. They demonstrated that if groups of two fibres would act together, the yarn rigidity would increase by a factor of three. In the complete lack of freedom case, the rigidity was estimated to be about \( \frac{N}{P_y} \), that of the complete freedom case as alluded to earlier.
In the investigations discussed so far it has been assumed, implicitly that the yarn retains the stress developed as a result of twisting. Platt et al. [37] investigated the effects of relaxation of these stresses. Their theoretical estimate suggested that a decrease in yarn bending rigidity due to relaxation was only nominal.

Popper [40] and Grosberg [41] idealised the yarn as a multilayer beam having friction between the layers. The role of fibres in the yarn is considered analogous to that of the postulated layers. They proposed that the inter-element friction produces (i) stiffness of the structure, (ii) nonlinearity in the moment / curvature relationship and (iii) energy loss and therefore non recoverability of the bending deformation on release. Grosberg argued that until the limiting frictional force between fibres is overcome, no slippage takes place, and the yarn acts as a rigid beam, as the limiting frictional forces are overcome the moment / curvature relationship becomes linear. The governing equations are of the form:

\[
\frac{1}{\rho} = 0 \text{ when } m \leq m_0 \tag{1.8a}
\]

and

\[
A_y / \rho = m - m_0 \text{ when } m > m_0 \tag{1.8b}
\]

where \( \rho \) is the radius of curvature and \( m_0 \) the couple required to overcome the frictional forces. The parameter \( m_0 \) is sometimes known as the coercive couple or as the frictional moment (in the literature of the Kawabata pure bending tester this parameter is referred to as \( 2HB \)).

The deformation of an assembly of elastic and frictional components has also been used by Olofsson [42] to investigate the cases of both loading and recovery.

In respect of bending of woven fabrics Olofsson [42] found that Livesey and Owens’s [34] experimental observations are in good agreement with the above equations.
Abbott et al. [43] have proposed an improved approximation of the moment curvature relation of yarn before the frictional forces are overcome. Their equation is:

$$\frac{1}{\rho} = \frac{(m - a m_0)}{A_y} \text{ when } m \leq 2m_0 \quad (1.9a)$$

and

$$\frac{1}{\rho} = \frac{(m - m_0)}{A_y} \text{ when } m > 2m_0 \quad (1.9b)$$

where $a = (m/m_0) - (m/2m_0)^2$

In this form of the equation after the initial nonlinear region, the slope of the moment curvature curve is constant. Hence for $m > 2m_0$ the solution is the same as that given by Grosberg (equation 1.8b).

Dhingra and Postle [32] have derived an expression for the coercive couple of a yarn which still retains all or part of the spinning stresses in the fibres. If 'Q' is the "radially directed lateral force per unit length" at the longitudinal axis of the yarn, then as defined by the authors

$$m_0 = 0.08 \times \mu \times l_t \times d_f \times N \times Q \quad (1.10)$$

where $\mu$ is the coefficient of interfibre friction, $d_f$ is the fibre diameter and $l_t$ is half the length of the twist repeat. The authors based their derivation for $m_0$ on a similar expression from the analysis by Grosberg [41], who derived his expression from the moment required to overcome the internal friction in a sheet laminar structure under externally applied transverse pressure. It approximates to the behaviour of a yarn in a woven fabric, where it experiences a lateral compressive pressure in the crossover regions. The geometry and the loading conditions of the problem defined by Dhingra and Postle [32] are entirely different. Here there are no externally applied lateral pressures. The radial compressive force or pressure created is entirely due to the tension in the constituent filaments, their geometrical configuration and their bending and torsional rigidities. Equilibrium requirements suggest that the radial pressure must increase monotonically from zero at the surface to a maximum value at the center. The concept of the 'radially
directed lateral force/unit length at the longitudinal axis of the yarn’ is therefore different from that considered by Grosberg [41]. Dhingra and Postle [32] have estimated the value of this parameter from the work of Batra [44] who showed that, for a filament under tension $T$ to be wound into a helical configuration with helix radius $a$ and angle $\phi$, a normal reaction force intensity (force/unit length) $F$ was required. $F$ may be defined as:

$$F = T \sin^2 \phi \left( \frac{A_f - C_f}{a^3} \right) \left( \sin^4 \phi - \cos^2 \phi \right)$$ \hspace{1cm} (1.11)

The above does not represent the radial pressure or force intensity at the axis of the yarn. Dhingra and Postle further suggested that the force $Q = F$ calculated by the above is contributed by all the fibres in the yarn cross section, and that these contributions are equal. The source of these assertions therefore is not clear.

Huang [45] in 1979 considered a logical modification of Grosberg’s moment/curvature model for yarn bending. He argued that (i) the relationship is well known to be nonlinear, (ii) the initial bending rigidity decreases as the curvature increases, until a limiting value is reached, and remains constant thereafter; and (iii) the decrease in bending rigidity is caused by the slippage of fibres in increasing numbers. At the limiting point, most if not all of the fibres are slipping past each other to accommodate the local deformations due to bending.

