THE INFLUENCE OF YARN PRODUCTION AND PROCESSING VARIABLES ON LOOP DISTORTION IN PLAIN KNIT FABRICS

A Thesis submitted to the University of Leeds in fulfilment
of the requirements for the Degree of Doctor of Philosophy

by

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Being an account of research carried out at
the International Wool Secretariat, Ilkley
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ABSTRACT

After reviewing past work into the geometry of the symmetrical idealised plain knit loop, an account is given of the present knowledge of loop distortion, which represents one of the major problem areas of the knitting industry. The shortcomings of this knowledge are shown to be that, although a large number of processing variables have been demonstrated to be associated with loop distortion, there have been no systematic studies of the defect and there have been virtually no attempts to explain it in terms of fundamental physical characteristics of the yarn.

Eleven yarn production and processing variables are examined within the framework of factorially designed experiments. The influence of these independent variables is statistically related both to ranked levels of loop distortion and to values of yarn physical characteristics. The two latter groups of data are also inter-related by rank correlation.

It is shown that loop distortion is dependent upon at least three yarn characteristics which, in turn, are dependent upon particular production and processing variables. These three are yarn bending hysteresis, bending rigidity, and count regularity. The greater propensity for wool to distort in comparison to acrylic is explained in relation to these characteristics, and to their different changes during processes such as steam setting and package dyeing.

The work is finally reviewed both from the point of view of the manufacturer, who wishes to be able to predict the likelihood that a particular yarn will cause distortion, and the textile technologist who is not only interested in choosing the optimum yarn production conditions for minimum distortion, but would like to improve the fabric appearance by changes or additions to established production routes.

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CONTENTS

CHAPTER ONE

THE PLAIN KNIT STRUCTURE

1.1 INTRODUCTION

The simplest form of weft knitting, that is a fabric in which the loops are formed sequentially along courses perpendicular to the direction of fabric growth, is the plain knit structure. Figure 1 shows a view of the idealised structure from the face (plain) and reverse (purl) sides. The fabric is produced on a single bed of needles.

The knitting action, illustrated in Figure 2, may be divided into four stages as follows:-

1. The needle rises to allow the old loop formed on the previous cycle to be cleared from the latch or beard (depending on the needle type) to rest on the shaft of the needle.
2. Relative movement between the needle and yarn feeder allows yarn to be fed into the hook or beard of the needle.
3. As the latch needle sinks, the old loop closes the latch over the new loop within the hook. For a bearded needle, the beard must be closed by a presser bar before the old loop can slide onto it.

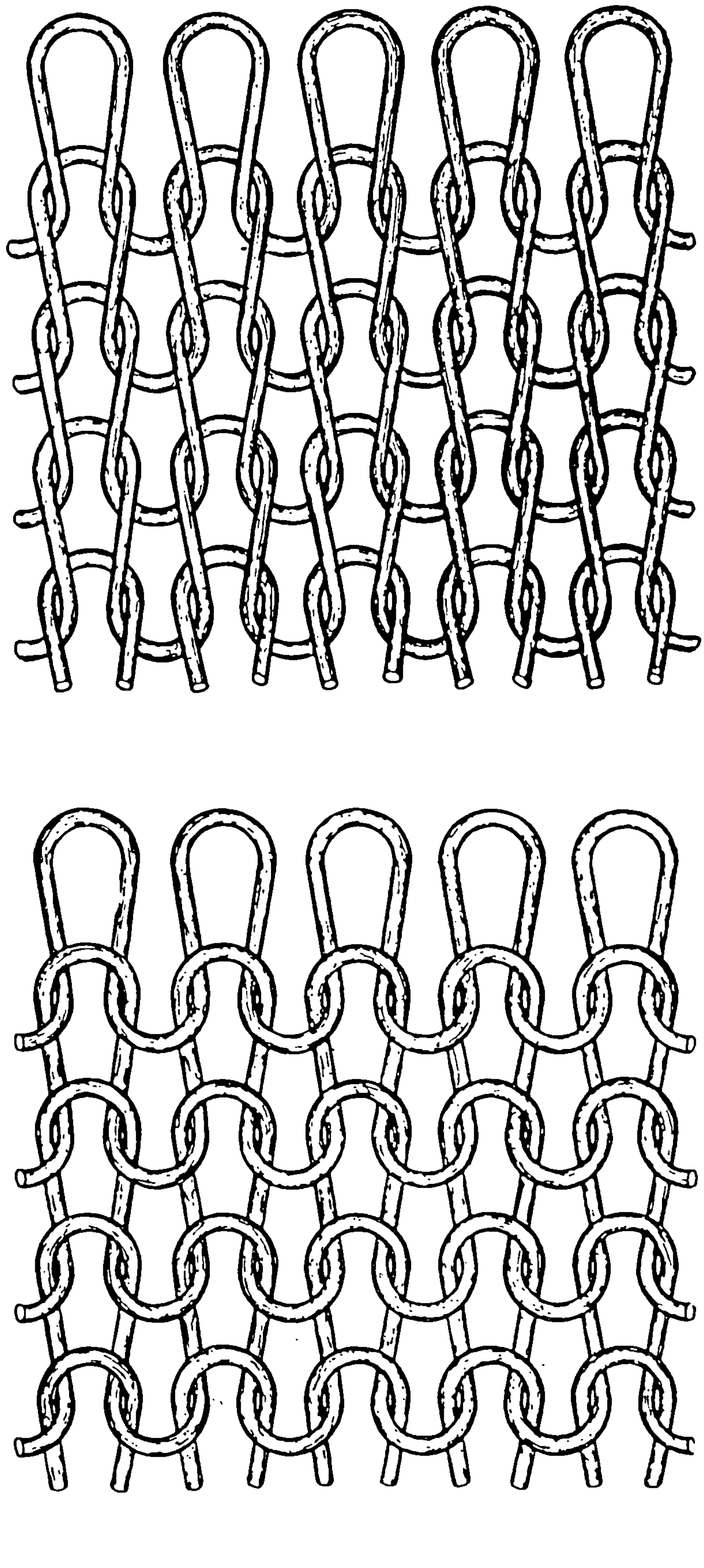


Figure 1. The Plain Knit Structure

a) Face Side

b) Reverse Side

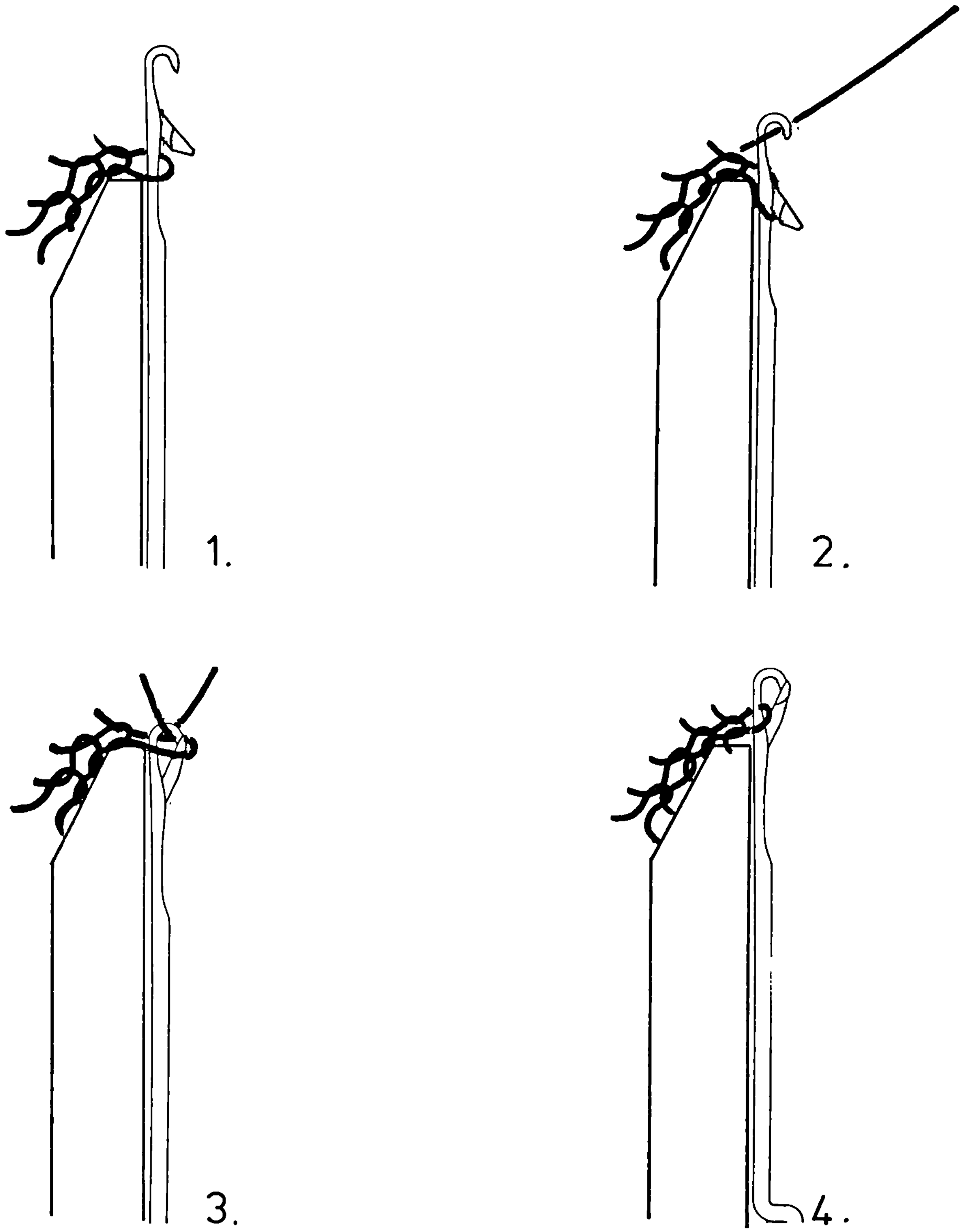


Figure 2. Latch Needle Knitting Action

1. Clearing
2. Yarn Feed
3. Knock-Over
4. New Loop Formed

4. As the needle sinks further, the old loop slides off the needle and interlaces with the new loop held by the needle.

Horizontal rows of loops are called courses; vertical columns of loops are called wales. Each loop has a three-dimensional configuration due to its interlocking. A loop's precise geometry is quite complex and will depend not only on such factors as the tightness of the structure but also on the degree of strain energy in the structure. For instance, immediately after knitting, the fabric tends to be stretched in the wale direction. The loops are longer and narrower than they would be in a more relaxed or less strained state and the configuration of the loops changes as they move towards this lower energy state during relaxation. The problems of defining the plain knitted loop in terms of both spatial configuration and internal energy distribution are discussed in further detail in Section 1.2 below.

The plain knit structure is popular for wool knitwear in a wide range of yarn counts. Fully fashioned knitting, either on Cotton's Patent machines, using bearded needles or, increasingly, on electronic flat bed machines, is particularly suited for wool because of the minimal waste of a relatively expensive yarn. Garment parts are knitted to shape rather than being cut from tubular fabric using the cut-and-sew method. Fully fashioned wool knitwear is popularly grouped into three types:- "Shetland-type", "lambswool" (both knitted from woollen spun yarns) and "botany", normally produced from a twofold worsted yarn.

Structural defects can occur in all types of knitwear, but in woollen knitwear the scouring and milling finishing routine, while imparting a soft surface texture, also tends to obscure irregularities in loop configuration. Botany knitwear, however, normally has a clear finish in which each loop can be distinctly seen. When irregularities occur in the structure they may result in an unacceptable product. There are two main structural faults found in plain knit botany knitwear which can be attributed to a deviation in the loop shape from the symmetrical configuration shown in Figure 1. These are usually termed "spirality" and "cockling".

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 then 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 fabric is produced from singles yarns which have not been properly set, or from twofold yarns which do not have the balancing ratio of singles twist to folding twist. Spirality is a subject which has been extensively studied and for further information the reader is referred to work by Davis et al.[1] and Nutting.[2]

Cockling is defined[3] as "an irregular surface effect caused by loop distortion". Loop distortion will be discussed in some detail later in Section 2.1. Cockling may be divided into three main types according to its distribution on the fabric surface:-

1. Cockling near to the interface of two different knitted structures. In knitwear this may occur in the plain knit area close to the rib or fashioning points. The cause of this cockling is basically due to the difference in the relaxed dimensions of the two structures. The narrower fabric (e.g. the rib) tends to pull in the wider fabric and so induce cockling, particularly in a yarn prone to distortion of the random all-over type (3., below).
2. Cockling near to the fabric panel edges. This is likely to relate to the knitting process and could be caused by twist redistribution due to acceleration or deceleration of the yarn feeder. When fashioning occurs, the cause of cockling is more likely to relate to the higher tension in the wale direction at the panel edge inducing distortions similar to those found at structural interfaces.
3. Random all-over short term loop distortion. This is a serious problem in the knitwear industry and much time has been spent in attempts to solve it. Little progress seems to have been made, however, in determining the fundamental cause of the fault. The present work is aimed at an elucidation of this root cause. Animal

Figure 3. An Extreme Example of Cockling in a Fully Fashioned Mohair Garment

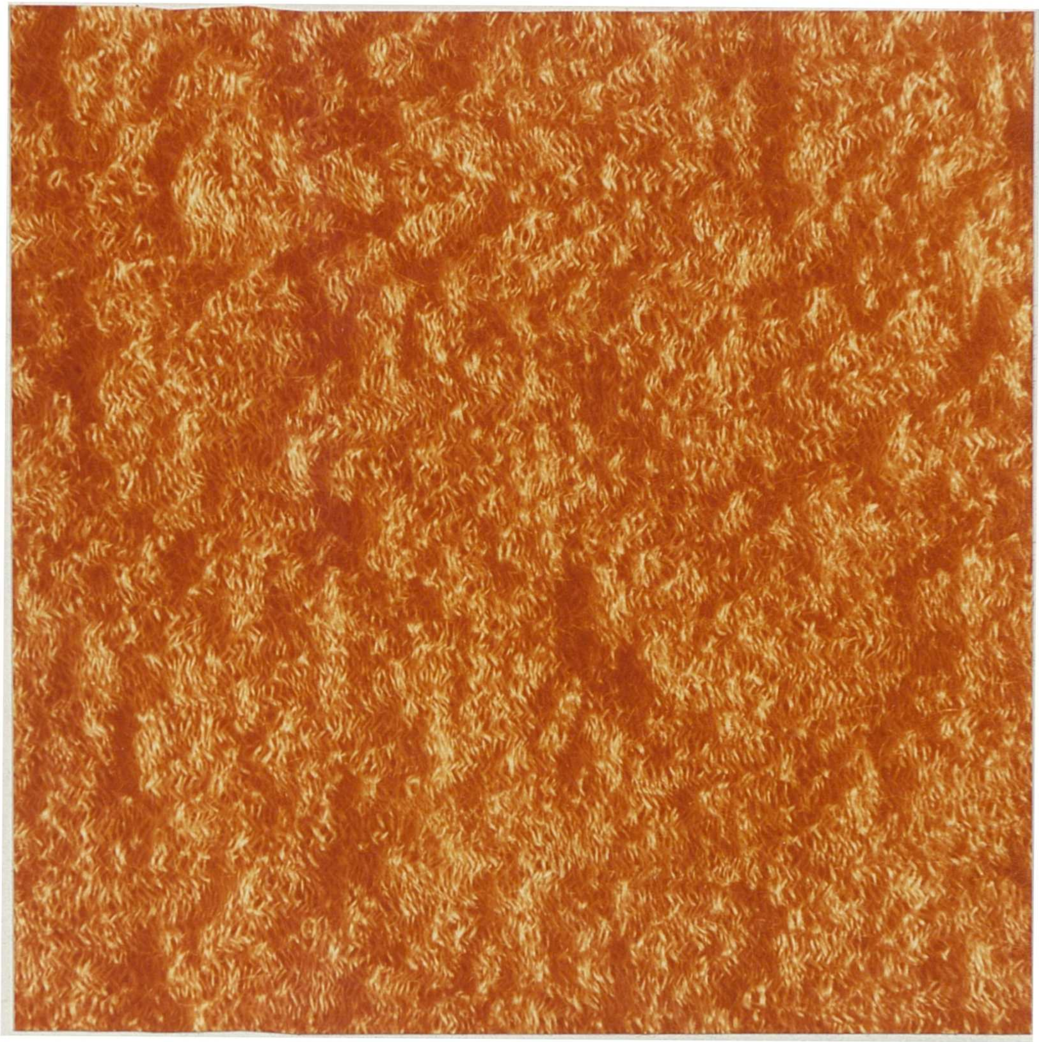


Figure 4. Loop Distortion in the Mohair Garment shown in Figure 3.

fibres such as wool and mohair seem to be particularly prone to loop distortion. Figures 3 and 4 show extreme loop distortion in a mohair garment.

1.2 THE GEOMETRY OF THE IDEAL PLAIN KNIT STRUCTURE

One of the earliest attempts to define the geometry of the plain knit loop was made by Tompkins[4] in 1914. Subsequent models produced by other workers, including Chamberlain[5], Pierce[6] and Shinn[7], made use of simplifying assumptions in order to facilitate the geometrical calculations. For instance, Chamberlain examined the plain knit loop in essentially two dimensional terms. By assuming that the centres of the knitted loops in a theoretically balanced fabric fell on the vertices of a regular hexangular lattice, he was able to conclude that-

$$\frac{\text{Courses per Unit Length}}{\text{Wales per Unit Length}} = \frac{2}{\sqrt{3}}$$

$$\text{and that} \quad \text{Loop Length} = \frac{3\pi+2\sqrt{13}}{4} \times \text{Wale Width}$$

But he remarked that "In practice, however, there are so many other factors involved that the results obtained theoretically do not agree with those obtained practically".

Pierce's approach to the problem was somewhat similar in that he produced a simple geometrical model, without direct reference to experimental observations. The third dimension of a plain knit structure was taken into account by the assumption that each course of loops lie on the surface of a cylinder, the course being parallel to the cylinder's axis. In Pierce's "Normal Structure" each yarn touched itself in every loop and each loop touched the course above and below, i.e. the structure was completely jammed. Analysis was carried out on a flattened version of this three-dimensional structure which is essentially the same as Chamberlain's model.

In Figure 5, the loop length (L) is given by:

$$L = AB = 4CF \text{ (assuming quarter-loop symmetry)}$$

where $$CF = CD + DE + EF$$

Hence, if the yarn diameter is d, we find

$$L = 4\left\{\frac{3\pi d}{4} + 3d\left(\frac{\pi/2 - \theta}{2}\right) + 2d\sin(\theta-\psi)\right\}$$

so that

$$L = 6d(\pi - \theta) + 8d.\sin(\theta-\psi)$$

Since the centres of the loops are assumed to coincide with the intersecting points of a lattice of equilateral triangles, values of θ and ψ may be calculated ($71^{\circ}24.6'$ and 30° respectively) to give

$$L = 16.663d$$

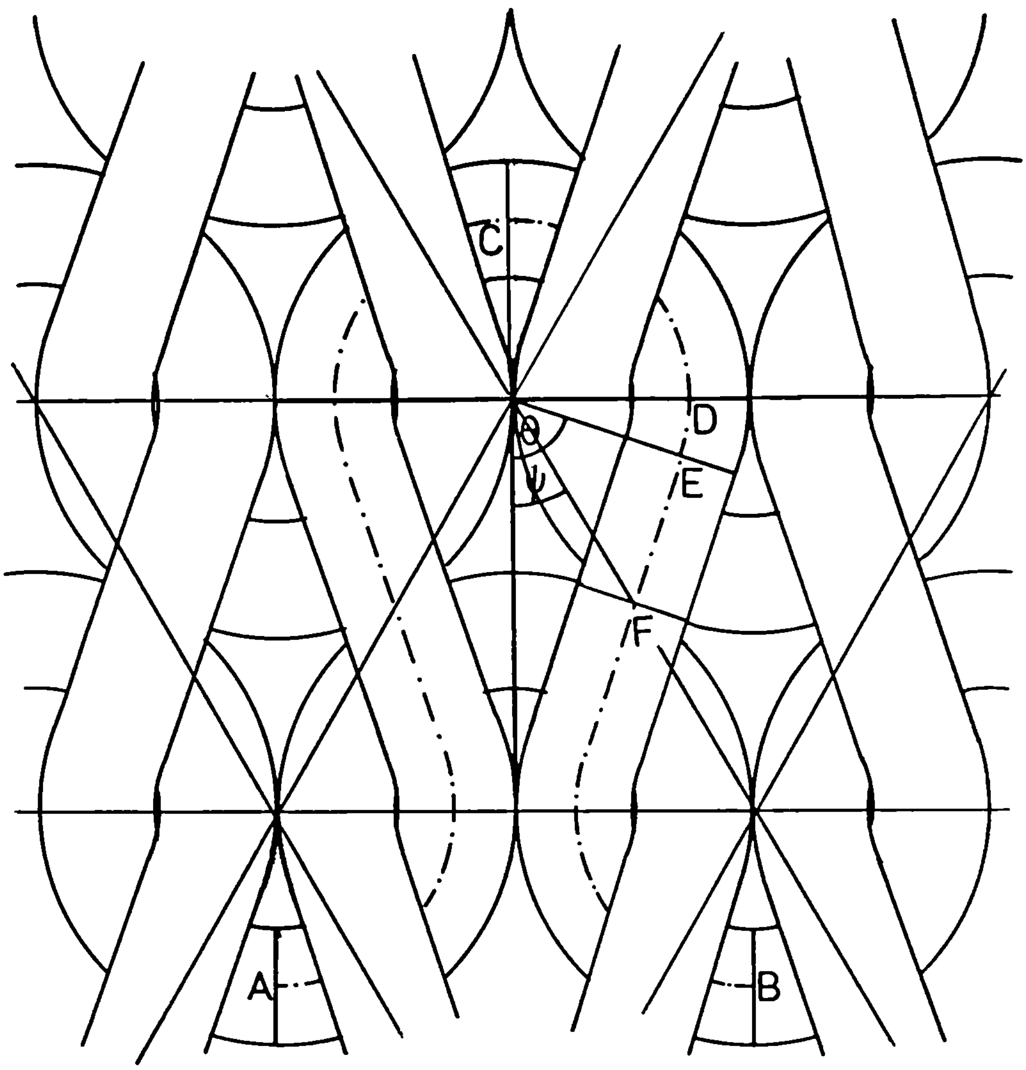


Figure 5. Pierce's Analysis of the Plain Knit Loop

If the wale spacing is given by W, then

$$W = 4d$$

and the course spacing for the two dimensional model, C_1, by

$$C_1 = 2\sqrt{3}.d = 3.464d$$

Geometrical analysis of the fabric cross-section (Figure 6) leads to a theoretical value of the cylinder radius (R), upon which each course lies, of

$$R = 4.172d$$

The course separation (C) now becomes

$$C = 3.364d,$$

this being the projection of the loop arc onto the fabric plane.

A more generalised set of equations for fabrics with loop lengths greater or less than the value required for the "Normal Structure" may be given by the introduction of a space e_1d between wales, resulting from the addition of a short section of yarn in the crown of each loop. The course separation may be increased by the addition of short pieces of yarn of length $e_2.d$ in the centre of each loop.

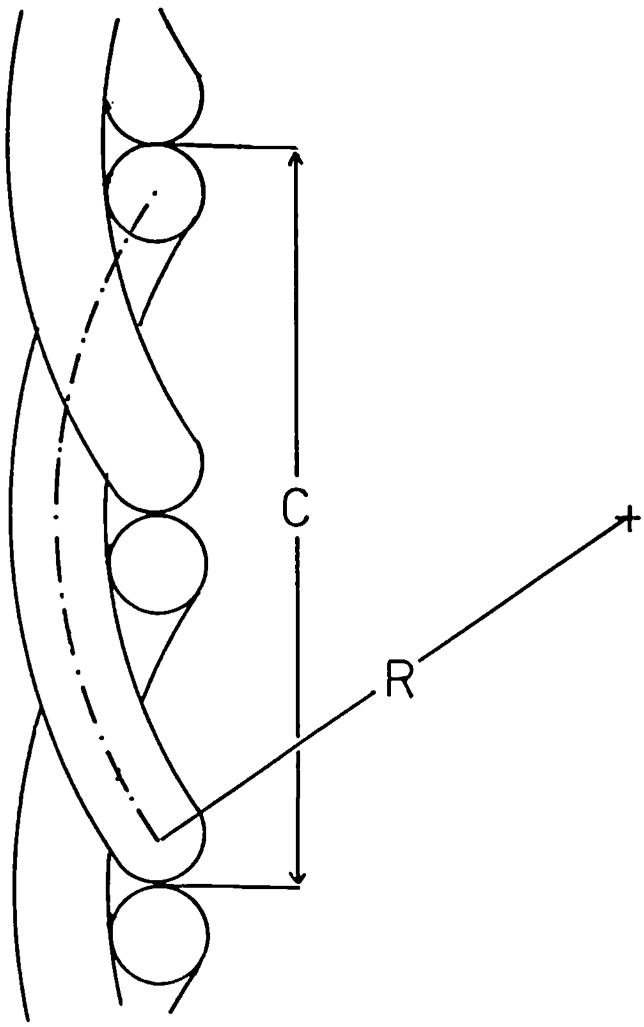


Figure 6. Cross-Section of Plain Knit Fabric

The loop axis is projected onto a cylindrical surface. (After Pierce).

In this case, $L = (16.663 + 2(e_1 + e_2)).d$

$W = (4 + 2e_1).d$

and, approximately, $C = (3.364 + e_2).d$

e_1 and e_2 may be eliminated to give the general equation

$$L = 2C + W + 5.94d$$

Shinn's analysis of the plain knit structure was very similar, except that he reverted to a two dimensional model. The ratio of the number of courses to wales per unit length was stated to be 1.15:1 in a normal relaxed fabric.

Early workers generally recognised the disparity between the results predicted by their simple plain loop models and practical experience. The primary object of their work was to enable knitters to be able to predict the finished dimensions of knitwear and fabrics from the yarn and loop dimensions. The workers placed particular emphasis on the importance of yarn diameter and machine gauge and assumed that the relaxed fabric followed the configuration of a triangular lattice. The failure of real knitted structures to follow the expected form caused workers to begin to re-examine the plain knit loop from a different standpoint.

Later work may be characterised in particular by the inclusion of two important factors which earlier workers had largely omitted:-

1. The influence of internal forces in determining the loop shape.

2. Changes in configuration of the loop during relaxation and the extent to which different relaxation procedures permit movement of the structure towards a minimum energy condition.

Despite the inclusion of these factors a number of assumptions and simplifications were made so that the analyses did not become over-complex. Typical assumptions were that the yarn was circular in cross-section, consisted of a uniform density of matter and was perfectly elastic.

Doyle's[8] work in the early fifties is generally recognised as being the forerunner of the modern view of the plain knit structure. In order to achieve useful results, he stated that "... it is necessary first to analyse the existing range of practical experience, secondly to express this experience scientifically in generalised forms, and thirdly to express it quantitatively so that end requirements can be so specified that exact design to these ends becomes possible".

Significantly, he did not derive a theoretical ratio for courses/unit length to wales/unit length (C/W) for a relaxed fabric, recognising the difficulties in defining a fully relaxed structure. He did, however, demonstrate the relationship between stitch density (N = C x W) and the length of yarn in the knitted loop (Figure 7) and the independence of the loop length from the state of relaxation of the fabric. Consequently, loop length (L) was shown to be an important

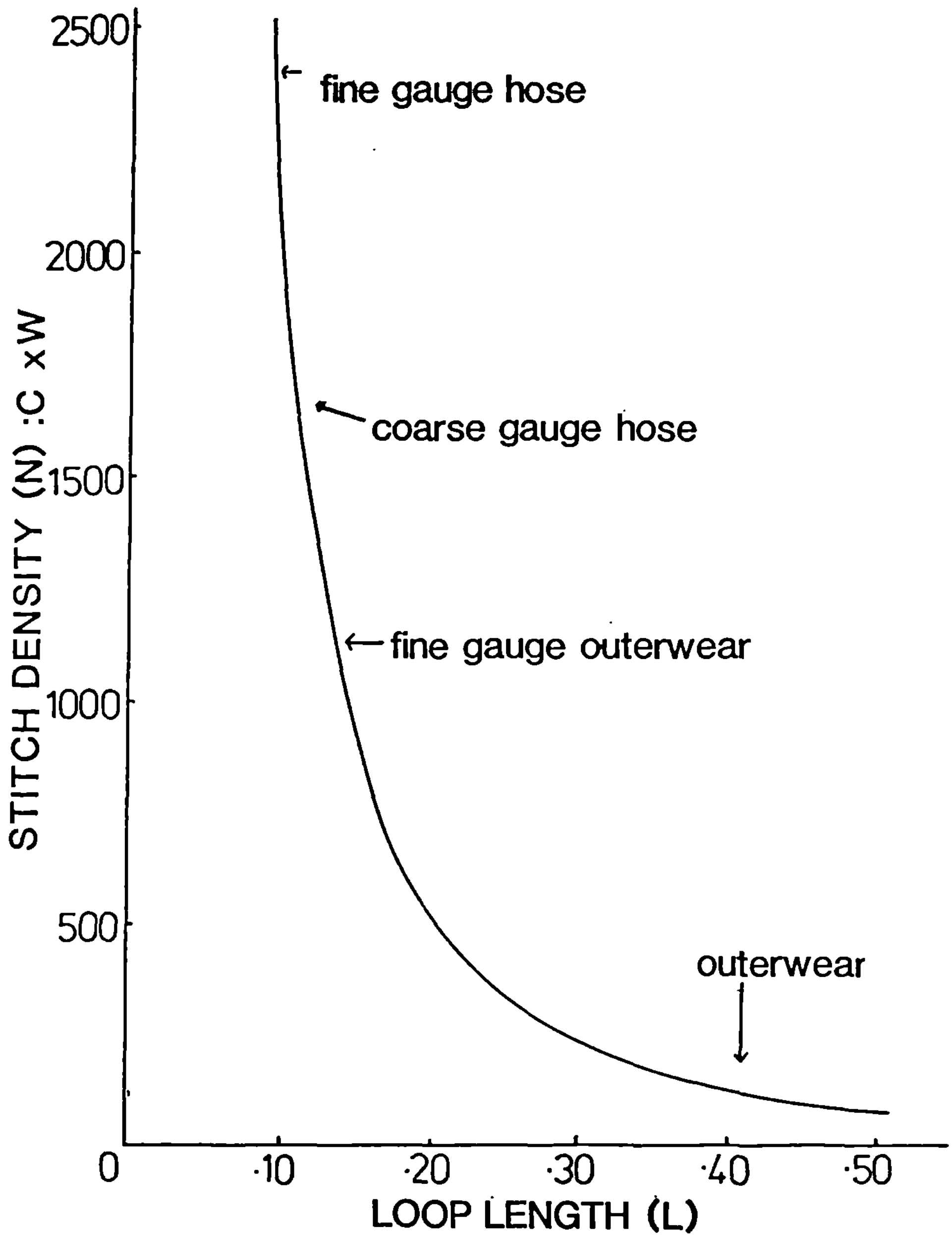


Figure 7. The Relationship Between Stitch Density ($N \doteq$ courses x wales per unit length) and Loop Length (L) $N=K/L^2$ where K is approximately equal to 20. (After Doyle).

control and measurement parameter in the knitted structure. The experimental relationship between loop length and stitch density was given by

$$N = K/L^2$$

where K had a value of approximately 20 for dry relaxed fabrics.

Another important advance in the study of plain knit loop geometry was made in 1955 when Leaf and Glaskin[9] showed the models based on Pierce's hypotheses to be untenable because of the implications of torsional discontinuities. A real loop in a knitted structure, which is able to move to a state of lower strain energy against the frictional constraints of neighbouring loops cannot display abrupt changes in twist level along its length, which the Pierce theory required.

A new model was proposed in which the straight central portions of the loop sides (length 2EF, Figure 5) were omitted, the loop now being composed only of circular arcs of yarn projected onto a cylinder with its axis parallel to the fabric courses (See Figure 8). Having derived equations defining the new loop model in three dimensions, Leaf and Glaskin were able to obtain an equation defining the loop length (L) in terms of other loop parameters:

$$L = \frac{8a/d\sqrt{(1 + b^2)}}{\pi} \cdot \int_0^{\pi/2} \sqrt{\left(1 - \frac{b^2}{1 + b^2} \cdot \sin^2 u\right)} \, . \, du$$

Where

d = the diameter of the yarn

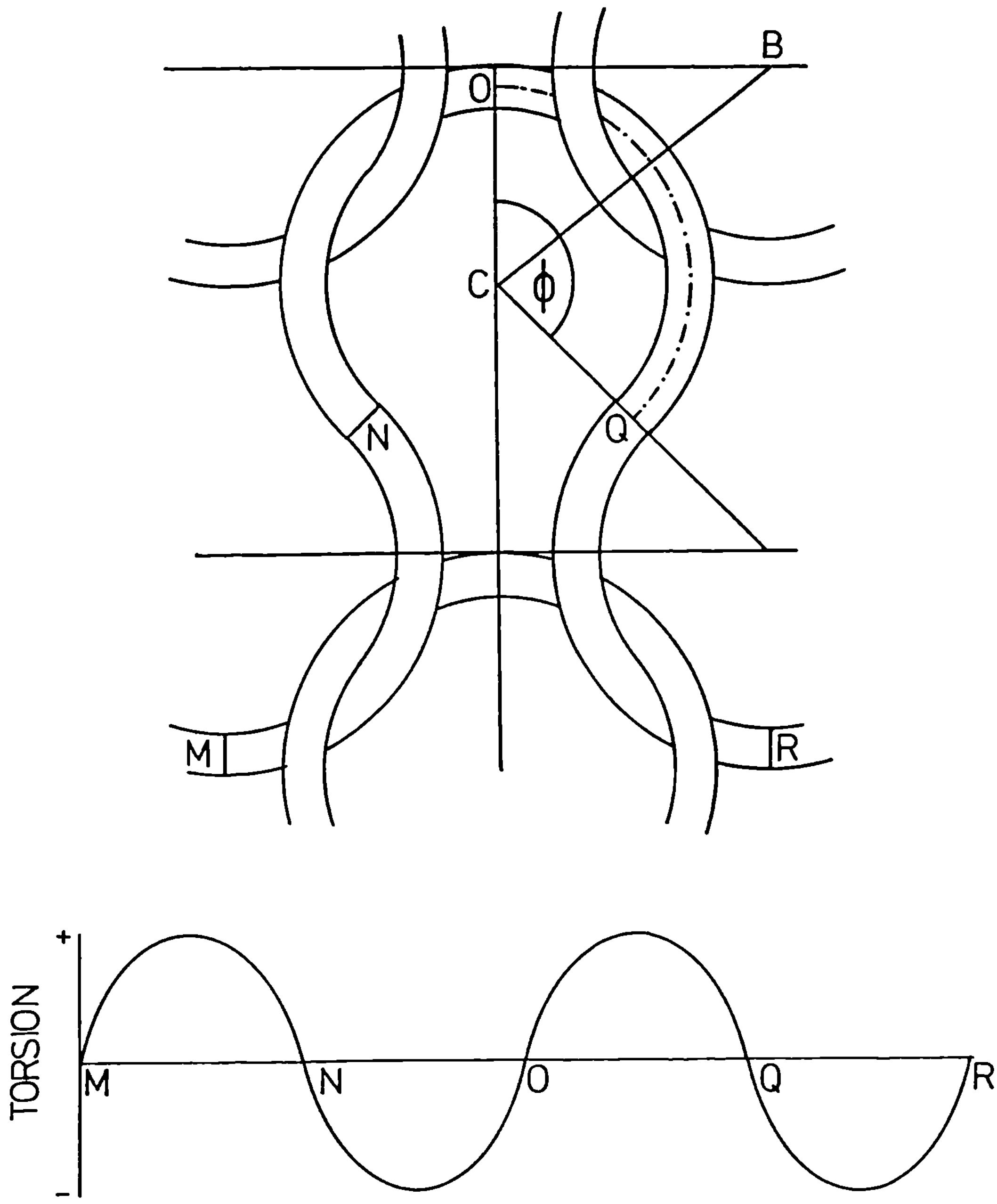


Figure 8. Leaf and Glaskin's Model of the Plain Knitted Loop Free From Torsional Discontinuities

$a.d$ = the radius of the central axis projection.