Huang therefore proposed that a bilinear moment/curvature relationship would be a more realistic representation of the actual behaviour and formulated the following set of equations:

\begin{align}
  m &= A \times K \text{ when } -m_a < m < m_a \\
  m &= m_a(1 - A/A^*) + A \times K \text{ when } m > m_a \\
  m &= m_a(1 + A/A^*) + A \times K \text{ when } m < -m_a
\end{align} \hspace{1cm} (1.12a,b,c)

where $A^*$ and $A$ are the initial and final bending stiffness respectively and $m_a$ is the value of the moment at the transition point.
Freeston and Platt [46] in 1964 assumed similar behaviour in their study of the bending recovery of monofilament yarns.

Grey [47] has made a very useful contribution to the bending behaviour of fabrics. He has postulated that the bending behaviour of a woven fabric can be represented by a block diagram of the kind shown below:-

\[
\begin{array}{c}
\text{GLVE} \\
\text{F}
\end{array}
\]

Here GLVE is a general linear viscoelastic element of the type described by Chapman [48] and F is a friction element. A large part of the work is taken up in showing that F can be split into two elements in series i.e.,

\[
\begin{array}{c}
\text{F} \\
\text{S} \\
\text{GLVE}
\end{array}
\]

in which S represents the friction at fibre to fibre contacts, and GLVE as before is a general viscoelastic element representing the fibre material which transmits the frictional forces. The complete model therefore becomes:-

\[
\begin{array}{c}
\text{GLVE1} \\
\text{S} \\
\text{GLVE2}
\end{array}
\]

Grey summarises his reasoning behind the development of the model as follows:-
(i) Fibre deformation and interfibre friction effects are independent and additive,
(ii) The moment arising from fibre deformation arises as a GLVE moment (GLVE1 in the model),
(iii) Frictional forces arising at a fibre surface are transmitted through the fibre before they become part of the fabric bending moment,
(iv) The moment arising from friction between fibres is transmitted through the fibre mass as a GLVE stress (GLVE2 in the model),
(v) The frictional force arising at a fibre to fibre contact depends on the normal load at the contact and the rate and direction of relative sliding. Thus $S$ is both speed and strain dependent.

The model behaviour was quantitatively similar to that found in real fabrics, but the final conclusion was that the model is still too simple to completely describe the behaviour found in real fabrics.

1.2.5.2 EXPERIMENTAL STUDIES

The first experimental study on bending of yams was carried out by Dhingra and Postle [32] using a pure bending tester based on the design of Chapman [49]. They have reported that the resistance to bending of a low twist yam depends on the bending rigidity of the fibre, the yam linear density and any setting treatment given to the yams. Yarn bending rigidity is approximated by a simple summation of the constituent fibre bending rigidities. For low twist yarns, a considerable freedom of movement exists between the fibres during yarn bending, and the interfibre friction increases proportionately with increase in yarn linear density. They have found that, in respect of worsted yarns, however, that bending rigidity decreases with increasing yarn twist, but twist has very little effect of the frictional couple.

They have demonstrated that the bending moment of a blended yam is equal to the sum of the individual components in the case of nylon-wool blended yams.
Elder and El Tawashi [33] have presented data on the bending properties of yarn. Looney [50] has measured the bending properties of 20 tex (65/35 polyester-cotton blended) yarn spun on ring, rotor and air jet machines using a Kawabata pure bending tester. His finding is that rotor spun yams are stiffer than the ring spun yarns and he attributes it to the presence of wrapper fibres in rotor spun yarn. Fibre denier was found to have a minor effect on the bending properties of the rotor spun yarns while it significantly affects the bending behaviour of air jet spun yarns. Hysteresis losses were found to increase with the use of finer denier polyester fibres, presumably due to an increase in the number of wrapper fibres.

Sakaguchi et al. [51] have studied the effect of yarn bending stiffness on the tensile property of wool fabrics. They have found that the bending stiffness of coarse wool yarn on the fabric tensile properties is not significant.

A recent paper by Collier et al. [52] discusses the bending behaviour of internally reinforced rayon fibres. Daneshwar [53] has investigated the frictional and bending properties of yarns. Ghosh et al. [54] have presented a critical review of the bending behaviour of plain woven fabrics.

1.2.6 BUCKLING

The idea that the comfort properties (a highly subjective property) of textile materials can be objectively assessed by measuring their mechanical behaviour when subjected to low stress is a fairly recent one.

Possibly the idea may have occurred earlier to some research workers but at that time the technology did not exist to pursue the concept to its logical conclusion.

The advent of electronic testers with automatic data logging permits not only the measurement of small forces and their effects, but also allows new modes of testing that can draw conclusions about factors that were previously considered too variable to be reliably tested.
The parameter axial compression is a measure which represents the ability of the yarn to resist buckling. The criteria which reasonably need to be observed in the conducting of these tests are that 1) the specimen weight should be small in comparison to the measured bending or buckling loads, 2) the compression device should introduce only a small error to the measured quantities and 3) the specimen aspect ratio of length to diameter should be large. It is a well known fact that if the compression load exceeds a critical value the yarn will buckle. The load at which this happens is called the buckling load and before buckling occurs the yarns are compressed a certain distance. The total compression at the buckling load is called the buckling compression and in the case of fabrics it determines the formability of the fabric. The buckling compression can be measured directly from the buckling curve or calculated from the compressibility in the plane of the fabric and the value of the bending stiffness. The compressibility is the inverse slope of the first portion of the buckling curve.

Grosberg [55] have summarised the work on buckling of fabrics, taking into account elastic behaviour and interfibre friction.

Olofsson [56,57] and Sadowsky et al. [58] have treated the buckling of microfibres in composite materials. Haringx [59] dealt with compressive buckle of helical springs, which in a way stimulated the structure of two or three ply yarn. He also considered the effect lateral elastic restraints in such structures.

Amirbayat and Hearle [60] have studied the buckling of reinforcing fibres in an elastometric matrix, as a result repeated flexing accompanied by slippage.

Menzies [61] has treated the buckling of twisted structures under the combined influence of torsion and tension. He was able to show the usefulness of the classical torsional buckling relationship for an elastic rod as applied specifically to yarn strands ie.

\[ \frac{L^2}{L^2} = 4 (EI \times P) + \frac{4(EI \times \pi)^2}{L^2} \]  

(1.13)

Where \( M_t \) is the torque at buckling, \( EI \) is the bending rigidity of the yarn, \( P \) is the tensile load and \( L \) is gauge length between the torsional jaws. Menzies
attempted to derive a value of $EI$ based on yarn geometry and fibre properties.

Since buckling also results when twisted fibre assemblies are subjected to axial compression some studies have been carried out using tire cord. Wood and Redmond [62] have attempted an analysis of the structural interaction of tire cords subjected to axial compression and their experiments bear out their predictions generally. The compression vs. load curve for rubber blocks containing 30 rayon cords has been studied by them. The studies included yarns with 5 and 12 twists per inch. The shape of the curves obtained with 5 TPI yarn is quite different from that obtained when the 12 TPI yarn has been used.

An added comparison between rubber embedded cord behaviour in tension and in compression has been made by Clark [63] for rayon cords. He reports similar data for embedded nylon cords, the elastic moduli being higher in tension than in compression.

Wood and Redmond [62] have used a transparent rubber slab for their compression tests and were able to show two distinct mechanisms of cord compression.

First at low twists, they observed distinct zig zag buckling of the cords. They also reported that when the cord reinforced slab bent for the first time it exerted a large resistance, which suddenly decreased as the low twist cords collapsed and buckled. At the point at which the cords buckled adhesion breakdown occurred in such a marked fashion that it was actually heard as the slab bent.

In the case of the high twist yarns, cord buckling was less pronounced and as twist increased and eventually a value was reached where it disappeared. At this twist and above separation of the cord plies was observed, with each of the single yarns forming the ply compressing in a manner similar to that of a spiral spring.

Busby et al. [64] have also observed the expansion of cord diameter during compression.
In twisted structures buckling takes place with a well defined relationship between torque and axial load. Menzies [61] found the form of the relationship was linear for 'Manila Cordage'. The difference in behaviour between his samples and those of Wood and Redmond [62] was that torsional buckling was a gradual process whereby the axis of the twisted structure assumes a helical configuration, localising into a loose loop which then tightens on itself. The end point was one of complete local distortion and strain concentration such that if the specimen was straightened and then tested again, early buckling would reoccur at the same position.

Olson [65] has investigated the buckling behaviour of polypropylene monofilament of 0.74mm diameter following heat setting. First he used a Cambridge Extensometer to measure the buckling, and since there were a number of errors in the instrument, he fabricated a compression cage for use on the Instron.

His main objective was to apply the energy method to fibre buckling, and then to make a comparison with the results calculated by the force method. In the experimental work on fibre bending under axial compression, theoretical approaches to fibre bending by force methods and energy methods were compared by him. A theoretical expression for the load compression behaviour could not be obtained as no computer was available to him. However by sacrificing some accuracy, he obtained a simplified expression for the load compression behaviour based on the energy method.

Although Olson's work is a useful contribution to the area of energy methods, his work has not dealt with the buckling of spun yarns.

Konopasek [66] pioneered the use of numerical analysis to solve a variety of boundary value problems occurring in the area of fabric deformation. Clapp and Peng [67] have obtained numerical solutions in the buckling of woven fabrics, using a computer program developed by Konopasek. The fact that the weight of a fabric plays a dominant role in its buckling was demonstrated by them and
their model can explain the falling load-compression curve as effectively as the frictional couple model of Grosberg and Swami [68]. Also a comparison of the three models showed that the linear and the nonlinear models represented the actual fabric behaviour more accurately when weight was taken into account.