ϕ = angle OCQ

$h.d$ = the maximum height of the axis above the plane of the fabric (at N and Q)

$$b = \frac{\pi h}{2a\phi}$$

θ = angle OCP (P being any point on the arc OQ).

$$u = \frac{\pi}{2} - \frac{\pi\theta}{\phi}$$

An approximation may be obtained by expanding this equation and neglecting powers of K greater than the second, where

$$K^2 = \frac{b^2}{1 + b^2}$$

It is then found that

$$L = 4\, a\, \phi\, d.$$

But from Figure 8, which is a projection of the three dimensional structure onto a plane surface parallel to the fabric, this second approximation can be seen to be equal to the loop length of a two-dimensional model (i.e. L = 4.OQ).

When the two equations for the loop length given above, and the equation derived by Pierce[6] were compared with experimental data obtained by Fletcher and Roberts[10,11,12] it was found that Leaf and Glaskin's two-dimensional approximation gave the closest fit, and that the two three-dimensional models tended to overestimate the loop length. Clearly, certain assumptions made, for instance the two-dimensional form of the bent loop or the curve into which the loop is bent in the third dimension, were at variance with loops in a real fabric structure. Leaf[13] later studied the bending of a homogenous elastic rod in order to obtain a mathematical expression defining the configuration of a loop. This was shown to be independent of the length of the loop and the thickness of the rod, and also independent of the material composing the rod, provided no plastic deformation occurred.

This idea of loop similarity was the basis of Munden's[14] paper published in 1959, which probably represents the first study of loop geometry to yield results of practical significance. No predetermined loop shape was assumed - the only important assumptions made were:

1. All loops are similar in shape
2. A plain knit structure tends towards a minimum energy condition irrespective of the physical properties of the yarn.

In practice, yarns are not perfectly elastic (particularly synthetic fibre yarns which are subject to plastic deformation during knitting) and there are interyarn forces. These factors determine the rate at which the structure moves towards a minimum energy condition. The minimum energy state itself will differ for plastic and non-plastic deformation. This state was assumed by Munden to be that at which so-called "minimum bending" occurred, the longest horizontal dimension of one loop coinciding with the shortest dimension of the interlocking loop above (AB, Figure 9a).

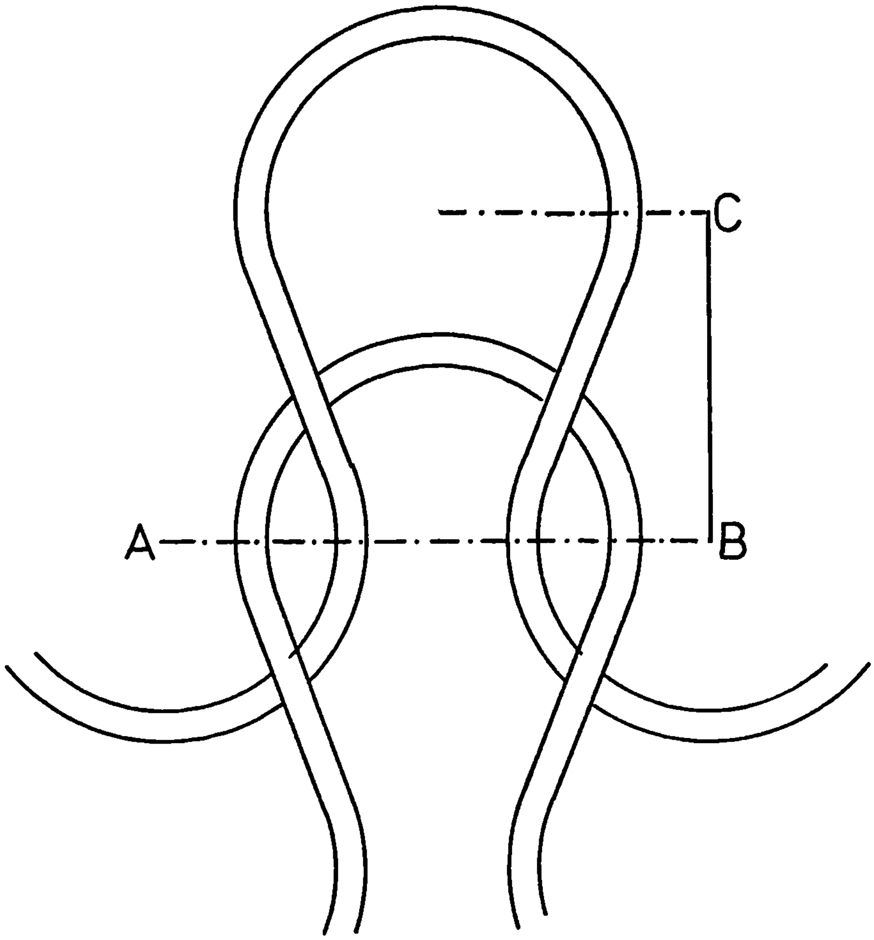


Figure 9a Munden's Minimum Energy Configuration for Interlocking Loops

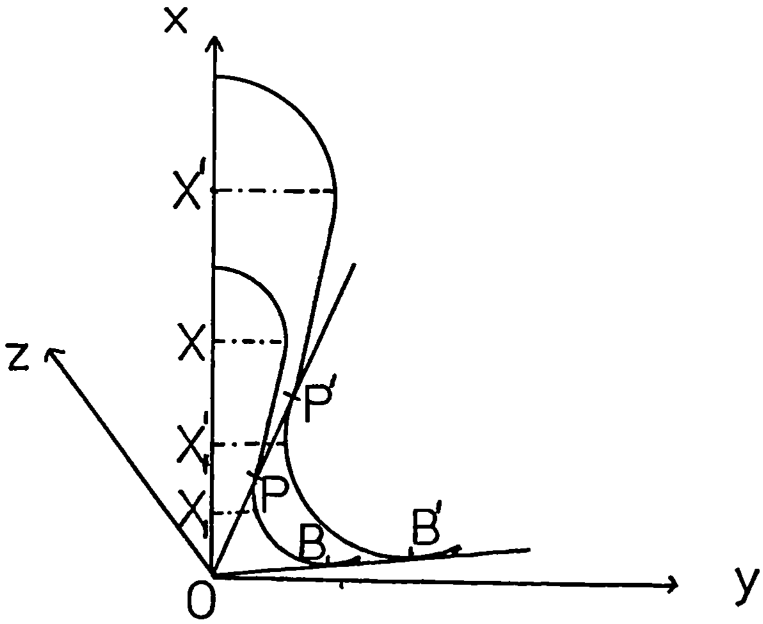


Figure 9b Geometry of Three-Dimensional Similar Loops (after Munden)

For two three-dimensional half loops of similar configuration, but different size, with a centre of similitude about origin O, then for any two points on the curves, on the same vector from the origin, the ratio of the distance of the two points from the origin is constant. In figure 9b, for instance,

$$\frac{OP'}{OP} = p \qquad \ldots.(1)$$

Hence the wale spacings (2OB, 2OB') are similarly related:

$$\frac{OB'}{OB} = p \qquad \ldots.(2)$$

By integration it can be shown that the ratio of the two loop lengths is

$$\frac{\ell'}{\ell} = p$$

The course spacing for the minimum energy condition assumed is equal to the vertical distance between the widest and narrowest parts of the loops (BC, Figure 9a). Hence the course spacing ratio is given by:

$$\frac{X'X_1'}{XX_1} = \frac{OX' - OX_1'}{OX - OX_1}$$

But $$\frac{OX_1'}{OX_1} = \frac{OX'}{OX} = p$$

Therefore $$\frac{X'X_1'}{XX_1} = p \qquad \ldots. (3)$$

From equations (1) and (2) above,

$$\text{wales / unit length} = \frac{\text{constant}}{\text{loop length}}$$

From equations (3) and (2) above,

$$\text{courses / unit length} = \frac{\text{constant}}{\text{loop length}}$$

And hence:

$$\text{stitch density} = \frac{\text{constant}}{(\text{loop length})^2}$$

Munden expressed these relationships as:

$$\text{Stitch Density (N)} = \text{CPI} \times \text{WPI} = K_1/\ell^2$$
$$\text{CPI} = K_2/\ell$$
$$\text{WPI} = K_3/\ell$$
$$\text{CPI} / \text{WPI} = K_4$$

Values of K_1, K_2, K_3, and K_4 calculated from previous loop geometry theories were compared with measurements made on dry and wet relaxed fabrics produced from yarns of different fibre types:

	LOOP THEORY		EXPERIMENTAL MEASUREMENTS			
	Chamberlain	Pierce	Doyle		Munden (Wool Yarns)	
			nylon	wool & cotton	dry rlxd.	wet rlxd.
K_1	20	20.6	16.7	19.2	19.0	21.6
K_2	4.8	4.9	-	-	5.0	5.3
K_3	4.15	4.15	-	-	3.8	4.1
K_4	1.15	1.18	-	-	-	1.3

The values derived from the loop theories only apply to specific loop configurations. Pierce's general equation, cited previously, does not give a constant value for K_1 with varying loop length or yarn diameter, implying that the stitch density will decrease if a finer count of yarn is used but the loop length remains constant. A fundamental principle of Munden's theory is that the loop length alone determines the stitch density in a completely relaxed structure. Factors such as yarn diameter, machine gauge or machine diameter are not relevant. This would imply that because of the dependence of K_1 on yarn diameter in Leaf and Glaskin's model, their model does not represent the minimum energy condition. In fact, subsequent work has suggested that Munden's theory may be an oversimplification and that loop length and yarn diameter do have a degree of influence on K_1.

The low K_1 value for nylon obtained from Doyle's work was attributed to partial plastic deformation during knitting. It was observed that values for the K-parameters for hydrophilic fibres such as wool and cotton tend to increase towards a minimum energy value as relaxation proceeds. A value for K_4 was not determined for dry relaxed fabrics since the ratio of courses to wales is very sensitive to fabric deformation. Even the value obtained for wet relaxed fabrics was considered as an approximation.

Munden's experimental K-parameters were used as the basis of two new theoretical loop models proposed by Leaf[15] in 1960. The models were based on the elastica - the form taken by a perfectly elastic straight rod buckled by axial forces applied at the ends.

A course of loops in the first model consisted of a series of elasticas alternately inverted and joined end to end. The third dimension was obtained by placing the course of loops on the surface of a cylinder whose axis was parallel to the course. Although conditions for the elastica could be calculated based on Munden's K-parameters for wet relaxed wool fabrics, it was not possible to find parameters based on the dry relaxed values.

The second model was similar to the first, except that the third dimension was obtained by laying the course on a surface whose cross section, perpendicular to the direction of the course, was a sine wave. In this case parameters for the elastica were derived for both dry and wet relaxed states, with the restriction that the loop length was at least 17.9 times the yarn diameter for wet relaxed fabrics and 17.5 times its diameter for dry relaxed fabrics.

The effect of water on setting loops of hydrophilic yarns into a configuration close to that required for minimum internal energy was examined from a practical point of view by Munden[16] and Nutting[17]. Munden observed that the minimum energy condition for dry relaxed fabrics is not the same as that when moisture is present. Nutting examined the influence of moisture regain on both dry and wet relaxed wool fabrics. Fibre swelling caused an increase in fabric dimensions (decrease in K_1) as the regain was increased, for both relaxed states. In the case of the wet relaxed fabrics the effect was reversible with a possible hysteresis effect but this was not so for dry relaxed fabrics. For fabrics in the dry relaxed state an increasing regain brings about a change towards a wet relaxed equilibrium state. The change from one state to another represents the release of internal stresses due to the lowering of interyarn forces as moisture setting takes place. Nutting obtained a value for K_1 of approximately 23.4 by wet relaxation at $70^{o}C$ for 1 hour or by steaming at $115^{o}C$ for 30 minutes. This value, being greater than Munden's original wet relaxed value of 21.6 (achieved by relaxation at 30°C), suggests that Nutting's measurements were carried out on fabrics closer to the stress-free equilibrium state.

Nutting and Leaf[18] later investigated the effect of wet relaxation temperature on the value of K_1 and recorded a general increase in the value of K_1 from about 21 at 10°C to Nutting's previous value at 100°C. It was also shown by Nutting and Leaf that the three dimensional configuration of a buckled and twisted elastic rod depends upon the ratio

$$\frac{\text{flexural rigidity of rod}}{\text{torsional rigidity of rod}}$$

and that the geometry of the loop shape may be influenced by this ratio. A brief experimental trial suggested that yarns with a higher torsional decay in water also tended to have higher fully relaxed values of K_1. This finding supports the hypothesis that rigidity values influence loop geometry.

There has been a trend in recent years away from the "descriptive geometrical" method of investigation by which loop models are analysed in a direct attempt to predict fabric dimensions in different relaxation states. Work has tended to diverge into two areas: firstly, largely empirical studies in which the relaxation conditions necessary to reach minimum internal strain energy, and hence predictable fabric dimensions, have been investigated; and secondly, mechanistic studies of the plain loop based upon analyses of moments and forces within an elastica or upon minimisation of the internal strain energy.

The existence of stable loop configurations of lower internal energy than the two originally proposed by Munden[14], i.e. dry relaxed and wet relaxed (static soak at 30°C) which had become apparent during the studies of Nutting[17] and Nutting and Leaf[18] was investigated further by other workers in an attempt to achieve a fully relaxed state representing an ultimate stable condition. The Centre de Recherches de la Bonneterie[19] employed a wet or steam relaxation treatment followed by tumble drying to achieve full relaxation of cotton knits. Postle[20] examined ten different routines in an attempt to discover a "universal" method of fully relaxing both hydrophilic and hydrophobic yarns. A combination of hot water (to set yarns and reduce internal elastic forces) and agitation (to overcome internal frictional forces) was found to be effective.

Knapton et al.[21] showed that Munden's K-parameters are predictable only in the fully relaxed state. In any other state of relaxation a number of yarn and machine variables must also be taken into account and the prediction of K-parameters would be very complex. The stitch density constant (K_1) was found to reach a maximum value after 15-30 minutes tumble drying; to reach a constant value for K_4 (course/wale ratio,or loop shape factor), however, required up to 1 hour of tumbling. In order to ensure the minimum energy state had been reached it was recommended that wet relaxation followed by 1 hour tumble drying at 70°C was carried out, to give a value of K_4 = 1.28. It was concluded that the dependence of values of K on yarn diameter and loop length was as follows:

> K_1 is independent of loop length but may have some dependence on yarn diameter in the fully relaxed state.
> K_2 and K_3 are dependent on loop length and yarn diameter, this dependence being least in the fully relaxed state.
> K_4 is only independent of loop length and yarn diameter in the fully relaxed state.

In a later study by Knapton and Fong[22], in which "completely relaxed" (ten machine wash/tumble dry cycles) fabrics were measured, all K-parameters were found to be independent of the tightness, defined as the ratio of yarn diameter to loop length (d/ℓ).

In 1967 Postle and Munden[23,24] took an approach similar to that used by Munden[14] eight years previously in order to obtain a definition of the dry-relaxed (elastic) plain loop. Rather than start with an assumed loop configuration and then derive values for the internal forces and couples caused by loop interlocking, as Leaf[15] had done, they made no assumptions as to the loop's shape, but analysed it only in terms of the system of interacting forces within the structure. Their first analysis was for a simplified two-dimensional structure and this was then extended to the third dimension.

The plain loop was divided into four similar quarter loops (Figure 10) the axis of each loop being divided into two sections by a horizontal line cutting the interlocking point (X), the point through which the

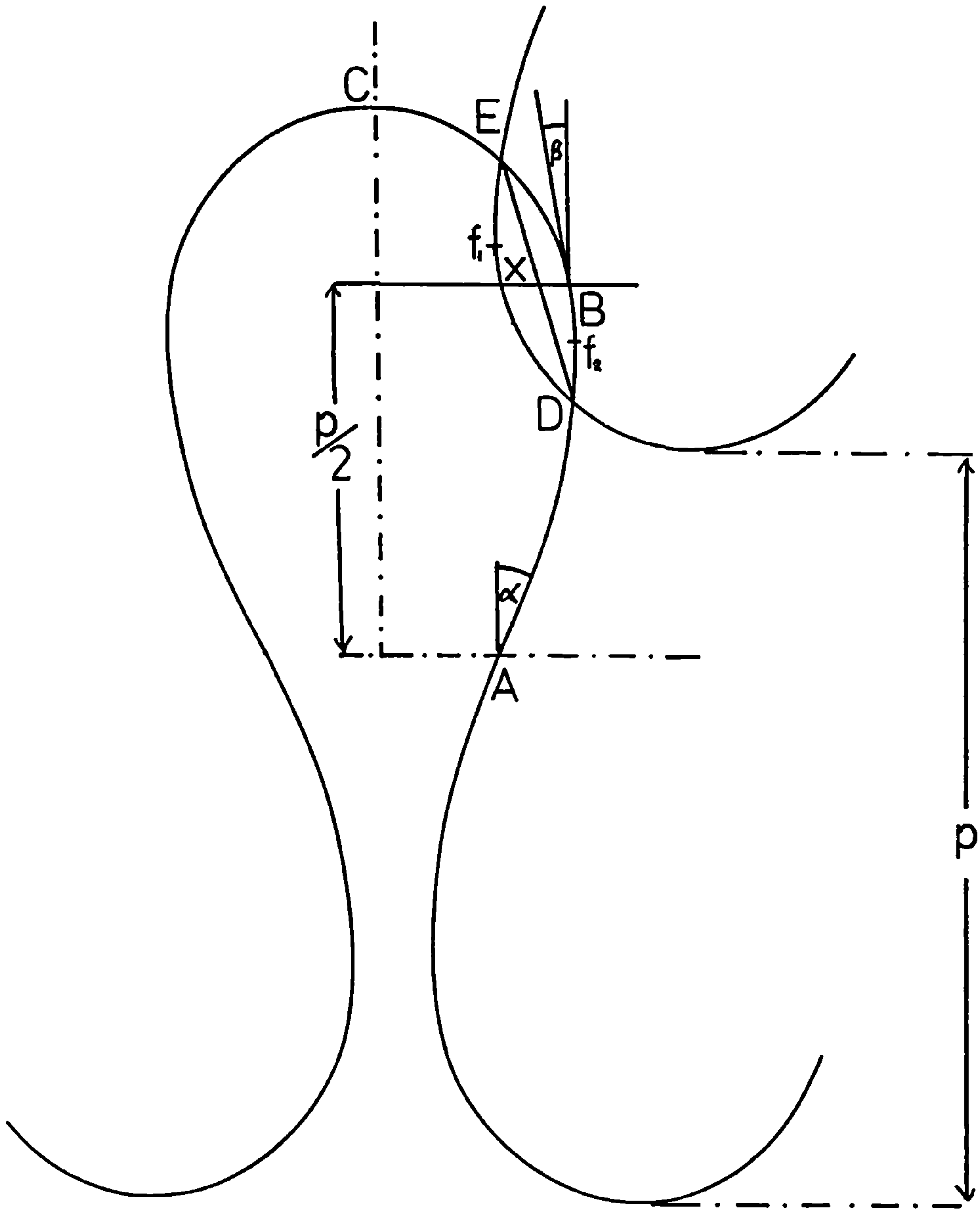


Figure 10. The Configuration of Yarn Axes in the Plain Knit Loop According to Postle and Munden's Two-Dimensional Analysis

resultant of forces acting along the contact region (ED) apparently acts. The yarn in each course was assumed to be trying to revert to its natural straight state without the influence of external forces. Because the fabric is in a relaxed state, there is no horizontally acting force on segment BC. A moment acts about C to curve the segment. In practice, the maximum and minimum horizontal dimensions of two interlocking loops(f_1, f_2), are not normally coincident, as Munden had previously assumed in his minimum energy configuration (Figure 9a). Frictional forces oppose movement to this configuration, so that the force at the interlocking point is a result of a tangentially acting frictional force and the horizontal elastic recovery force of the two loop segments. The resultant force acts at an angle β to the vertical, the interlocking angle, where

$$\text{Tan } \beta = \mu$$

(μ = static yarn/yarn frictional coefficient)

Geometrical relationships subsequently obtained were subject to the limitations of loop jamming in width and length directions. Width jamming occurs when a loop touches itself at the narrowest horizontal dimension. Loops jammed in the length direction touch the loops in the next but one course at the back of the fabric. Whether or not jamming occurs depends upon both the loop angle (α) and the interlocking angle (β).