Recently Amirbayat and Bowman [69,70] described a simple method to measure the buckling of fabrics when loaded by a pair of concentrated forces along the center line.

1.2.7 LATERAL COMPRESSION

A great deal of research work has been carried out on extension, bending, and torsional properties of fibres, yarns and fabrics. However in some technological applications, compressional properties are also important. The compressional properties of textile materials have direct relevance to the bulk, handle of fibre masses, structure of yarns and handle of fabrics [71]. For example the compressional forces may play a very important part in the breakdown of pile fibre in the carpets. During drafting, fibres are compressed between a pair of rollers moving at a certain velocity and under a certain pressure. The fibres are compressed at higher twist factors in a yarn. In knitting operation, yarns are compressed to make them in the form of loop. The lateral compression property of yarn influences mechanical properties of fabrics to a large extent. In weaving, the warp yarns and the weft yarns are compressed. During determination of the handle of fabrics, the fabric is compressed between the fingers. Thus in all stage of manufacture, the textile materials are subjected to compressive forces. Apart from playing these roles, compressional properties also have been considered in formulating equations for yarn and fabrics.

Textile fibres range in diameter between 10 and 50 µm, and are elastic under small strains of the order of 1 or 2%. Thus in order to determine the lateral compression modulus of a single fibre, change in diameter of not more than 1 µm must be measured and distances less than this distance must be detected.
with reasonable accuracy. On account of the size of the displacement involved, in investigation of any method of measuring lateral compression requires special apparatus built with precision merely to determine whether the method is practicable.

In general, a number of methods have been employed to measure lateral compression of fibres. These include Denby's method [72], Hadley's method [73], Mason's method [74], Morris's method [75], Batra and Syed's method [76], Bendit and Kelley's method [77], Phoenix and Skelton's method [78], as well as Lai and Onion's method [79]. Further Backer [80] Miles [81] and Elder [82] have measured the initial modulus of compression monofilament. Freeston and Schoppe [83] have determined the compressive modulus of monofilament from the bending and tensile moduli.

Instead of determining the compressive properties of single fibres, compression properties of fibre masses have been determined. It appears that fibres like cotton, wool, jute and synthetics, which are fine and difficult to handle, have been used as an assembly for determining their bulk properties.

In all these methods, the fibre mass is compressed between a cylinder and a piston. Kolb et al. [84] placed 0.3 g of fibre in a cylinder of 0.5" in diameter, measured the height under a load of 1 gf, and then compressed it under a pressure of 100000 lbf/in² (689 mN/mm²) for 1 minute by the cross head of an Instron. The methods used by Rees [85], Varma and Meredith [86] use a thickness gauge with large presser foot moving in a perspex cylinder. The dimensions of the cylinder vary from method to method and several modifications have been effected to derive parameters representing compressional properties.

A method which is simple, inexpensive and quick in giving the compressional properties has been reported by Morgan and Pitts [87]. The Wool Research Association New Zealand have developed the WRONZ Bulkometer for determining the bulk compressional properties of wool fibres [88]. Carnaby [71] has dealt with the compressional properties of fibrous assemblies. Dunlop [89]
has described a method for determining the compressive bulk modulus of fibre masses from measurements of the acoustic impedance. Dynamic bulk modulus measurements [89] were also made from acoustic impedance measurements. The fibre mass is held constant and the modulus determined from small deflections of the fibres caused by the acoustic excitation.

A number of workers have studied the compression of yarns by different techniques. In many of the methods, the yarn is subjected to a compressive load through the load layer. Skau, Honold, and Boudreau [90] have described an apparatus for measuring yarn softness in terms of the percent increase in yarn width when the yarn is subjected to lateral pressure between two parallel plane surfaces. By means of an optical arrangement, the vertical distortion of the yarn is magnified and readings are taken. De-Jong [91] has determined the yarn compression behaviour on the Instron tester employing the parallel plates.

In Kawabata’s [92] method, the yarn is compressed between two parallel plates, and the deformation is measured.

Oxenham [93] has described the instrument fabricated by Anderson and Settle [94] for determining the compressibility of yarns, and this has been refined by him.

Onions, Oxtoby, and Townend [95] have made yarn thickness measurement on a range of worsted spun yarn using the instrument developed by Anderson and Settle [94]. This involves the compression of 0.5 cm length of stationary yarn between parallel flat steel plates under known loads and it provides well defined and reproducible conditions for measuring yarn thickness. The light ray is concentrated into a yarn mounted horizontally across a slit in the plate. The image of the yarn is passed through lens into mirror, the angle of which is altered by the position adopted by the optical layer on which it is mounted according to the yarn thickness. The deflected light beam is then conveyed in mirror onto the paper chart mounted on the out side of the curved transparent screen. Transverse loads ranging from 2 to 200 g/cm were used.
Dhingra's [96] technique relies on Onions et al. [95] method but uses an Instron. A plate which lines up two surfaces (top and bottom plates of Instron) has been fabricated and a series of yarns are laid between them. The bottom plate is having a wedge shape.

KES-FT compression tester [97] which is commercially available, is now used for measuring the lateral compression property of the yarn. The sample of yarn is kept on a sample plate which is the top end of the bottom plunger, of which lower part is directly connected to the force transducer. The compression plunger descends at the rate of 1mm/50 sec driven by the synchronous motor to compress the sample. The displacement of the plunger is detected by a potentiometer. The relation between compression strain and stress is automatically recorded in an X-Y recorder.

A number of workers have suggested different parameters to represent compressional properties.

Denby [72] uses compression modulus for representing compression properties. Mason [74] has measured compression in terms of percentage. Also, parameters viz % residual shear, shear modulus have been considered. Phoenix and Skeleton [78] have determined transverse compressive modulus, axial tensile modulus and filament longitudinal modulus to transverse modulus ratio. Bendit and Kelly [77] propose transverse compression modulus. Batra and Syed [76] estimate elastic modulus in lateral compression from the compressed diameter and the area of the contact. Batra et al. [102] have also done work on non-woven fabrics. Chaudri and Whiteley's [103] technique involves the use of specific volume for fibre masses whereas WRONZ [88] considers the height of the sample at the commencement of the tenth cycle. For the determination of yarn compression properties, Oxenham [93] considers the yarn diameter at a series of pressures applied. Workers like De Jong [91] and Postle [100] assume a compression energy function of the form $C(R_0/R)^n$ where $R_0$ and $R$ are the
original and compressed yarn radii respectively and \( C \) and \( \gamma \) are constants for a particular yarn.

Onions, Oxtoby and Townend [95] have expressed the compression properties in terms of the thickness estimated at 1 g/cm, the thickness index and the compression index.

Several workers have defined the term resilience in different ways—as the ratio of work to compress to work recovered, the ability to absorb work, the energy returned after compression and the area of hysteresis loop.

Compressibility has been also defined in many ways as the change in volume under a change in pressure, the volume or density at a specific pressure. Other terms such as specific volume, pliability and softness have also been used. Dunlop [104] feels that two independent parameters, \( KY \) and \( P_0 \) or \( V_0 \) are required for characterizing the compression properties of fibre masses.

In the KES-FT-3 compression tester [97] three parameters, viz, compression work (\( WC \)), resilience (\( RC \)) and linearity (\( LC \)) are determined either for yarns or fabrics. Brown [99] has used five parameters viz. thickness, resilience, crush factor, hardness and compression modulus to characterise the compression properties. Knapton [101] proposes an index known as hardness index for fabrics.

Kaswell, Barish and Lermond [105] have suggested two measures to represent the compression, namely, percent compression, and permanent set.

A mechanical model of fabric in compression has been suggested by De Jong et al. [91]. They have derived a set of equation from Van Wyk’s model, and have been able to identify the incompressible layer and its magnitude.

Starting from Schiefer [98] and ending with De Jong et al. [91] in this period of about 60 years, one observes, that a number of new measures have been proposed to measure the compressibility. It is interesting to note that the parameters suggested by Kawabata [97] are not very different from Schiefer [98]
and Kaswell [105]. Fox and Schwartz [108] have stated that the compressional resilience is capable of giving an idea about the recovery.

Compression index has been found to be a sensitive parameter from the data provided by Oxtoby [106] in his M.Sc., Thesis. Thickness index can be taken as a measure of bulk since it is measured at a smaller strain. The parameter percent compression is a dimensionless parameter which is capable of giving an account of the incompressible layer at very high loads. The parameters WC, LC and RC which are obtained from the hysteresis curve have also been found to represent the compressibility of yarns. It may also be noted that what is measured in the case of yarns is the minor yarn diameter in lateral compression studies.

Although a number of studies have been made on the compressional properties of fibres, fibre assemblies, yarns and fabrics, nevertheless no systematic studies seem to have been carried out on various structures of yarns such as open end, friction, air jet, core spun, siro spun and wet spun. The effect of fibre denier and the humidity conditions on the compressibility of yarn also deserve a detailed study. As has been pointed out by Leaf and Oxenham [107] much work remains to be done on the compression characteristics.

1.2.8 FRICTION

Friction is commonly known as a resistance to motion. From the point of subsequent processing the frictional property of yarn is an important parameter. As force is applied to move one surface over the other the frictional force opposing the movement (static friction) also increases till a limiting value (the limiting friction) is reached. Then the two surfaces begin to move and the frictional force drops to a steady value (dynamic friction).

Frictional force is classically expressed as a coefficient (designated \( \mu \)) whose value is determined from the formula:-

\[
\mu = \frac{F}{N}
\]  

\( (1.14) \)
where $F$ is the force required to slide one surface over the other when they are pressed together with a force equal to $N$.

There are several theories as to the causes of friction. Coulomb's theory [109] states that friction is due simply to mechanical interlocking of surface irregularities and that frictional work consists of lifting the sliding surface over these asperities.