The actual shape of the loop depends upon the loop angle and the point of interlocking upon the interlocking angle. Hence, Munden's K-parameters are dependent upon the values of α and β, subject to jamming limitations. The relationships between the angles and K-parameters were plotted and it was shown that the linear parameters (K_2, K_3) were less critically dependent upon the angles than the ratio of the two values (K_4), and that the least dependent parameter was the stitch density (K_1).

The relationship between α and β and ℓ/d was obtained, showing that a minimum value for ℓ/d in a completely jammed structure is 16.0. Values of α and β under these conditions are 27.5^o and 4.5^o respectively. For the slackest commercial fabrics (ℓ/d = 20) values of α can range from 23.7^o (length jammed) to 25.8^o (width jammed). For β the equivalent range is 3.7^o to 18.0^o. Consequently, the practical range of values for the loop angle is only 3.8^o (27.5^o-23.7^o) but the interlocking angle can have a range of 14.3^o (18.0^o-3.7^o).

Only an approximate definition of the configuration of the loop when bent into the third dimension was possible, primarily because of the difficulties of defining the form of the loop segment AB (Figure 10). This is subjected not only to horizontal forces at the interlocking points, but also to two couple components acting about perpendicular axes which have the effect of distorting the segment into the third dimension.

The work of Postle and Munden was later extended by Shanahan and Postle [25] who derived a purely theoretical model based upon a fundamental analysis of the internal forces and couples within a loop. Again, a number of basic assumptions were made in the three-dimensional analysis. Interyarn contact was assumed entirely along the interlocking zone, although some workers[26] considered this to be inconsistent with assumptions made concerning the action of couples on this segment of the loop.

The existence of a minimum internal energy state was demonstrated by expressing the loop shape solely as a function of the interlocking angle for a given fabric tightness. Values of the sine of the interlocking angle were plotted against the strain energy of the loop. The minimum plotted was shallow - a fact which was said to explain the difficulty in reaching a truly relaxed fabric state.

However, in a later paper by Shanahan and Postle[27], inconsistencies in their three dimensional model were recognised and theories of the value of the interlocking angle at minimum strain energy were abandoned.

A further, purely theoretical, analysis of the three dimensional structure, based on internal forces and couples without a predetermined loop shape, was carried out by Hepworth and Leaf[28]. The contact between loops was assumed to occur at two points along each quarter-loop rather than entirely along a contact zone. Equations for equilibrium forces and couples for the three distinct quarter loop segments (BD, DC, CA), were obtained, subject to freedom from jamming. The loop shape was shown to be a function only of the ratio yarn diameter/loop length (d/ℓ) provided this value did not exceed 0.031, i.e. for very slack fabrics outside the normal commercial range of cover factors.

A similar mechanical model of the plain loop was developed by Konopasek[29]. His application of spatial elastica theory, originally developed by Kirchoff during the last century, is a basic feature of loop configuration analysis in terms of moments and forces within the structure. This technique, in addition to energy optimisation, has been used by a number of workers in recent years.

The uncertainty regarding the positions and magnitudes of forces and couples, onset of jamming, loop symmetry, yarn compressibility etc. necessitated many assumptions in order to render a solution to the complex problem of loop configuration possible. Different assumptions and methods of approach to the problem led to some debate between workers in the early 1970's[30-33].

Studies by de Jong and Postle into the use of optimal control theory for plain knit analysis were published in 1977[35,36] and their method of energy optimisation was summarised in a paper published three years later[34]. In simple terms, the total strain energy in a loop is represented by the sum of the individual energy terms in the loop, viz:

$$E = \int_0^{\ell} (E_b + E_T + E_c + E_t).ds$$

Where E_b, E_T, E_C and E_t are respectively the yarn strain energies for bending, torsion, lateral compression and longtitudinal tension per unit length. ℓ is the loop length and s is the arc length of the yarn axis. Minimising the value of E by computer integration[37] gives values for the control vectors, subject to imposed boundary conditions.

Contemporaneous with the development of the optimal control method of loop analysis was that of a second group, whose work was based upon that originally described by Hepworth and Leaf. Their original model was limited by the exclusion of loop jamming and hence it was applicable only to very slack structures. Length and width jamming was included in the revised model published in 1976[38]. The principle of the method was to set up and solve the equilibrium equations for forces and moments within the structure, including interyarn forces caused by loop jamming. Assumptions were as for the previous unjammed model, namely that the yarn is incompressible, naturally straight, inextensible and circular in cross-section. Loops were assumed to be symmetrical (hence quarter-loops only were studied) and the fabric's tendency to curl was opposed by couples applied to the horizontal and vertical edges of the fabric. There were no external forces applied in the plane of the fabric. The effect of external loading was considered in a subsequent paper.

After establishing the positions and directions of action of the forces on each quarter loop, equations were set up relating the forces to the shape of the axis of each of the five segments in the quarter loop, the length of each segment being defined by points on the axis through which forces act. Equilibrium equations for points along each segment were obtained by relating them to the forces and moments applied to the ends of the segment.

When applied to the five sections of a jammed quarter loop, the equations for the end of one section must equal those for the start of the next to maintain continuity. Using known relationships between the Euler angles at the ends of the quarter loop and between different forces acting on the quarter loop it was possible to optimise the set of equations for specific values of yarn parameters, using a method previously developed by Hepworth[39]. Loop shape was shown to vary widely with the ratio yarn diameter/loop length (d/ℓ). Course jamming was found to occur for values of d/ℓ greater than 0.0313 and wale jamming for values above 0.0597.

The work was extended in a subsequent paper[40] to fabric subjected to uniform loading in the course and/or wale directions. Boundary conditions were established for three states: wale loading only, course loading only and biaxial loading. Values of d/ℓ from 0.05-0.07 were examined for uniaxially loaded states. Values of 0.05 and 0.065 were used for the biaxially loaded model. The particular value of the results obtained were that they isolated the effect of loop jamming from frictional and compressional effects. The onset of jamming was shown to result in a very pronounced reduction in fabric extension as loading increased.

The foregoing work was summarised in a subsequent paper[41] and extended by an examination of the effect of inter-yarn forces during fabric bending. Practical implications of the work were discussed in a later paper [42], in particular the effects of fabric tightness on loop shape and hence fabric dimensions. In contrast to Munden's[14] earlier work, yarn diameter was shown to significantly affect loop shape; a minimum value of W/C occurs at the onset of wale jamming for the idealised model (See Figure 11).

In conclusion, we may briefly consider the relevance of the findings of workers on idealised plain knit loop geometry with regard to loop distortion in real plain knit fabrics. A first reaction might be that the "idealised" yarns, typically frictionless, uniform in density, of circular cross section and perfectly elastic, are so far in character from, for instance, a twofold worsted spun yarn that these findings can be of academic interest only. There may be a degree of truth in this, particularly in the case of some of the more recent analyses dealing with strain energy distributions or the equilibrium equations of forces and moments. But a study of loop distortion is, in effect, a study of the factors which influence loop shape, so if these theories could be developed to take account of, for instance, a compressible yarn comprising a twisted fibre assembly then perhaps more information of practical use could be obtained. Nevertheless, aspects of some of the more recent findings are worth considering from a practical point of view. One example might be the influence of the ratio of flexural to torsional rigidity, discussed by Nutting and Leaf[18], on the three-dimensional loop shape. This ratio may vary according to the chemical treatment applied, fibre type, etc.

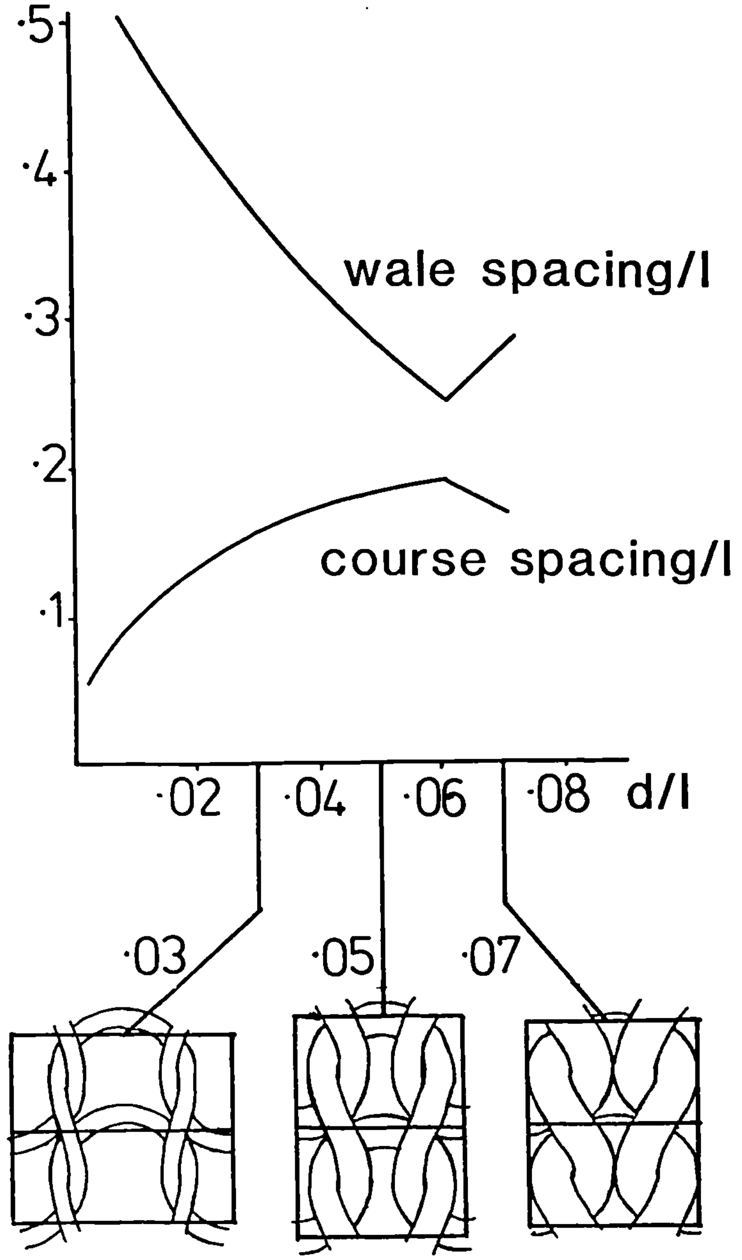


Figure 11. The Influence of Fabric Tightness (d/l) on Course and Wale Spacing and Unit Cell Dimensions (after Hepworth)

Again, Hepworth's[42] work showing that loop shape is influenced by yarn diameter suggests that a fabric knitted from a yarn of irregular count will consist of loops of a variety of shapes.

Perhaps the most important aspect of the earlier work is a recognition of the need for complete fabric relaxation to obtain a stable loop shape at the equilibrium state of minimum internal strain energy. This is important when studying loop distortion because as relaxation progresses loop distortion increases (i.e. the loop shape moves away from the perfectly symmetrical configuration produced on the knitting needles). The constants originally proposed by Munden[14] and later evaluated by Nutting[17] for a completely relaxed plain knit structure are a useful check that analysis of a fabric is being carried out in this equilibrium condition.

CHAPTER TWO

LOOP DISTORTION IN PLAIN KNIT FABRICS

2.1 INTRODUCTION

Having reviewed the history of plain knit loop analysis it may seem surprising that studies into loop distortion, a deviation from the symmetrical configuration, have been almost entirely empirical. Bearing in mind, however, that in even the most recent analyses of the idealised structure, variables have been excluded to reduce the problem to one of a looped cylindrical yarn of uniform density and circular cross section, then the complexities of the configuration of a loop of yarn consisting of a varying number of fibres bundled together with varying twist and susceptible to changes in physical characteristics from various external factors are obviously extreme.

The subject of loop distortion in knitwear was introduced in Section 1.1, and the fault divided into three manifestations: structural interface cockling, panel edge cockling and random all-over loop distortion.

Figure 12a shows an example of the first type of loop distortion which results in cockling of the fabric at the interface of two structures. It is caused by a difference in the relaxed widths of adjacent structures, and may be reduced by methods which have the effect of

a

b

Figure 12. Cockling Resulting From Differences in the Relaxed Dimensions of Adjacent Structures

a) rib / plain knit cockling

b) selvedge cockling due to fashioning

minimising this difference, e.g.

1. An anti-cockle treatment of the garment, essentially a "shock" setting treatment. This might consist of immersion in a boiling solution containing 1g/litre wetting agent, and often containing 3% (o.w.f.) sodium metabisulphite, for 10 minutes. The treatment would be followed by rinsing, hydro-extraction and tumble-drying at 90°C.

2. Increasing the knit tightness of the structure with the greater width (usually the plain knit) in order to bring the relaxed widths of the two structures closer together.

3. Reducing the knit tightness of the structure with the lesser relaxed width (usually the rib), or increasing the number of stitches in the width and doubling up stitches at the interface. The latter is perhaps the more common practice commercially, i.e. knitting wider ribs and doubling.

Although these remedies are effective in reducing cockling, they have the undesirable effect, in the case of rib/plain cockling in knitwear, of also reducing the "waisting" effect of the garment which provides a close fit. Further details of this type of cockling are to be found in a paper by Brown et al [43].

A second type of loop distortion is that found at the panel edges of fully fashioned knitwear. This may be sub-divided into two groups, one occurring close to fashionings where the fabric width is changing and a second which may occur close to the panel edge even if fashioning is not taking place.

Panel edge cockling close to fashioning can sometimes be quite severe. Its cause is similar to that of interface cockling - a difference in the relaxed dimensions of neighbouring structures. Loops are stretched in length when fashioning takes place and this tends to result in contraction of the adjacent normal plain knit fabric (See Figure 12b), allowing cockling to take place. To reduce the defect steps may be taken similar to those listed for interface cockling:-

1. Use an anti-cockle treatment on the garment (e.g. reductive setting).

2. Reduce as far as possible the rate of change in fabric width. The greater the angle between the panel edge and the wales, the more cockling can be expected since then the contracting force at the panel edge will be correspondingly greater.

Loop distortion close to panel edges which are parallel to the wales has been accounted for by the "twist blocking" effect of the knitting machine feeder. Twist redistribution may occur as a result of variations in the feeder velocity. As the feeder accelerates at the start of a fully-fashioned course, the edge of the feeder tube may hold back some of the yarn twist. An equilibrium is maintained in the centre section of the course, where the feeder velocity is constant. When the feeder slows to a halt at the end of the course, the blocked twist may then be released. These short lengths of low twist yarn at the start of a course and high twist at the end of a course are likely to result in loop distortion. This type of loop distortion was examined by Parker [44] who devised a modified yarn feeder claimed to reduce twist blocking.

The types of distortion described above are fundamentally a consequence of the knitting process - machine and knitted structure variables. The third type of distortion is different in that it appears to be produced by an inherent characteristic of the yarn. Furthermore, yarns prone to this type of distortion are apparently more likely to be subject to structural interface and panel edge cockling. This third type of distortion is a short-term random all-over distortion, an extreme example of which was shown in detail in Figure 4. More usually it takes the form of that seen in the sample of wool botany fabric shown in Figure 13. It is this type of loop distortion, with which animal fibres are particularly associated, that forms the subject of the present work. To differentiate between this type and those described previously it will be described as "yarn-related loop distortion".

2.2. ASSESSMENT OF YARN-RELATED LOOP DISTORTION

Before examining the results of investigations carried out in recent years we shall briefly consider the methods which have been used to evaluate the level of yarn-related loop distortion in a fabric.

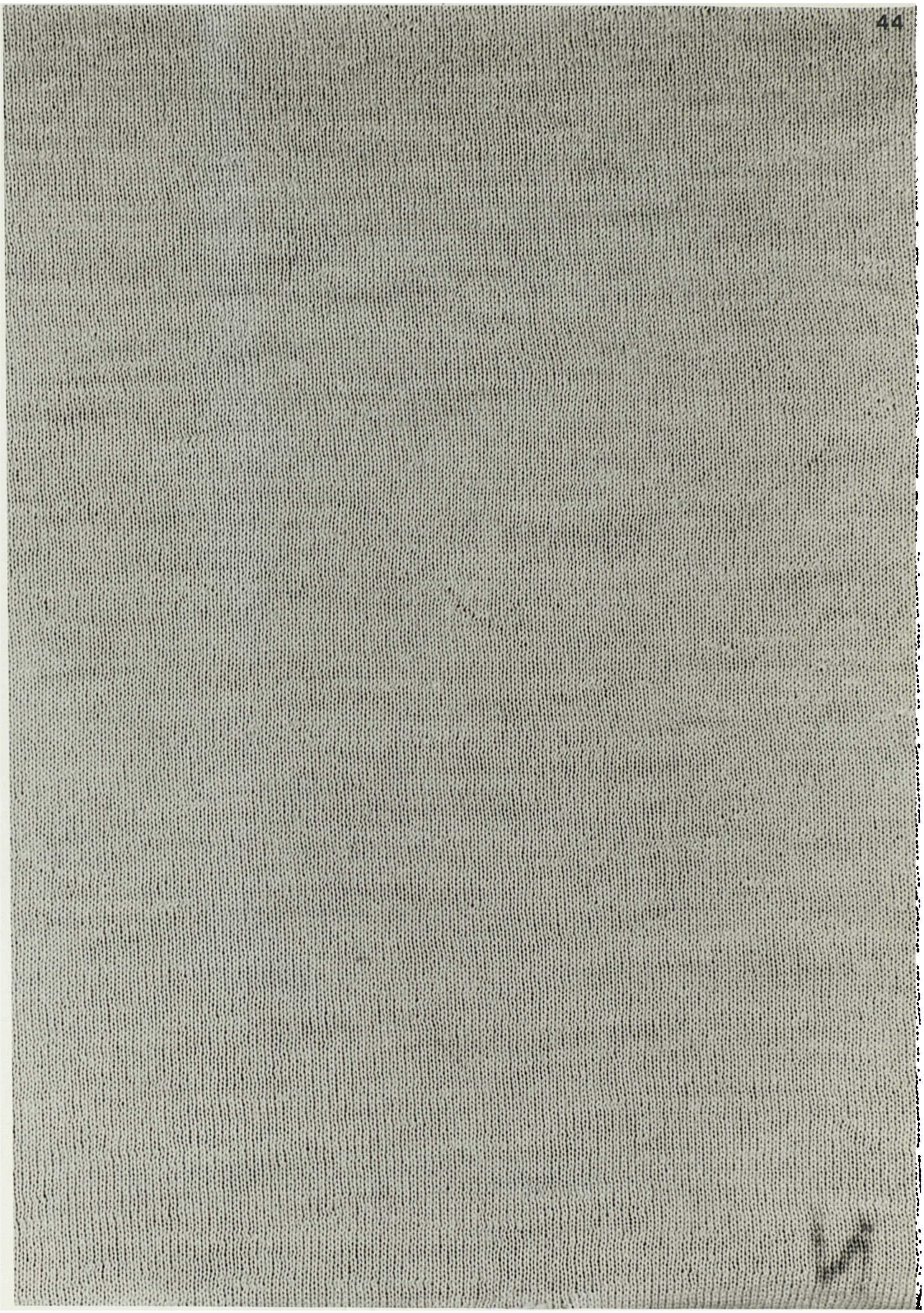


Figure 13   Random All-Over Loop Distortion in Botany Wool Plain Knit Fabric

Ideally an objective method should be used to accurately relate distortion to variations in influencing parameters. It is clear from Figure 13 that this cannot be a simple matter. If there were merely two configurations for a loop, symmetrical and distorted, then loop distortion could, by counting loops, be expressed as a percentage, i.e. "x% distortion". Unfortunately, loops gradually twist out of the symmetrical position so that the onset of distortion is largely a subjective matter. A fabric sample may contain loops distorted through a wide range of angles. An ideal objective method, therefore, would measure the distortion angle of each individual loop, over a minimum of, perhaps, 20,000 loops, (for instance a 20cm x 20cm fabric sample). Merely summing the individual levels of distortion would not be sufficient - the distorted appearance depends also on the distribution of distortion. A small number of very distorted loops are more objectionable than many moderately distorted ones. Furthermore, the distribution of distorted loops over the fabric surface has an important bearing on the acceptability of the apearance. A dozen distorted loops widely scattered individually over an area are more acceptable than if they occur as a single prominent row. Finally, it is the subjective assessment of the consumer which is ultimately of importance and it is against subjective opinion that any proposed quantitative determination would have to be compared.

A rudimentary objective assessment method was used by Robinson et al. [45,46] in two of a series of papers from the South African Wool Textile

Research Institute on cockling in fully fashioned knitwear. Loop distortion was expressed as:-

$$\% \text{ cockling} = \frac{\text{no. of cockled loops}}{\text{total number of loops}} \times 100$$

The mean number of loops in each "cockle" (group of distorted loops) was also reported. Measurements were made over 25 sq.cm of fabric (approx. 1100 loops). At least two objections to this method may be put forward. Firstly, as already discussed, a subjective determination is required to assess whether or not an individual loop is actually distorted. Secondly, the area measured is too small for an accurate representation of the extent of loop distortion to be made. A 25 sq.cm. sample (e.g. one approximately 2 inches square) could be cut from a fabric and give a very unrealistic impression of the actual degree of distortion because of the often irregular distribution of the defect. It is suggested that a sample at least of about 400 sq.cm. (e.g. 20cm x 20cm) is needed for any determination of loop distortion, whether quantitative or subjective.

A second method proposed by S.A.W.T.R.I. employs Standard Photographs described in a paper by Robinson et al.[47] and used in a number of S.A.W.T.R.I. papers on cockling in fully fashioned knitwear [48-51]. A set of five photographs was published showing samples ranging from "no cockling"[5] to "very severe" [1]. The principle is to compare a fabric sample with the photographs and grade it to the closest level of cockling. Half grades may be given, so that there is a total of nine possible levels of cockling.

This method of assessing loop distortion is obviously very rapid, particularly when compared with the previous laborious counting technique. It could be useful as a quality control method similar to those used for snagging and pilling evaluation. Unfortunately, it has limitations which preclude its use as an accurate method of determining changes in loop distortion with changes in influencing parameters. Surprisingly small variations in levels of loop distortion can be detected by eye and it is possible to rank, say, ten samples in order of loop distortion even though the level of distortion in each is of approximately the same order. The S.A.W.T.R.I. Standard Photograph method does not permit fine gradations of distortion to be distinguished so that useful research information may be lost. There are also problems in grading fabrics which have different cover factors or are produced from yarns of different counts to those illustrated in the photographs.

The majority of workers have used some form of visual ranking system to assess loop distortion. A typical method was that used by Benson[52] in which each member of a panel of six judges was asked to place a set of samples in order of degree of loop distortion. Values of 1(best) to n(worst) were awarded, where n samples were present in each set. Having obtained an average ranking value (r) for each sample the value was used to calculate a ranking number between 0 (worst possible) and 100 (best possible):-

$$\text{RANKING NUMBER} = \frac{n - r}{n - 1} \times 100$$

For large sets of samples, an improved method of ranking is that of paired comparisons[53] which has the further advantage of distinguishing inconsistencies in judging, a likely occurrence in the ranking of samples with similar levels of loop distortion. This method was used by Haigh[54] in determining the effect of package dyeing on loop distortion. Further details of the ranking method of assessment are given in Section 5.8

2.3 FACTORS INFLUENCING YARN-RELATED LOOP DISTORTION

2.3.1 Recent Investigations

It may be postulated that the potential for a yarn to distort in a fabric can be introduced at any stage in the processing route between fibre and fabric. Indeed, about thirty different processing variables have been examined by workers in recent years and a large number of these have been found to influence loop distortion. Unfortunately, there may have been a tendency for the issue to become obscured, since many of the influencing factors are only of secondary importance; they permit the release of a distortion potential already present in the yarn. An example of a secondary influencing factor could be fabric tightness. The tighter a fabric, the less easily are loops able to twist out of the symmetrical position, so that tightness may control the extent of distortion development.

Figure 14 summarises the conclusions of recent studies relating individual variables to loop distortion in wool plain knit fabrics.

INDEPENDENT VARIABLE	TREATMENT LEVEL	REFERENCE NUMBER																							
		45	46	48	49	50	51	52	54	55	56	57	58	59	60	61	62	63	64	65	66[i]	67[j]	68[j]	69	106
FIBRE TYPE[a]	ACRYLIC : WOOL	−2								−2		−2	−2								0				−2
FIBRE DIAMETER	COARSE : FINE			+2	+2		+2			+2			+2				+1								+2
FIBRE LENGTH	SHORT : LONG					0	0							−1											
FIBRE CRIMP	STRAIGHT : CRIMPED		+2	+2	+2		+2							+1											
TOP DYEING	UNDYED : TOP DYED					+1[c]								f											
TOP ANTICOCKLE TREATMENT	UNSET : SET					+1[c]																			
TOP CHLORINATION	UNTREATED : CHLORINATED					+2			−2[d]									+2[h]							
TOP CHLORINE / HERCOSETT	UNTREATED : CHL/HERC TRTD.					+1[c]		0	0				0				−2	0						−2	0
YARN COUNT	FINE : COARSE				+1								0												
YARN COUNT REGULARITY	IRREGULAR : REGULAR	+2	−1				+2	+1		+2			+2		+2										
YARN TWIST	LOW : HIGH							0		+1			0	e	0						−1			0	+1
YARN TWIST REGULARITY	IRREGULAR : REGULAR	+2	−1				+2	+1		+2	+2		+1		+2						+2				
YARN REGAIN	LOW : HIGH												+1		+2	+2[g]									
YARN SURFACE FRICTION	LOW : HIGH							0					0					+1							+1
YARN BENDING RIGIDITY	LOW : HIGH											−2		−2											
YARN PACKAGE DYEING	UNDYED : DYED					+1[c]			−2					f						+2					
YARN HANK DYEING	UNDYED : DYED													f											
YARN ANTICOCKLE T/MNT	UNSET : SET					+1[c]		+2		+1															
YARN PACKAGE STEAMED	UNSET : SET		−2					−2					−1						+1	+2	+2		+1[k]		−2
YARN SHRINK RESIST T/MNT	UNTREATED : TREATED	0				+1[c]																			
YARN HANK RELAXATION	UNRELAXED : RELAXED																				+2	+1			
YARN PACKAGE HARDNESS	SOFT : HARD												0												
KNITTING SYSTEM	CIRCULAR : FULLY FASHIONED			−2[b]			0		−2												−2				−2
YARN FEEDING TENSION	LOW : HIGH							0					0								−1				
LOOP FORM/N TENSION	LOW : HIGH													0											
KNITTING COVER FACTOR	SLACK : TIGHT						+1	−1		+2			0						+2	+2		+1	+2		
PIECE DYEING	UNDYED : DYED					+2[c]																			
PIECE ANTICOCKLE T/MNT	UNSET : SET		+2			0[c]	+1							+2			+2								
PIECE RELAXATION	UNRELAXED : RELAXED	−2	−2	−2			−2						−2	−2		−2		−2		−2	−2	−2	−2	−2	
PIECE SHRINK RESIST T/MT	UNTREATED : TREATED					+2[c]	+2																		

FIGURE 14. RESULTS OF PAST WORK INTO THE INFLUENCE OF DIFFERENT VARIABLES ON LOOP DISTORTION IN PLAIN KNITS

KEY

EFFECT OF REPLACING FIRST TREATMENT LEVEL BY SECOND

+2 SIGNIFICANT IMPROVEMENT
+1 SLIGHT IMPROVEMENT
0 NO EFFECT
−1 SLIGHT WORSENING
−2 SIGNIFICANT WORSENING

NOTES

a) All other variables listed relate to wool only.
b) The opposite effect was found for coarse wools.
c) Chlorine/ Hercosett application,dyeing and anticockle treatments were carried out together at each stage (fibre, yarn, piece). Independent effects were not investigated.
d) Deterioration with increased chlorine dosage only occurred as an interaction with package dyeing. See Reference 63.
e) Optimum twist ratio singles : folding was 1 : 1.8
f) Hank dyeing gave less loop distortion than top dyeing; top dyeing gave less loop distortion than package dyeing.
g) The reduction in loop distortion due to increasing the yarn regain was only apparent before wet relaxation.
h) The shrink resist treated yarns were produced from wool 2.0 micrometers coarser than the untreated yarns.
i) This paper relates to Self-Twist yarns, and some of the effects observed may not be applicable to ring-spun yarns. However, the results may be of relevence regarding the effects of extreme twist irregularity which is essentially independent of variations in yarn count.
j) Self-Twist yarns again - see i) above.
k) Improvement unstable to wet relaxation.

Brief details of the consensus view on the influence of each variable on loop distortion are given below:

2.3.2 Fibre Type

Acrylic fibre is the most common synthetic alternative to wool in knitwear and the conclusion of trials based on knitwear produced from ring spun yarns was that acrylic knitwear appeared to be almost entirely free of loop distortion even when the yarn was spun intentionally to a high level of irregularity [55]. A determination of the important difference between wool and acrylic fibres in this respect could indicate the fundamental cause of loop distortion in wool knitwear. Factors postulated have been the increase in the untwisting torque of a wool yarn in relation to acrylic in the presence of water[55] and differences in flexural resistance [57]. Other related factors may be regain:relative humidity characteristics, fibre cross-sectional shape and yarn torsional rigidity.

Comparisons between wool and mohair might also prove useful, since mohair has a significantly higher tendency to produce loop distortion than wool.

2.3.3 Fibre Diameter

There is clear evidence that a reduction in fibre diameter can be related to a reduction in loop distortion. Fibre diameter is likely to influence yarn count regularity and twist regularity, yarn torsional and bending characteristics and is often correlated with fibre length. Such interactions make determination of the primary cause of loop distortion difficult to establish. A recent report[106] has also highlighted the danger that a small proportion of coarse wool in an otherwise fine blend may cause loop distortion.

2.3.4. Fibre Length

In general, shorter wool fibres are finer than longer wools. It is, therefore, important when making a comparison of wools of different fibre length that the fibre diameters are not significantly different. There is little strong evidence to suggest a significant influence of fibre length on loop distortion. Longer fibres have been shown to be more likely to induce loop distortion[59] although the mean fibre diameter of the longer wool compared was slightly coarser.

2.3.5 Fibre Crimp

The relationship between high crimp and low loop distortion has been demonstrated, although no explanation has been proposed. Problems of interdependence of the processing variables are apparent when the results of work by Robinson et al[51] are examined.

The correlation coefficients below have been calculated from the published results in which 21 different wools were compared for cockling after spinning into Nm 31.25/2 (R16/2 tex) yarn and knitting into a plain knit structure.

	Crimp	Fibre Length	Fibre Diameter	Yarn Irreg.	Cockle Rating
Crimp	1.00				
Fibre Length	0.03	1.00			
Fibre Dia.	-0.83	-0.15	1.00		
Yarn Irreg	-0.61	-0.18	0.84	1.00	
Cockle Rating	0.88	0.20	-0.89	-0.66	1.00

Although both crimp and fibre diameter were correlated with "cockle rating" at the 0.1% significance level, the correlation between crimp and fibre diameter themselves was also significant at this high level of 0.1%. Hence it is not really possible to draw conclusions about either variable independently.

2.3.6. Top Dyeing

Top dyeing does not appear significantly to influence loop distortion and in this respect is preferable to package dyeing of yarn, discussed below.

2.3.7. Top Anti-cockle Treatment

This is an unconventional stage at which to carry out this treatment. No conclusions about the influence of the treatment at this stage can be drawn from the study made [50] because it was not carried out independently of other factors.

2.3.8 Top Chlorination

Chlorination may have the effect of reducing loop distortion[63]. This might be related to the oxidative degradation of the fibre leading to a change in the flexural and torsional properties of the yarn. A possible interaction between chlorination and package dyeing of yarn has been reported[54] in which increased chlorine dosage produced increased loop distortion on package dyed yarns.

2.3.9. Top Chlorine/Hercosett Treatment

Opinions have been somewhat diverse; some studies have suggested that the treatment reduces loop distortion[50], others that it increases it[62] but the majority that it has no significant effect[52,54,58,63].

2.3.10. Yarn Count

Varying yarn count at a fixed fibre diameter would be expected to result in a variation in count regularity because the number of fibres in the cross-section would vary. If the number of fibres in the cross-section were kept constant then the fibre diameter would have to be varied. Hence it is difficult to examine yarn count as an independent variable. Slight improvements in cockling relating to an increase in count [49] may have been due to a reduction in irregularity.

2.3.11. Yarn Count Regularity

Yarn count regularity is accepted as being an important factor in terms of the extent to which loop distortion develops. Of interest, however, is work carried out by S.A.W.T.R.I.[55] on very irregular acrylic yarns which did not produce cockled knitted fabrics. This suggests that irregularity alone is insufficient to cause loop distortion and that at least one other variable may have a significant influence which is necessary for the defect to develop.

The importance of count regularity could be its influence on twist regularity. It is well known that if a constant level of twist is inserted into an irregular yarn, redistribution of twist to the more torsionally stable state of higher twist in thin places and lower twist in thick places will tend to occur during subsequent relaxation[70,71]. Twist regularity is discussed further below.

2.3.12. Yarn Twist

There are two aspects of yarn twist to consider: the level of twist inserted and the ratio of singles twist to folding twist. Although these factors are obviously important with regard to the development of spirality, the evidence relating their importance to loop distortion is not strong and occasionally contradictory.

2.3.13. Yarn Twist Regularity

It is difficult to examine yarn count regularity independently of regularity in twist. The reverse, however, is more easy to achieve, and studies of Self Twist yarns[66] and storage feed units on fully fashioned machines [56] have shown that extreme loop distortion in these cases can be attributed primarily to large variations in twist. Details of Self Twist yarn and plain knitted fabric are shown in

Figure 15.

A number of workers have commented that distorted loops in plain knits are apparently characterised by zones of higher count and particularly of low twist:-

"The loops appear to slant at a more acute angle in one direction, and that part of the stitch which becomes more predominant on the surface appears to have a very low twist in the yarn"[45].

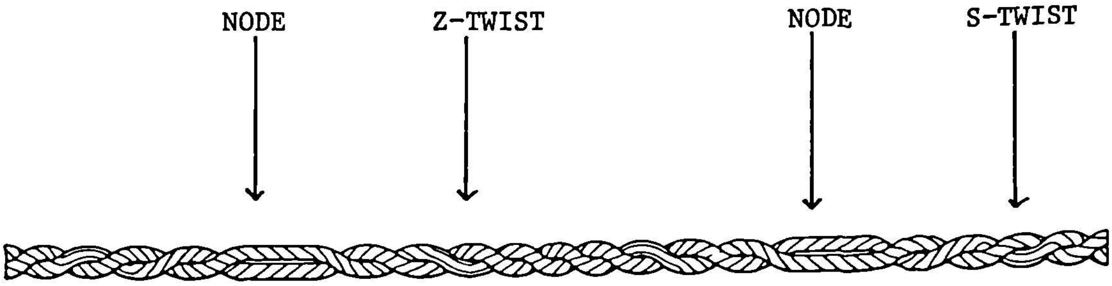
"Yarn in the distorted places is always bulkier and lower twisted, and the loop geometry is such as to eliminate the folding twist and allow the single yarn to develop preferred independent helices"[106].