This theory modified by the concept of 'molecular welding' at the actual points of contact is probably the most widely held view of friction today.

The classical laws of friction (Amonton's laws [110]) state that friction is proportional to the normal load and is independent of the actual area of contact. Textile materials in general do not follow this law, and for them the frictional force varies with the area of contact.

The simplest method of measuring the coefficient of friction is the inclined plain method. If an object placed on a plane (whose angle to the horizontal is increasing), begins to slide when the angle of the plane is '0' then equation 1.14 resolves to:-

$$
\mu = \tan(\theta)
$$

In this method the value of $\mu$ determined is that of limiting friction.

A major difficulty has been to devise satisfactory methods of measuring friction of the different fibre assemblies. The Kawabata surface roughness and friction tester will probably become the standard instrument for measuring the friction of fabrics. However the instrument in its present form is not suitable for measuring the friction of yarns.

Yarn and fibre friction can be measured by a number of methods, however no single standard method has been decided on and various the methods give values that cannot be readily compared with each other since the testing conditions differ. This is in spite of the fact that fibre to fibre friction has important effects on most aspects of fibre, yarn and fabric processing, and on the various properties of the end products.
Most studies of textile friction concentrate on the limiting friction. This is of importance in the case of describing the initial behaviour of textile structures (like yarns and fabrics) under load and in situations like the yarn tension in looms where the start-stop motion of the warp causes the warp tension to constantly rise and fall so that for a significant percentage of the time, the yarn tension is above the value that would be indicated by the value of dynamic friction.

However, the value of dynamic friction gives a truer idea of the energy loss and the abrasive heating and wear after the yarn or its constituent fibres have begun moving. This includes the actual spinning, any subsequent winding and the behaviour of textile assemblies in the later stages of a strain test.

The dynamic friction is not difficult to estimate, but unlike the limiting friction does require that the absolute force must be measured. This means that a balance or a force indicator of some kind is essential. The Kawabata instrument uses a force transducer to measure the dynamic friction at a fabric to metal interface.

Methods like the 'triangle of forces' or the various adaptations of the 'inclined plain' principle, cannot be applied to accurately estimate dynamic friction.

Abrasion resistance is also of considerable importance as in subsequent processing it will rub against other surfaces. Most of these surfaces will be metal or ceramic especially designed to be smooth (low friction) and abrasion resistant. In the loom, the threads of the warp sheet will rub against each other and the weft threads as well as against the healds, the reed and the various guides.

The study of abrasion resistance has been done by a number of different methods. All involve rubbing the yarn till it breaks and recording the number of cycles required for this to happen. A number of yarn abrasion testers have been developed. It is generally considered that the best of these is the Reutlingen Webster device which was specifically developed for work on sizing efficiency and which is commercially available.
Available testers can be divided into two types; those that abrade yarn against yarn and those that abrade the yarn against another surface. The Reutlingen Webster device mentioned above is a device of the second type and uses 3 ceramic pins as the abrading element. An interesting feature of this device is the provision to take up the yarn, moving it the way the warp sheet move in the loom. It has been stated that a tester which has the provision for yarn traverse is preferable as it can discriminate between weavable and nonweavable yarns.

In this study, a special yarn abrasion tester fabricated in the department based on the work of Veer [110a] and Faasen & Van Harten [111] is used to test the abrasion resistance of the yarns. This was originally a yarn to yarn abrasion tester. For this study however it has been converted to a tester of the second type.

The frictional behaviour of textile materials is complicated by the ease with which such materials deform as well as their irregular contours. These complications probably account for the small amount of work that has been done in this field.

Balls [112] has described a method of determining fibre to fibre friction, which involves measuring the strength of an untwisted roving. The measurement of the clinging power of single cotton fibres was done by finding the force required to pull a cotton fibre from between two pads of cotton wool, the fibre being pulled at right angles to those on the pads O'Neill's apparatus being used to measure the force of extraction.

Lipson [113] developed a method involving the theory of a rope sliding around a post (capstan). Using this technique the friction between a single fibre and a cylinder of horn was studied, this being chosen because its composition was similar to wool and hair.

A similar technique was used by Martin and Mittelman [114] to study friction between wool fibres and soft surfaces like rubber, the apparatus being designed to be able to record stick-slip phenomena with very small amplitudes.
A method of measuring fibre to fibre friction has been developed by Gralen and Olofsson [115]. The apparatus has a vertical torsion wire with a balance arm which can take a fibre in an adapter. Another fibre is mounted on a arm which can move to bring the two together like a bow to a violin. The arm can be rotated to adjust the angle of contact between 10° to 90°. The lower fibre is given a steady movement and the stick-slip behaviour of phenomenon is recorded photographically. Gralen et al. have also devised another method [116] in which two fibres are twisted together for a few turns and the force required to cause the fibres to slip is measured by means of a recording system involving two torsional balances one attached to each fibre.