2.3.14 Yarn Regain

There is clear evidence that a yarn conditioned at a high relative humidity will distort significantly less than a drier yarn, after knitting. Some workers have recommended conditioning yarn to a high regain as a solution to loop distortion [60] but it has been shown that the improvement obtained by knitting with high regain yarns may not be stable to fabric relaxation[61].

2.3.15 Yarn Surface Friction

There is evidence that lubricating wool knitting yarns may tend to slightly increase loop distortion but, relative to other factors, friction appears to be of minor importance.



a)

b)

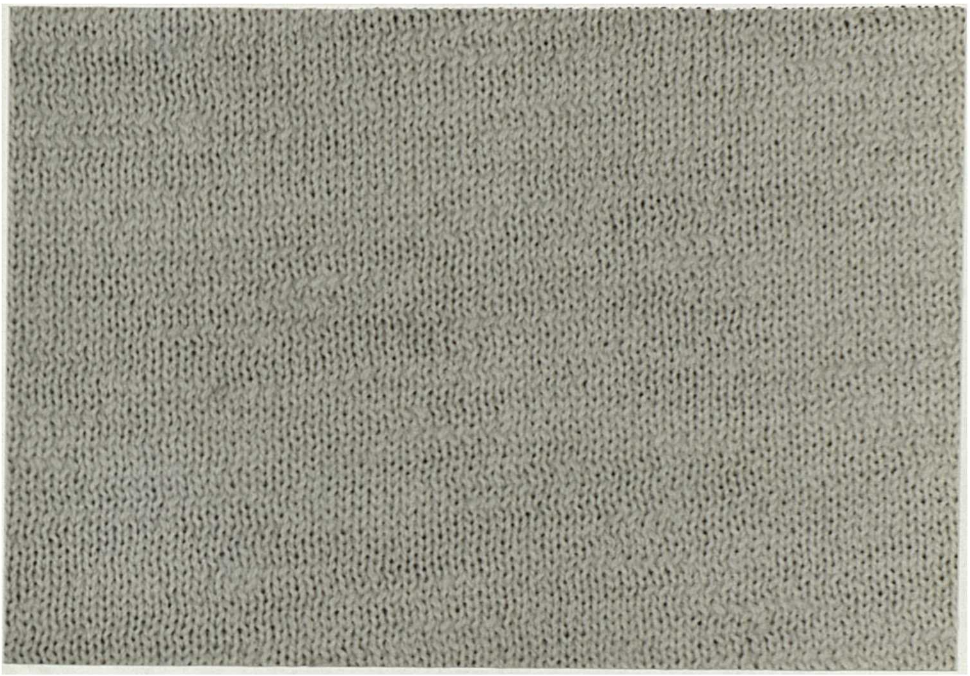


Figure 15. Self-Twist Yarn - an Example of Extreme Twist Irregularity

a) The concept was originally proposed by Henshaw[72] in 1962. The singles twist changes between S and Z with approximately sinusoidal distribution. The two ends are twisted out of phase to prevent twistless nodes.

b) Loop distortion in fabric knitted from ST yarn.

2.3.16. Yarn Bending Resistance

Work by Bodenschatz[57] indicates that there may be a significant correlation between loop distortion and the flexural rigidity of a yarn and that loop distortion increases as a yarn becomes stiffer. The importance of factors such as fibre type, yarn treatment etc. on loop distortion could be determined at least in part by their influence on the rigidity characteristics of a yarn.

2.3.17. Yarn Package Dyeing

Fabrics knitted from package dyed yarns appear to distort not only more than those knitted from ecru yarns but also more than those knitted from yarns dyed by other methods (top, hank, piece). Package dyeing may possibly be regarded as a form of yarn setting and in this respect has a similar effect to autoclave setting on package (see below).

2.3.18. Yarn Hank Dyeing

The one study of this dyeing route[63] suggested that, for ring spun yarns, it may result in less loop distortion than dyeing carried out at the top or package stage.

2.3.19 Yarn Anti-cockle Treatment

It is of interest to note that the reductive setting of yarns in hank[55] or package[52] form appears to improve loop distortion, whereas the setting of yarns by steaming or dyeing on package leads to a deterioration. Possibly the different effects of steam or water and reductive treatments on the molecular bonds in the wool fibre influence the physical characteristics of the yarns in different ways.

2.3.20 Yarn Steam Setting on Package

In the case of ring spun yarns, most workers agree that package steaming results in increased loop distortion. This is an interesting phenomenon in that spirality, to which loop distortion has sometimes been related[44], can be significantly improved by package setting. Loop distortion in Self Twist yarns can also be improved by steam setting[66,68].

2.3.21 Yarn Shrink Resist Treatment

There is no evidence that shrink resist treatment (chlorine/Hercosett) applied at the yarn stage, independently of other treatments, influences loop distortion.

2.3.22 Hank Relaxation

Although hank relaxation has been shown to improve loop distortion in self-twist yarns, no work has been published relating to ring-spun yarns.

2.3.23. Knitting Package Hardness

Knitting package hardness (winding tension) has no apparent influence on loop distortion.

2.3.24. Knitting System

It is frequently reported that Cotton's Patent fully fashioned machines are more likely to produce cockled fabric than circular machines. Taken overall, one might expect this since, as discussed earlier, a reciprocating feeder and a fashioned structure can produce additional types of cockling not present in circular knit goods. In addition, the type of feeder normally used on fully fashioned machines may be more prone to causing twist-blocking, resulting in higher twist irregularity.

However, it is not clear whether or not yarn-related loop distortion taken in isolation is greater for fully fashioned machines since comparisons have been made without isolating different types of cockling.

If yarn-related loop distortion is to be analysed without the confusion of superimposed cockling of different types, the work is best carried out on a circular machine.

2.3.25. Yarn Feeding Tension

There is no evidence to show that variations in feeding tension on ring spun yarns during knitting influence loop distortion.

2.3.26. Loop Formation Tension

Again, tension variations during loop formation have not been shown to effect the development of loop distortion.

2.3.27. Knitting Cover Factor

Virtually all workers are agreed that loop distortion can be reduced by knitting a tighter fabric. There can be little doubt, however, that cover factor is a secondary factor in terms of its influence on loop distortion. It merely controls the extent to which the yarn is permitted to relax into a distorted configuration.

2.3.28. Piece Dyeing

No published work on the independent influence of piece dyeing on cockling in relation to other dyeing routes is known. Verbal reports from industry suggest that loop distortion is significantly less if knitwear is piece dyed than if it is produced from package dyed yarns.

2.3.29. Piece Anti-Cockle Treatment

A reductive anti-cockle treatment, carried out immediately after knitting, can be very effective in halting the development of distorted loops. Nevertheless, the influence of such a "shock" setting treatment is of a secondary type, and is a way of overcoming problems in a yarn which is of a type susceptible to distortion. A better approach would be to avoid using such a yarn in the first place.

2.3.30. Piece Relaxation

The presence of loop distortion implies that relaxation of the loops from the symmetrical but strained configuration on the knitting machine needles to a relatively distorted equilibrium state of lower internal energy has occured. The greater the degree of relaxation, or proximity to the minimum strain energy state, the more loop distortion will be displayed assuming that the yarn has the potential to develop the defect.

The influence of different variables on loop distortion is best determined by ensuring that the full potential of loop distortion has been developed during a complete relaxation treatment. The effectiveness of different routes, as determined by Munden's K-parameters has been discussed earlier (Section 1.2).

2.3.31. Piece Shrink Resist Treatment

Shrink resist treatment in piece, independently of other treatments, has not been examined.

2.4. CLASSIFICATION OF FACTORS INFLUENCING YARN-RELATED LOOP DISTORTION

Figure 16. classifies the production and processing variables which have been examined in terms of yarn-related loop distortion. In this respect the fabric-related variables may be regarded as being of secondary importance where they are of significance, in that their effect is essentially the control of the development of distortion. Strictly speaking one should perhaps refer to "fibre and yarn related loop distortion" although factors relating to a fibre, such as shrink resist treatment, are also functions of the yarn. In the next chapter the choice of independent processing variables for further study is discussed in terms of the conclusions from previous work.

	FIBRE			YARN			FABRIC		
	VARIABLE	A	B	VARIABLE	A	B	VARIABLE	A	B
PRODUCTION VARIABLES	FIBRE TYPE	*	*	COUNT			KNITTING SYSTEM		
				COUNT REGULARITY	*	*	FEEDING TENSION		
				TWIST		*	LOOP FORMATION TENSION		
				TWIST REGULARITY	*	I	COVER FACTOR	*	
				(TWIST METHOD)		*			
PROCESSING VARIABLES	TOP DYE		*	PACKAGE DYE	*	*	PIECE DYE		
	TOP ANTICOCKLE			HANK DYE			PIECE ANTICOCKLE	*	
	TOP CHLORINATE	*	*	YARN ANTICOCKLE	*		PIECE RELAXATION	*	
	TOP CHLORINE / HERCOSETT		*	AUTOCLAVE SET	*	*	PIECE CHLORINE / HERCOSETT		
				HANK STEAM					
				YARN CHLORINE / HERCOSETT					
				PACKAGE HARDNESS					
				CONDITIONING REGAIN	*	*			
PHYSICAL CHARACTERISTICS	DIAMETER	*	*	SURFACE FRICTION		*	LOOP DISTORTION		
	LENGTH			BENDING RIGIDITY	*	*			
	CRIMP	*		(TORSIONAL RIGIDITY)		*			
				(BENDING HYSTERESIS)		*			

Figure 16. Classification of Production and Processing Variables and Dependent Physical Characteristics in Relation to Loop Distortion

NOTES

1. Columns "A": * refers to a factor significantly related to loop distortion
2. Columns "B": * refers to a factor to be examined in the present investigation
3. Variables in brackets : included in present investigation, but no previous study known
4. "I" : not included as an independent variable but indirectly due to dependence on count regularity

CHAPTER THREE

EXPERIMENTAL DESIGN

3.1. EXPERIMENTAL AIMS

The intention of this investigation is to relate fibre and yarn production and processing variables to the occurrence of loop distortion in the plain knit structure with particular emphasis on wool botany fabrics. It is also hoped that these production and processing variables can be related to certain physical characteristics of the yarns which, in turn, can be correlated to the occurrence of loop distortion. If these two aims can be achieved they will provide both a valuable practical guide to knitting yarn manufacturers and also an indication of the fundamental mechanism of the phenomenon of loop distortion.

3.2. CHOICE OF INDEPENDENT VARIABLES

The classification proposed in Figure 16 lists, in the columns "A", variables and physical characteristics which, from previous investigations, appear to be significantly related to the occurrence of loop distortion. These factors should be included, if possible, in an experiment which permits a study not only of these main effects but also interactions between them. Columns "B" indicate the variables and physical characteristics which were chosen for investigation in this study.

The influence of the fibre type and the effect of top chlorination (in the case of wool) were the first choices in relation to independent fibre variables. Top dyeing was included next because it was felt that the previous work had not provided conclusive results and that the effects of dyeing at this stage, in comparison to package dyeing, should be more clearly established. Top chlorine/Hercosett treatment was likewise included because previous work had sometimes yielded contradictory results and because of the importance of this variable from a manufacturer's point of view.

Diameter, length and crimp have been classified as fibre physical characteristics, implying that they are dependent upon the previous processing treatments. Fibre diameter was chosen as an important factor to include. In practice, its dependence on the processing route is insignificant and so here it has been treated as an independent variable, a choice being made between one of two diameters - "coarse" or "fine".

Crimp was not included in the series because it was felt that it would be virtually impossible to achieve only two levels of crimp (required for the type of factorial design that will be employed) for all the different conbinations of fibre production and processing variables proposed. Unlike diameter, crimp is a physical characteristic of the fibre which is likely to be significantly affected by the previous treatments. Count regularity and twist level were included in the yarn production variables examined. Implicit in the inclusion of count regularity is twist regularity, since the two are closely related. Twist level was included because it was felt that previous findings were not entirely conclusive and because it could relate to the third yarn production variable - the method of twisting. Although this factor has not apparently been examined before, reports from industry suggest that modern twisting machinery may lead to an increased occurrence of loop distortion, perhaps through a less even distribution of twist in the folded yarn. All the yarn processing variables previously shown to be of importance were included in the design, except for yarn anti-cockle treatment. It was not planned to include preventative measures, such as anti-cockle treatments, in the plan. Similarly, other "control" variables such as knitting tightness and the extent of fabric relaxation were also excluded.

A total of eleven independent variables was, therefore, investigated. The five fibre-related variables became, in effect, functions of the yarns into which they were made, so that, for the purposes of the experiment, loop distortion was examined in terms of eleven independent yarn-related variables.

3.3 FACTORIAL EXPERIMENTAL DESIGN

An experiment requiring an estimate of the effect of eleven independent variables, plus many of the interactions considered likely to be of importance, upon one or more dependent variables is best tackled in terms of a factorial design[73]. A 2^{11} design, for instance, uses every possible combination of the eleven "treatments", each "treatment" or "main effect", being represented at one of two levels. There would, however, be a number of objections to such a direct approach. Firstly, 2048 different yarns would have to be spun and knitted, which is not feasible in practice. Secondly, some of the treatments are incompatible. It is, for instance, not possible to apply a chlorine/Hercosett shrink-resist treatment to acrylic top. Thirdly, this large design would provide estimates of multi-factor interactions which would have little obvious meaning. We are really only concerned with interactions between two different main effects at one time. The experiment was reduced to a more manageable size firstly by splitting the variables into six designs (most variables being represented in at least two designs) and secondly by using a half replicate of a 2^n trial for each design. In this way it was necessary to spin and knit only thirty seven different yarns. The six design groups were as follows:-

INDEPENDENT VARIABLE	Design Group					
	1	2	3	4	5	6
Fibre Type					X	
Top Dyeing	X		X			
Top Chlorination	X	X				
Top Chlorination/Hercosett Treatment			X	X		
Fibre Diameter	X	X	X	X		
Yarn Count Regularity					X	X
Yarn Twist Level					X	X
Twisting Method						X
Package Dyeing		X		X		
Autoclave Setting	X	X	X	X	X	X
Conditioning Regain					X	

Each of the variables was represented at two levels, e.g. fibre type as "wool" or "acrylic", top chlorination as "treated" or "untreated", etc. Further details of the actual levels of the variables are given in Chapter Four. The two levels are designated in each case as "Low" (-) or "High" (+). The complete set of treatment levels for all thirty seven samples is tabulated in Figure 17.

Figure 18 gives the matrices for Designs 1-4. These designs form a single group structured to investigate the following variables for a wool yarn:-

(a) Fibre diameter.

(b) The difference between package and top dyeing in terms of loop distortion.

(c) The difference between chlorination and chlorine/Hercosett treatment in terms of loop distortion.

(d) Autoclave setting and its possible interactions with the other independent variables.

Four designs were required because chlorination and chlorine/Hercosett treatment are incompatible (it would not make sense to chlorine/Hercosett treat top which was already chlorinated. The level of chlorination would be excessive for the desired pick-up of resin), and similarly a yarn would not be both package and top dyed, as a single design would require. Each design, therefore, includes four main effects and three interactions, each of which includes the main effect of autoclave setting. A possible interaction between autoclave setting and shrink resist treatments has previously been reported [63].

SAMPLE CODE	VARIABLE LEVEL										
	fibre type	fibre diam.	top chlor	top Herc.	top dye	count reg.	twist level	aut. set	twist meth.	pack. dye	mois. regn.
1	−	−	−	−	−	−	−	−	−	−	−
2	−	−	−	−	−	−	−	+	−	−	−
3	−	−	+	−	+	−	−	−	−	−	−
4	−	−	+	−	+	−	−	+	−	−	−
5	−	+	+	−	−	−	−	−	−	−	−
6	−	+	+	−	−	−	−	+	−	−	−
7	−	+	−	−	+	−	−	−	−	−	−
8	−	+	−	−	+	−	−	+	−	−	−
9	−	−	+	−	−	−	−	−	−	+	−
10	−	−	+	−	−	−	−	+	−	+	−
11	−	+	−	−	−	−	−	−	−	+	−
12	−	+	−	−	−	−	−	+	−	+	−
13	−	−	+	+	+	−	−	−	−	−	−
14	−	−	+	+	+	−	−	+	−	−	−
15	−	+	+	+	−	−	−	−	−	−	−
16	−	+	+	+	−	−	−	+	−	−	−
17	−	−	+	+	−	−	−	−	−	+	−
18	−	−	+	+	−	−	−	+	−	+	−
19	−	−	−	−	−	−	−	−	−	−	+
20	+	−	−	−	−	−	−	+	−	−	−
21	+	−	−	−	−	−	−	+	−	−	+
22	−	−	−	−	−	−	+	−	−	−	−
23	−	−	−	−	−	−	+	−	−	−	+
24	+	−	−	−	−	−	+	+	−	−	−
25	+	−	−	−	−	−	+	+	−	−	+
26	+	−	−	−	−	+	−	−	−	−	−
27	+	−	−	−	−	+	−	−	−	−	+
28	−	−	−	−	−	+	−	+	−	−	−
29	−	−	−	−	−	+	−	+	−	−	+
30	+	−	−	−	−	+	+	−	−	−	−
31	+	−	−	−	−	+	+	−	−	−	+
32	−	−	−	−	−	+	+	+	−	−	−
33	−	−	−	−	−	+	+	+	−	−	+
34	−	−	−	−	−	−	−	+	+	−	−
35	−	−	−	−	−	−	+	+	+	−	−
36	−	−	−	−	−	+	−	−	+	−	−
37	−	−	−	−	−	+	+	−	+	−	−

Figure 17. Table of Variable Levels for the Complete Set of Samples Required for the Six Half Factorial Designs

Sample Code	D	T	C	A	DA	TA	CA
1	−	−	−	−	+	+	+
2	−	−	−	+	−	−	−
3	−	+	+	−	+	−	−
4	−	+	+	+	−	+	+
5	+	−	+	−	−	+	−
6	+	−	+	+	+	−	+
7	+	+	−	−	−	−	+
8	+	+	−	+	+	+	−

Design 1.