Of the many methods to measure the friction between fibres and other surfaces the most accurate is that devised by Mercer [117] using a modified form of the stick-slip apparatus of Bowden [118] et al.

Sikorski, Woods and Whewell [119] also studied stick-slip behaviour using an extensometer to measure the work required to draw a fibre over two horn cylinders. A special adapter for this purpose was designed and the coefficient of friction was calculated by the capstan equation.

Frishman, Smith and Harris [120] designed a chainomatic device for loading the fibre. Mercer [117] also used the device mentioned above [120] to study fibre to fibre friction.

Friction assumes an important role in the technology of rotor spinning. It has been found in the literature that very little work has been done on the frictional properties of rotor spun yarns. Theoretical analyses of the effects of friction in rotor spinning have been presented by Cormack [121], Ho [122] and Singh [123].

In rotor spinning the fibre supply is reduced to individual fibres by a drafting system or by an opening roller. The fibres are carried on an airflow and centrifugal force to the inner surface of the rotor where a fibre ring is formed by the superimposition of numerous layers of fibre.
The yarn arm peels the ring from the collecting surface. Twist is inserted and the newly formed yarn passes through the doffing tube to the take up rollers. The frictional forces that occur between the rotor circumference and the fibre ring during the twisting process generates a breaking moment which balances the twisting moment in the yarn crank and enables the twisting.

Direct measurement of the coefficient of friction between fibres and the collecting surface of the rotor presents a difficult problem. An attempt to resolve this involved making a pin out of the same alloy as the rotor and giving it a similar finish and measuring its coefficient of friction by using the Shirley friction tester. The properties of the pin were presumed to represent those of the collecting surface.

Data on the frictional properties of rotor spun yarns have been provided by Nield and Ali [124], Subramaniam et al. [125] and Kalyanaraman and Prakasam [126]. Saad [127] has carried out an interesting study on the measurement of friction in rotor spinning by modifying the yarn torsional rigidity apparatus. This has some resemblance to the method adopted by Warzee and Quintelier [128] who have described an apparatus for determining the torque-twist curves for tire cords. Torsional modulus and torsional energy and friction were also studied by them. In the case of 1650 denier tire cord they have found that as the coefficient of friction increases the torsional modulus and torsional energy show an increase in an exponential manner. Hence friction and torsional rigidity are interrelated.

Hari [28] has demonstrated that the interfibre friction is higher in the case of rotor spun yarns, compared to ring spun yarn because of the presence of wrapper fibres. An increase in the coefficient of friction in respect of the rotor spun yarns can be attributed to the greater area of contact due to the low packing factor; the surface also is responsible for the increase in friction.

London and Jordan [3] found that the coefficient of friction of a polyester-cotton rotor yarn is significantly higher than that of the equivalent ring spun yarn.
The coefficient of friction of rotor spun yarns has at various times been reported to be greater than equal and lower than that of ring spun yarns. Hunter and Smith [129] and Buhler and Haussler [130] have shown that after optimum lubrication (waxing) there is little difference between the frictional values of rotor and ring spun yarns.

As far as abrasion resistance of the rotor spun yarns is considered, it has been found that the value increases with twist and is higher than that of ring spun yarn [131]. This has been attributed to the bipartite structure and the presence of wrapper fibres. A comparison of the abrasion resistances of 24 tex rotor and ring spun yarns made from 65/35 polyester-cotton blend revealed that the ring spun yarns were generally superior [3]. Other workers have found the abrasion resistance of rotor and ring spun yarns to be similar [132]. Under wet conditions the abrasion resistance of rotor spun yarns have been reported as ten times that of ring spun yarns. Subramaniam et al. [125] have presented data on the abrasion resistance of open end yarns and ring spun yarns.

1.2.9 WICKING

The ability of textile materials to move water has been used to study their structure and properties. The means of transport of water through a textile material can be divided into processes that involve the diffusion of water in the vapour phase and those involving the transport of liquid water. The latter is a topic that has been under study for more than forty years. The early studies usually were concerned with waterproofing and water repellence, but workers involved in determining the comfort of fabrics began to study the wickability of fabrics in the 1950's.

It was understood quite early on that the phenomenon of 'wicking' (named after the practice of studying the phenomenon by measuring the rise of liquid in wicks of textile assemblies) was due to hydrodynamic flow of liquid through capillaries.
Theoretical analysis based on the laws of hydrodynamics has yielded the equation:

$$S^2 = \frac{\gamma \cos(\theta_A)}{2\eta} \times r_e \times t$$  \hspace{1cm} (1.16)

where $S$ is the distance the liquid has moved, $\gamma$ and $\eta$ are the surface tension and the viscosity of the liquid, $r_e$ is the effective radius of the capillary and $\theta_A$ is the apparent contact angle which varies from the actual contact angle by a factor that depends on the roughness of the yarn forming the capillaries. The parameter $\frac{\gamma \cos(\theta_A)}{2\eta} \times r_e$ is known as the 'rate of transport' and is constant for a given liquid and assembly of fibres. This parameter is referred to as $k_s$ and equation 1.16 is written as

$$S^2 = k_s \times t$$  \hspace{1cm} (1.17)

Experimental proof of this equation was derived from the fact that plots of $S$ versus $\sqrt{t}$ approximately fell in a straight line.