Sample Code	D	P	C	A	DA	PA	CA
1	−	−	−	−	+	+	+
2	−	−	−	+	−	−	−
9	−	+	+	−	+	−	−
10	−	+	+	+	−	+	+
5	+	−	+	−	−	+	−
6	+	−	+	+	+	−	+
11	+	+	−	−	−	−	+
12	+	+	−	+	+	+	−

Design 2.

Sample Code	D	T	H	A	DA	TA	HA
1	−	−	−	−	+	+	+
2	−	−	−	+	−	−	−
13	−	+	+	−	+	−	−
14	−	+	+	+	−	+	+
15	+	−	+	−	−	+	−
16	+	−	+	+	+	−	+
7	+	+	−	−	−	−	+
8	+	+	−	+	+	+	−

Design 3.

Sample Code	D	P	H	A	DA	PA	HA
1	−	−	−	−	+	+	+
2	−	−	−	+	−	−	−
17	−	+	+	−	+	−	−
18	−	+	+	+	−	+	+
15	+	−	+	−	−	+	−
16	+	−	+	+	+	−	+
11	+	+	−	−	−	−	+
12	+	+	−	+	+	+	−

Design 4.

KEY

D Fibre Diameter
T Top Dye
C Top Chlorination
A Autoclave Set
P Package Dye
H Top Chlorine / Hercosett Treatment

Figure 18. Design Matrices 1-4

A half-replicate of a factorial design inevitably means that some of the interactions are aliassed with main effects or other interactions. For instance, in Design 1, an estimate of fibre diameter as a main effect would be aliassed with an estimate of the interaction between top dyeing and top chlorination. Such interactions, if they exist, are assumed to be insignificant in relation to their aliassed main effect. Similarly, all the two-factor interactions, which include autoclave setting in these four designs, are aliassed with other three-factor interactions. These three-factor interactions have been assumed to be relatively unimportant.

Figure 19 gives the matrices for Designs 5 and 6. Design 5 introduces four new variables - fibre type, count regularity, twist level and moisture regain. Autoclave treatment is included in all six designs and provides an element of reference between them. Design 6 introduces a new variable, the method of twisting. This trial is concerned particularly with twisting; not only the method of twisting but also the regularity of twist (as a function of count regularity), the twist level and the setting of twist by autoclave steaming. All interactions studied include the twist level.

Sample Code	F	R	S	A	M	FM	RM	SM	AM	RS	SA	FS	RSM	FSM	SAM
1	−	−	−	−	−	+	+	+	+	+	+	+	−	−	−
19	−	−	−	−	+	−	−	−	−	+	+	+	+	+	+
20	+	−	−	+	−	−	+	+	−	+	−	−	−	+	+
21	+	−	−	+	+	+	−	−	+	+	−	−	+	−	−
22	−	−	+	−	−	+	+	−	+	−	−	−	+	+	+
23	−	−	+	−	+	−	−	+	−	−	−	−	−	−	−
24	+	−	+	+	−	−	+	−	−	−	+	+	+	−	−
25	+	−	+	+	+	+	−	+	+	−	+	+	−	+	+
26	+	+	−	−	−	−	−	+	+	−	+	−	+	+	−
27	+	+	−	−	+	+	+	−	−	−	+	−	−	−	+
28	−	+	−	+	−	+	−	+	−	−	−	+	+	−	+
29	−	+	−	+	+	−	+	−	+	−	−	+	−	+	−
30	+	+	+	−	−	−	−	−	+	+	−	+	−	−	+
31	+	+	+	−	+	+	+	+	−	+	−	+	+	+	−
32	−	+	+	+	−	+	−	−	−	+	+	−	−	+	−
33	−	+	+	+	+	−	+	+	+	+	+	−	+	−	+

Design 5.

Sample Code	R	S	A	X	RS	AS	XS
1	−	−	−	−	+	+	+
34	−	−	+	+	+	−	−
22	−	+	−	−	−	−	−
35	−	+	+	+	−	+	+
36	+	−	−	+	−	+	−
28	+	−	+	−	−	−	+
37	+	+	−	+	+	−	+
32	+	+	+	−	+	+	−

Design 6.

KEY

F Fibre type
R Count Regularity
S Twist Level
A Autoclave Set
M Moisture Regain
X Twist Method

Figure 19. Design Matrices 5 and 6

CHAPTER FOUR

YARN AND FABRIC PRODUCTION

4.1 QUANTITIES

Thirty seven different yarn samples were produced, as listed in Figure 17. Approximately 1 kg. of each was produced, half used for testing of physical characteristics and half knitted into plain knit fabric. Small quantities of each of the sixteen different singles yarns (sixteen different combinations of variable from "fibre type" to "twist level" inclusive) were retained for testing.

4.2. FIBRE TYPE AND DIAMETER

Two fibre types were used : wool (-) and acrylic (+). Wool was obtained in two fibre diameters, "fine"(-) and "coarse"(+), and acrylic in "fine" only. The wools were chosen so that although the mean fibre diameters were different the mean fibre lengths were almost identical; the mean fibre length of the acrylic was somewhat longer. Fibre length, as discussed in 2.3.4. above, would not, however, be expected to have a significant influence on loop distortion. Details of the three fibres used (all obtained in top form) are shown in Figure 20.

FIBRE TYPE	SUPPLIER	DESCRIPTION	MEAN FIBRE DIAMETER (μ)	CV%	MEAN FIBRE LENGTH[75] (mm)	CV%
WOOL	Woolcombers Ltd. Bradford, England	52's quality Untreated	35.4 ± 0.9 **	26.1	77.1 ± 3.4	59.6
WOOL	T. Burnley & Son Ltd. Gomersal, Eng.	60's quality Untreated	25.2 ± 0.7 **	25.0	76.2 ± 2.7	47.7
ACRYLIC	Monsanto Ltd.	5 denier	24.7 ± 0.8 *	-	103.6 ± 2.5	32.6

* Acrylic fibre diameter determination : the "dogbone" shape of the acrylic fibre precluded mean fibre diameter measurements by test IWTO 8/66 . This was determined by the following equation:

$$\text{fibre diameter} = 2.\sqrt{\frac{T.10^{-6}}{\pi.D}}$$

where T = fibre linear density (tex - in this case 0.555 ± 0.028)
D = fibre density (for acrylic, 1160 ± 20 $Kg.m^{-3}$)

More correctly, therefore, the mean diameter determined is that of circular fibres of the same cross-sectional area

** i.e. $\pm$ 2.5% arithmetic mean for 95% confidence limits (450 samples)[74]

Figure 20. Fibre Test Results

4.3. SHRINK RESIST TREATMENTS

A description of oxidative (e.g. chlorination) and resin (e.g. Hercosett, a water-soluble cationic crosslinked polyamide-epichlorohydrin polymer) continuous shrinkproofing processes may be found in a review by Lewis[76]. Chlorination and chlorine/Hercosett treatment of the wool tops was carried out under commercial conditions at Robert Jowitt and Sons Ltd., Bradford, England. The process employed consisted of the following operations applied sequentially to top:

(a) treatment with chlorine gas in water
(b) neutralisation and anti-chlorination
(c) rinse
(d) resin application
(e) treatment with softener
(f) dry

For chlorination only operations (d) and (e) were omitted. The wool tops were processed at 8 metres/min. Different levels of chlorine and Hercosett were applied to the two qualities of wool in terms of percentage of fibre weight. The resin dosages used have been established by commercial practice to give equivalent degrees of shrink resistance to the two fibre qualities.

Mean Wool Fibre Diameter (micrometres)	% Chlorine o.w.f.	% Hercosett resin o.w.f.
25.2	1.85 ± 0.02	1.5 ± 0.1
35.4	1.76 ± 0.02	1.3 ± 0.1

These are normal commercial treatment levels for the two wool qualities.

Chlorine gas was applied in aqueous solution using the Kroy system (Kroy Unshrinkable Wools Ltd., Toronto, Canada). Subsequent neutralisation and anti-chlorination was carried out in a bowl containing an aqueous solution of sodium sulphite (5 $gm.l^{-1}$) and sodium carbonate (5 $gm.l^{-1}$) at 25^{o}C, pH8.5. This treatment was followed by a cold water rinse. The chlorinated-only tops were removed from the processing line at this stage and air dried at 120^{o}C.

The resin treated tops were subsequently immersed in a bowl containing an aqueous solution of Hercosett 125 (Hercules Chemical Company, Erith, England), at 35^{o}C, pH 8.0 (maintained by the addition of sodium carbonate solution). The resin treated tops were then passed to a softener bowl containing an aqueous solution of Alcamine CA New (Allied Colloids Ltd. Bradford, England) (0.75% w/v) at 40^{o}C, pH7.5. Finally the tops were air dried at 120^{o}C.

4.4 TOP DYEING

In order to avoid the difficulty of visually assessing fabrics of different colours, both top dyeing and package dyeing treatments were carried out without the addition of dyestuff, so that no significant shade change occured. It was assumed that the overriding factors, in terms of loop distortion, were the presence of water, the time of treatment, and the temperature of the liquor, and that the dyestuff itself had no significant influence on the physical properties of a yarn. The top dyeing blank cycle used was intended to simulate that which would be carried out for the application of 3% o.w.f. of a reactive dyestuff.

Dyeing was carried out in an Obermaier pressure dyeing machine by the following route:-

a) Top added and machine sealed

b) Water circulated for 5 minutes at 50°C to wet out fibre

c) Dyestuff auxiliaries added as follows:

	% o.w.f.
Ammonia sulphate	4.0
Acetic acid (80%)	2.0
Albegal B	1.5

pH adjusted to 5.3-5.1

d) Temperature of circulating liquor raised to 100°C over 30 minutes

e) Liquor boiled for 70 minutes

f) Liquor cooled to 80°C and adjusted to pH 8.5 for neutralisation before final rinse

g) After rinsing, tops hydro-extracted and dried in Fleissner continuous air drying machine

4.5 SPINNING

The ten different tops, each of approximately 20 $gm.m^{-1}$, were converted to double strand rovings, nominally 2 x 750 tex, by the following gilling route:-

GILL	NUMBER OF ENDS	DRAFT RATIO
1	7	7
2	7	7
COMB	12	-
3	7	7
4	7	7
5	7	7
6	7	7.4
7	2	5.9
ROVER	1	8.5

Two parameters were varied at the spinning stage, twist level: low (-) or high (+); and regularity: normal (-) or irregular (+). All yarn was spun to a mean count of Nm 27.00 ±0.20Nm (37.04 ±0.28 tex).

The mean low (normal) twist level was 402 turns/metre and the mean high twist was 556 turns/metre. Hence the twist factors (turns/metre x $(\text{Nm count})^{-0.5}$) were 77.4 and 107.0 respectively. Other spinning details were as follows:

Machine:	Ring spinner, J. & T. Boyd Ltd., Glasgow
Atmosphere:	$20^{o}C \pm 1^{o}C$, 65% ±2% r.h.
Spindle Speeds:	7400 r.p.m. (low fibre diameter)
	4600 r.p.m. (high fibre diameter and irregular yarns)
Traveller Gauge:	No. 21
Twist Direction:	Z

High irregularity yarns were produced by using a drafting gear modification developed at the I.W.S. Technical Centre[77]. This is shown schematically in Figure 21. A clutch and override device is used so that it is possible for the back and apron rollers to be driven at one of two different speeds, depending on whether or not the clutch is activated. The system incorporates two draft change points so that the mean counts of the thick and thin places in the yarn can be varied independently.

The power supply to the clutch is controlled by means of a random switching device whereby the lengths of the thick and thin places are controlled independently. The switching device controls the length of time the clutch is activated or deactivated, this time being random within the maximum limits of 0.1 and 9.9 seconds. For instance, one could set the device to energise the clutch for a random time varying between 1.5 and 7.5 seconds and de-energise it for a random time varying between 3.0 and 6.0 seconds. The mean lengths of the thick and thin places would be the same (4.5 seconds x yarn delivery speed) but the variation in the lengths of the thick places (energised time) would be greater than that of the thin places between them.

The shortest length of a thick or thin place is governed by the maximum length of fibre present; the length of the thick or thin place should be at least 1.5 times this length. Because the time ranges could only be controlled in steps of 0.1 seconds a slight difference in the range of lengths between the low and high twist

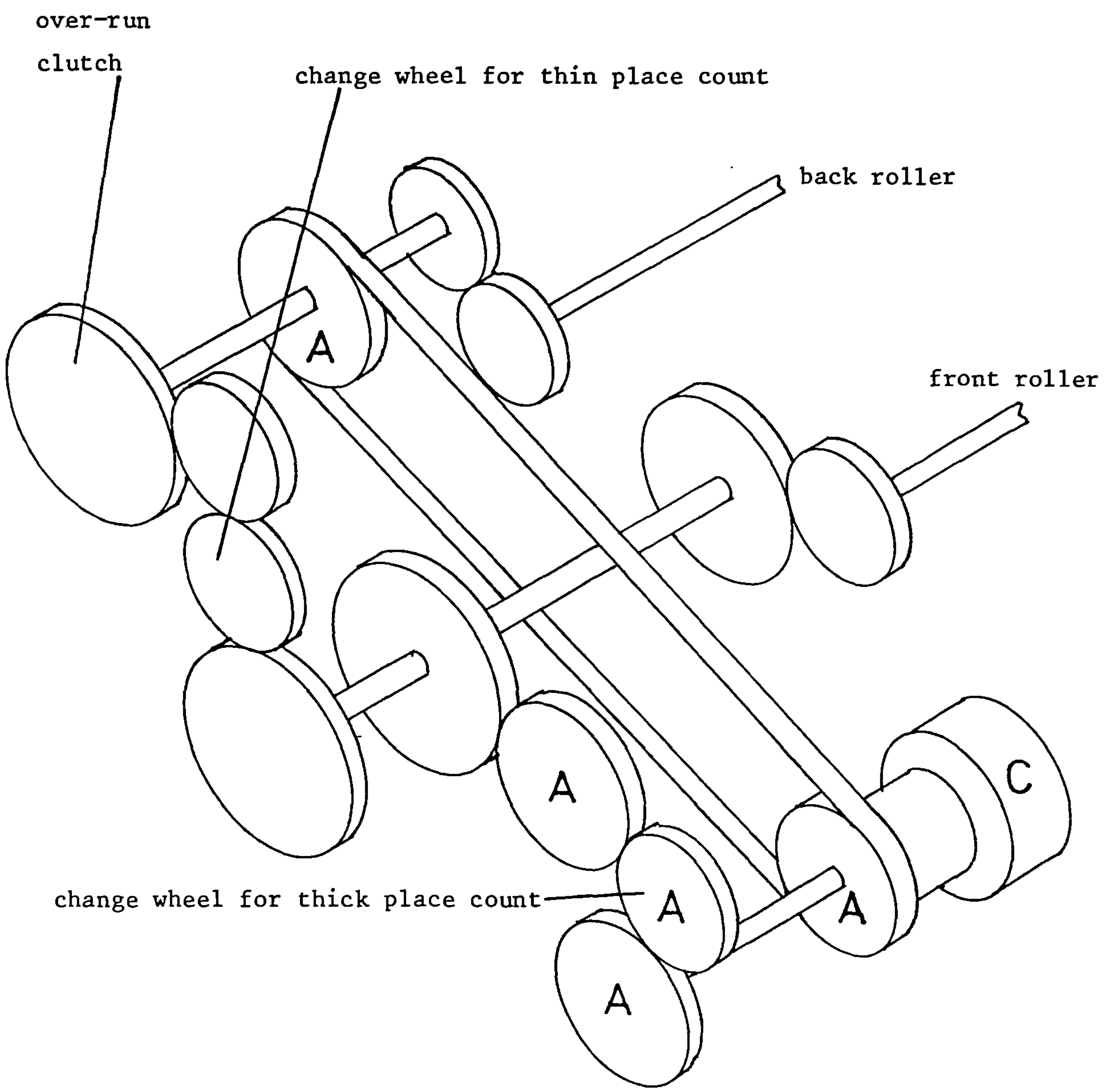


Figure 21. Schematic Diagram of Draft Gearing for Very Irregular Yarns
Wheels "A" and clutch "C" are added to the original draft gearing assembly.

yarns was unavoidable. Specifications of the irregular yarns are as follows:

Mean Yarn Count	Nm 27.00 ±0.20 (37.04 ±0.28 tex)
Mean Count thin places	Nm 40.50 ±0.20 (24.69 ±0.28 tex)
Mean Count thick places	Nm 20.25 ±0.20 (49.38 ±0.28 tex)

	LOW TWIST	HIGH TWIST
Minimum length of thick and thin places (mm)	153	153
Maximum length of thick and thin places (mm)	230	222

4.6 AUTOCLAVE SETTING

Autoclave setting, where carried out (indicated by + on the experimental designs), was carried out on a yarn at both the singles stage, on spinning tubes, and after twofolding, on cones prior to conditioning. Other samples were not autoclave set at any stage. The same procedure was used for both singles and folded yarns. A Sanderson and Co., Ltd. (Todmorden, England) autoclave was used. The cycle used was:-

a) vacuum*
b) steam 2 minutes at 80 ±3°C
c) vacuum* 5 minutes
d) steam 5 minutes at 80 ±3°C
e) vacuum* 15 minutes

* vacuum to 90 KPa below atmospheric pressure

4.7 TWISTING

Twisting was carried out by one of two methods. Yarns were either ring twisted (-) (J. & T. Boyd Ltd. twisting frame, Glasgow) or twisted from assembly wound packages on a two-for-one twister (+) (Volkmann VTS-07, Krefeld, W. Germany). The yarns were S-twisted to achieve a theoretically balanced two-fold yarn, where folding twist = 0.67 x spinning twist[78]. Nominal twist levels were as follows:

TWIST LEVEL	SINGLES TWIST T.P.M.	SINGLES TWIST FACTOR TPM x $NM^{-0.5}$	FOLDING TWIST T.P.M.	FOLDING TWIST FACTOR TPM X $NM^{-0.5}$
LOW (-)	402	77.4	268	72.9
HIGH(+)	556	107.0	370	100.7

4.8 PACKAGE DYEING

Yarn samples for package dyeing were wound onto dyeing springs and blank dyed in a Celcon pressure dyeing machine. The routine followed was the same as that used for top dyeing, described in Section 4.4. The packages, after the final rinse, were hydro-extracted and oven dried at 70°C before winding onto knitting cones.