In the ideal case (circular yarns and circular fibres) the average radius of a capillary can be computed from the formula :-

$$r = \frac{1}{2} \left( \frac{D^2}{n} - d^2 \right)^{1/2}$$  \hspace{1cm} (1.18)

where $D$ is the yarn diameter and $d$ the fibre diameter and $n$ the number of fibres in the average cross section.

The effective capillary radius $r_e$ can be expressed in terms of $r$ by the formula

$$r_e = r \times f(y)$$  \hspace{1cm} (1.19)

where the function $f(y)$ does not have any simple form for real yarns. However for similar yarns we can assume that the function is approximately constant and a comparison of $r$ is a comparison of the actual structures.

Further since the term $\cos(\theta_A)$ also will tend to be similar for similar fibres and liquids, the rate of transport $k_s$ gives a good comparison of the yarn structure differences between roughly similar yarns. This study is concerned with the
wickability of rotor yarns spun from cotton under varying conditions of opening roller and rotor speeds.

There are numerous mechanisms that can operate to move fluids through porous materials[133] but the viscous flow of water by capillary action accounts for the major portion of the flow that actually occurs[134]. Washburn's[135] fundamental work in the hydrodynamics of capillary flow has been used to describe water movement in a number of porous materials including paper, soil and leather. Palmer[136] and Preston et al. [137] have demonstrated that a yarn can be treated as an assembly of capillary tubes. Hollies et al.[138,139] have applied Adam's[140] work to develop a theoretical model for water transport in yarns (eqns. 1.16–1.19) and fabrics and demonstrated with experiments that the model is a good representation of the actual conditions that occur in textile materials. They have shown that randomness in the internal structure of the yarns slows down and in sometimes even stops the movement of water.

Minor et al.[141] have done work with a number of non aqueous solvents and a number of yarns made from different materials, both natural and synthetic and have demonstrated that the work of Hollies[138-139] is generally valid. They have carried out work using twisted filament bundles as yarn models and also studied the case of wicking where the liquid available is limited.

On rotor spun yarns, Lord[142] has suggested various methods for studying their wicking behaviour and comparing them with ring spun yarns. An interesting variation he developed was the limited time wicking test where the one end of the yarn was immersed in dye liquor for 15 seconds before being removed from the bath. The height of climb was taken as a measure of wickability. He reached the conclusion that wicking height is not very sensitive to changes in the twist of open end yarns.

De Boer[143] has suggested three types of measuring methods namely (i) vertical wicking test, (ii) determination of saturation value and (iii) drop test.
These tests cover both the parameters of amount of fluid absorbed and the rate of absorption.

Sengupta et al.[144] investigated the wicking behaviour of open end and ring spun yarns at various twist factors and came to some general conclusions on the effect of twist on wickability. Prime among them was that the wicking test is not very sensitive in the case of rotor spun yarns.

Harnett and Mehta [145] have measured wicking of knitted fabrics by four different methods. On the basis of the results obtained they have concluded that wicking is often not sufficient and that a combination of methods is required for a meaningful assessment of fabric wicking properties.

Subramaniam et al.[146] have done work on the wickability of siro spun yarns. They have also reinterpreted Sengupta's [144] results [147], showing that the wicking test is more appropriate for rotor spun yarns than was previously thought.

1.2.10 TENSILE PROPERTIES

The strength of a textile yarn depends on the strength of the constituent fibres and the extent to which this strength is used. Considerable work has been done to investigate the latter parameter. Studies by Hearle and others [148-151] have led to the generally accepted idea that higher fibre strength leads to a yarn with greater strength for any type of yarn structure. The early work concentrated on ring spun yarn but there has been considerable work on rotor yarns also. Salhotra et al. [152] have shown that the core of a rotor yarn suffers the maximum fibre damage during yarn break and that the minimum length of fibres that rupture during yarn break is greater in the case of rotor yarns. Thus the core of a rotor yarn uses the strength of the constituent fibres less efficiently than a ring yarn does in spite of the pressure form the sheath of fibres pressing down on the core. This is reflected in the lower strength and work of rupture of such yarn.
1.2.11 CONCLUSION

In recent years, the yarn production from rotor spinning has increased considerably. It is necessary from a technical viewpoint to obtain a thorough understanding of the process of rotor spinning.

It can be seen from the synopsis of published research on rotor spinning that most of the work carried out so far relates to the effects of various parameters on the high stress properties of rotor spun yarns.

Very little work has been reported on the effects of these parameters on the low stress properties (bending, buckling, compression, friction etc.) of these yarns. These aspects have been considered in the present study.