4.9 YARN CONDITIONING

Different levels of regain for the two fibre types were achieved by conditioning in two different atmospheres - "low" relative humidity

(65 ± 2% r.h. at 20 ± 1°C) and "high" relative humidity (92.5 ± 2.5% r.h. at 20 ± 1°C). All yarn samples were conditioned from the dry side on knitting cones. A Standard Conditioned laboratory was used for the lower relative humidity, and a conditioning cabinet (Aminco-Aire, Aminco, U.S.A.) for the higher relative humidity. Samples were conditioned for at least 25 days before knitting or testing. Regain was measured by weighing samples before and after drying for six hours at 105°C. Moisture regain measurements (% on weight of dry fibre) were as follows:-

	Low Regain % (-)	High Regain % (+)
Wool Yarns	14.10 ± 0.08	24.06 ± 0.08
Acrylic Yarns	1.87 ± 0.08	2.99 ± 0.08

4.10 KNITTING

The yarns were knitted consecutively on a 10 gauge (10 needles/inch) circular Stibbe plain knit machine. A cover factor of 0.400 ($cm^{-1}.Nm^{-0.5}$) was used, the loop length required for a Nm 27/2 yarn being 6.804mm. A positive feed device, consisting of a pair of rollers driven from the machine motor via a variable speed gearbox, was used to ensure constant loop size. The cone of yarn being knitted was maintained at the required relative humidity by storage in a polythene container containing a salt solution. Figure 22 illustrates the arrangement.

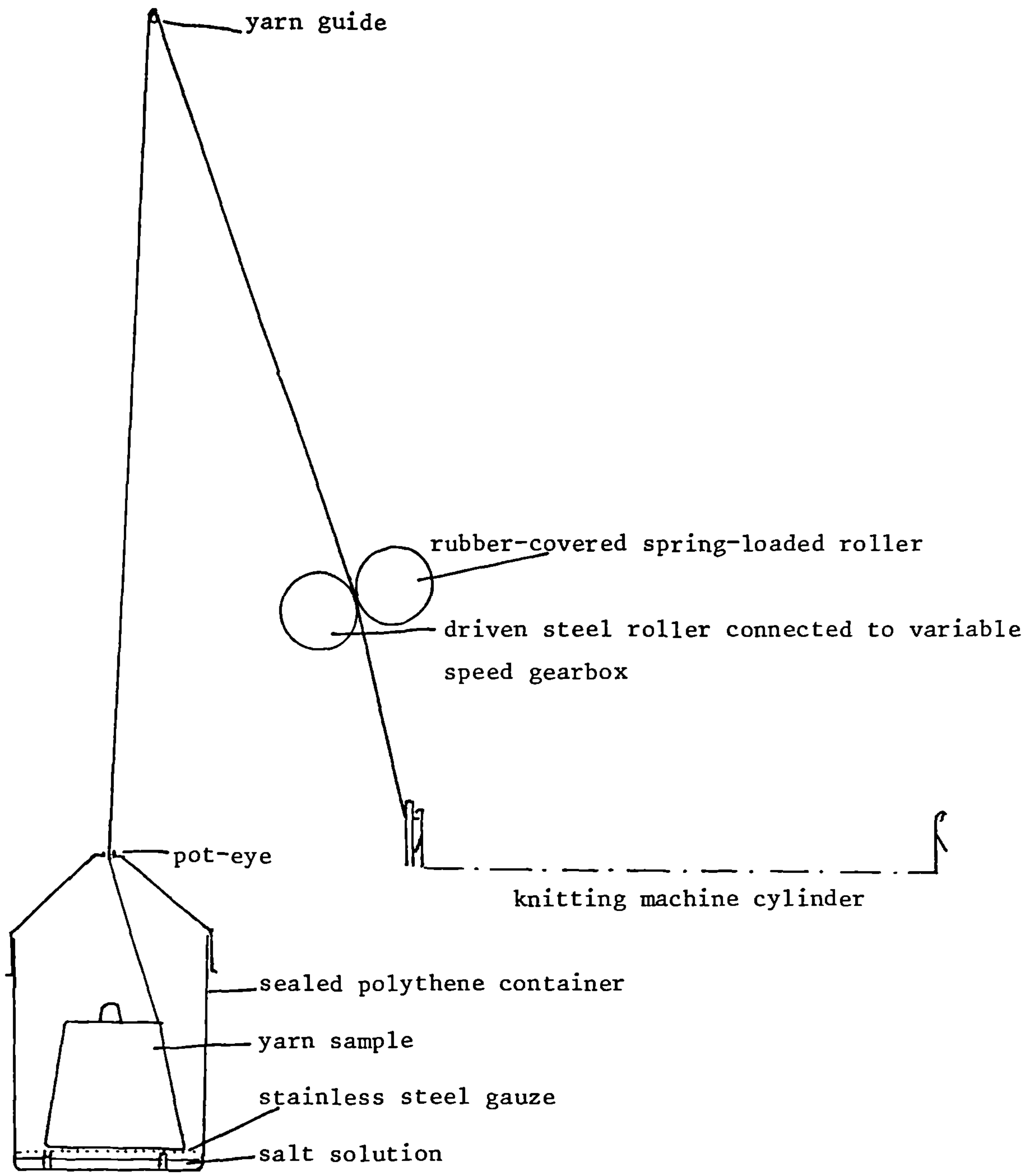


Figure 22. Schematic Diagram of the Knitting Arrangement

Approximately 50cm length of fabric was produced from each yarn. When all the fabric had been knitted the samples were separated and overlocked at the top and bottom to prevent curling.

4.11 FABRIC FINISHING

The fabrics were finished so as to achieve as nearly as possible a fully relaxed state. A knitwear milling machine (Cherry Tree Machinery Ltd., Blackburn, Lancs.) with a capacity of approximately 450 litres was used in the following procedure:-

(a) 150 litres of water at 40°C were added to the machine. 0.1% non-ionic wetting agent was dissolved in the water.

(b) The samples (total weight 2.5 kg) were added and the machine switched to "Intermittent" for a total time of 15 minutes. The "Intermittent" sequence is: 1 second clockwise, 20 seconds static, 1 second anti-clockwise, 20 seconds static.

(c) The machine was switched to "Continuous" for 3 minutes. The "Continuous" sequence is: 15 seconds clockwise, 2 seconds static, 15 seconds anti-clockwise, 2 sec static.

(d) The machine was drained and 150 litres water at 40°C was added. A 1 minute "Continuous" cycle was used in rinsing the samples.

(e) The water was drained and the samples transferred to a hydro-extract machine. A 5 minute cycle was used.

(f) The samples were transferred to an industrial tumble drier, and tumbled for 45 minutes at 70°C, the drum reversing direction every 30 seconds.

(g) In order to remove creases which could detract from the assessment of loop distortion, the samples were lightly pressed on a Hoffman press as follows: open steam 10 seconds, steam and press (head locked) 5 seconds, open steam 10 seconds.

CHAPTER FIVE

THE DEPENDENT VARIABLES : YARN TESTING AND FABRIC ASSESSMENT

5.1 INTRODUCTION

The ultimate dependent variable of interest, and the only one determined for the fabrics (apart from the stitch density constant K_1), is loop distortion. These determinations were carried out by a subjective assessment procedure, described in Section 5.8. In relation to loop distortion, the physical characteristics of the twofold yarns, rather than the singles yarns from which they were twisted, are thought to be of more importance. However, certain tests were carried out on both singles and twofold yarns. Previous work had suggested that some yarn physical characteristics were unlikely to relate to loop distortion but where determinations of such variables could be made easily,this was done. The yarn testing programme was as follows:

SINGLES	TWOFOLD
twist	twist
count	count
twist regularity	twist regularity
count regularity	count regularity
	surface friction
	torsional rigidity
	flexural rigidity
	bending hysteresis

Measurements relating to twist and count, made on both singles and twofold yarns, were carried out to examine the distribution of these values about nominal predetermined levels set on the spinning machine. The actual regularity, for instance, would be expected to vary for a single "fixed" level because of its dependence on other variables such as fibre diameter. All other determinations, except for friction, related to the stiffness of the twofold yarns.

5.2 MEAN YARN TWIST AND TWIST IRREGULARITY

The nominal twist levels, as set on the spinning and twisting machines, are tabulated in Section 4.7. However, variations in the mean twist are likely to occur in practice and, of particular relevance in the case of loop distortion studies, local twist redistribution will take place as a consequence of count variations.

Each of the thirty seven yarns was tested for singles and twofold twist. Differences between many of the twofold yarns resulted from process treatments subsequent to spinning and therefore it was only necessary to test the sixteen different component singles yarns. Fifty measurements were made on each yarn sample under standard conditions at $65\pm2\%$ relative humidity, $20\pm1^{o}C$. A 50mm test length was used, equivalent to the length of yarn in a typical "cockle" of about seven loops. Each measurement, made on a James Heal twist tester, was made with an accuracy of ±2 turns per metre. Mean twist levels and coefficients of variation are listed in Figure 23. The actual

YARN CODE	MEAN SINGLES TWIST*	CV% SINGLES TWIST	MEAN SINGLES COUNT@	U% SINGLES REG.	MEAN 2-FOLD TWIST*	CV% 2-FOLD TWIST	MEAN 2-FOLD COUNT@	U% 2-FOLD REG.
1	421	29.1	26.3	14.0	284	12.2	26.7/2	10.6
2	421	29.1	26.3	14.0	279	15.6	26.3/2	9.9
3	404	22.7	25.6	14.9	276	15.5	26.7/2	10.1
4	404	22.7	25.6	14.9	289	17.4	25.0/2	10.0
5	433	40.6	27.8	17.8	282	18.7	27.0/2	13.1
6	433	40.6	27.8	17.8	279	21.6	26.0/2	12.6
7	391	40.1	25.6	17.1	279	15.8	25.3/2	12.1
8	391	40.1	25.6	17.1	287	14.9	25.0/2	12.3
9	402	18.5	26.3	14.6	277	12.6	26.7/2	10.3
10	402	18.5	26.3	14.6	291	13.8	27.4/2	10.3
11	409	23.0	23.3	17.8	274	14.9	25.3/2	11.9
12	409	23.0	23.3	17.8	276	19.9	25.3/2	12.4
13	376	22.6	27.8	15.3	282	11.4	26.3/2	9.8
14	376	22.6	27.8	15.3	296	18.5	26.0/2	10.1
15	373	30.3	26.3	17.5	275	15.6	26.0/2	12.5
16	373	30.3	26.3	17.5	277	16.9	25.3/2	11.9
17	402	23.1	25.6	14.0	296	12.1	26.3/2	9.8
18	402	23.1	25.6	14.0	269	14.8	26.0/2	10.1
19	421	29.1	26.3	13.9	284	12.2	(26.0/2)	11.2
20	417	20.2	25.6	11.5	281	11.3	25.6/2	8.2
21	417	20.2	25.6	11.5	281	11.3	(25.6/2)	8.5
22	581	19.2	27.0	13.9	395	12.7	25.6/2	10.0
23	581	19.2	27.0	13.9	395	12.7	(25.6/2)	10.9
24	580	18.0	25.0	11.4	366	10.5	25.0/2	8.2
25	580	18.0	25.0	11.4	366	10.5	(25.0/2)	8.3
26	427	51.5	27.8	27.3	289	25.4	27.8/2	18.1
27	427	51.5	27.8	27.3	289	25.4	(27.8/2)	18.3
28	413	47.7	27.0	28.0	301	30.6	27.0/2	18.4
29	413	47.7	27.0	28.0	301	30.6	(27.0/2)	19.3
30	542	38.8	27.0	26.8	351	31.2	26.7/2	17.7
31	542	38.8	27.0	26.8	351	31.2	(26.7/2)	17.2
32	574	53.5	25.6	29.1	406	34.8	25.6/2	17.5
33	574	53.5	25.6	29.1	406	34.8	(25.6/2)	17.7
34	421	29.1	26.3	14.0	280	12.9	26.3/2	9.6
35	581	19.2	27.0	13.9	412	15.8	26.0/2	9.3
36	413	47.7	27.0	28.0	281	29.6	27.0/2	20.5
37	574	53.5	25.6	29.1	406	24.0	25.6/2	19.2

* turns per metre   @ Nm count

Figure 23. Twist and Count - Mean Values and Variation for Singles and Twofold Yarns

overall mean twist levels were as follows:

TWIST LEVEL	SINGLES TWIST T.P.M.	SINGLES TWIST FACTOR TPM x $Nm^{-0.5}$	FOLDING TWIST T.P.M.	FOLDING TWIST FACTOR TPM x $Nm^{-0.5}$
LOW (-)	406	78.1	282	76.8
HIGH (+)	569	109.5	389	105.9

These twist levels are slightly higher than the nominal values, but the overall singles twists were within 2.4% of the nominal twists and the twofold twists were within 5.3%

5.3 MEAN YARN COUNT AND COUNT IRREGULARITY

Singles and twofold mean yarn counts were measured using the British Standard BS2010:1963 test method. Results are listed in Figure 23. The twofold yarn counts in brackets indicate that, although these were the counts measured under standard conditions, the counts at the time of knitting were rather heavier, since these yarns were subsequently conditioned to high regain. All fabrics were assessed at 65$\pm$2% r.h. so at that time the yarn counts were as indicated. The mean counts were Nm 26.19/1 for the singles yarns and Nm 26.11/2 for the twofold yarns, approximately 3% heavier than the nominal values.

Count regularity was measured using an Uster Eveness Tester (Zellweger Uster Ltd., Switzerland). Values quoted are U%, the percentage mean deviation of the variation in yarn linear density. 250 metre samples of singles and twofold yarns were tested at a speed of 100 metres per minute. If the mass/unit length variations in a yarn are known to be normally distributed, the coefficient of variation of the yarn count can be expressed as:

$$CV\% = U\%.\sqrt{\pi/2}$$

However such a distribution can not be assumed here, particularly in the case of yarns spun intentionally irregularly, so count irregularities have been expressed only by the U% values. These are tabulated in Figure 23.

5.4 YARN SURFACE FRICTION

The "Shirley" Yarn Friction Recorder (Shirley Developments Ltd., Manchester, England) was used to determine the dynamic coefficient of friction of the yarns against stainless steel. Measurement was made at a constant speed of 60 yards/minute for two minutes. Values of the coefficient of friction (μ) were determined with an accuracy of ± 0.01 using a transparent calibrated scale on the circular paper test chart. Tests were carried out under standard conditions with the yarns conditioned to "low" or "high" regain as required. Results are given in Figure 24.

5.5 YARN TORSIONAL RIGIDITY

5.5.1. Introduction

The importance of the torsional rigidity of a yarn in determining its three-dimensional configuration under the influence of external

YARN CODE	COEFFICIENT OF FRICTION (μ)	TORSIONAL RIGIDITY $N.m^2$ x10^{-7}	CV% TORSIONAL RIGIDITY	FLEXURAL RIGIDITY $N.m^2$x10^{-10}	BENDING HYSTERESIS N.m x10^{-8}	FLX.R./TOR.R. x10^{-2}
1	.30	0.413	8.30	13.5	7.50	3.27
2	.30	0.413	8.44	11.3	4.47	2.75
3	.30	0.460	7.06	12.7	5.72	2.77
4	.30	0.445	7.88	12.3	3.63	2.75
5	.30	0.695	8.26	23.7	12.75	3.40
6	.30	0.610	8.96	22.1	5.95	3.62
7	.30	0.652	8.38	21.3	9.11	3.27
8	.30	0.667	7.12	21.9	5.48	3.28
9	.28	0.405	6.24	10.8	2.23	2.66
10	.29	0.399	8.14	11.1	2.89	2.78
11	.27	0.653	5.50	20.2	5.48	3.10
12	.28	0.637	5.14	21.4	4.18	3.36
13	.30	0.459	7.44	12.5	6.27	2.71
14	.31	0.418	6.40	12.7	3.97	3.04
15	.30	0.618	11.0	21.0	7.82	3.40
16	.31	0.672	8.88	17.3	3.97	2.57
17	.25	0.427	5.94	11.6	3.07	2.73
18	.28	0.439	7.04	11.0	2.70	2.50
19	.48	0.242	9.94	8.2	6.88	3.39
20	.28	0.533	7.24	13.1	9.70	2.45
21	.27	0.523	16.3	14.2	9.19	2.73
22	.30	0.470	7.20	12.1	8.58	2.57
23	.49	0.332	9.78	7.5	7.14	2.27
24	.28	0.712	7.76	14.8	8.51	2.08
25	.28	0.714	8.18	14.4	8.30	2.02
26	.28	0.515	9.94	18.3	17.02	3.54
27	.28	0.510	8.96	17.9	13.58	3.50
28	.30	0.361	9.82	13.5	4.80	3.74
29	.45	0.231	14.2	9.4	5.74	4.08
30	.28	0.709	13.9	21.0	18.68	2.96
31	.28	0.685	14.2	18.5	16.75	2.71
32	.30	0.410	3.82	12.4	4.04	3.02
33	.45	0.273	8.48	8.4	5.65	3.03
34	.30	0.406	9.44	12.1	5.12	2.98
35	.30	0.424	8.16	11.0	4.32	2.59
36	.30	0.395	8.64	14.3	7.69	3.60
37	.31	0.441	9.52	15.6	9.59	3.54

Figure 24. Frictional and Rigidity Characteristics of Twofold Yarns

stresses was described in Chapter One. Torsional rigidity, or resistance to twisting, is defined as the couple induced when a unit length of a material is twisted through 360°. In terms of the shear modulus (G) of the material, the torsional rigidity (T) of a homogeneous rod is defined as:

$$T = E.G.s^2$$

where s is the cross-sectional area and E is a shape factor, equal to unity for a circular cross-section.

A variety of methods is available for determining torsional rigidity. These fall into three main groups: torsion pendulums, torsion balances and adaptations of the viscometer.

Figure 25 shows the three types of torsion pendulum which have been used for measuring the torsional rigidity of fibres and yarns. These are the simple pendulum[79-81], the compound pendulum[82] and the double pendulum[83].

Each method relies upon measuring the time of oscillation (t) of a suspended bar of known moment of inertia(I) about the point of suspension. For a simple pendulum

$$T = \frac{8.\pi^3.I.L}{t^2}$$

where L is the length of the sample.

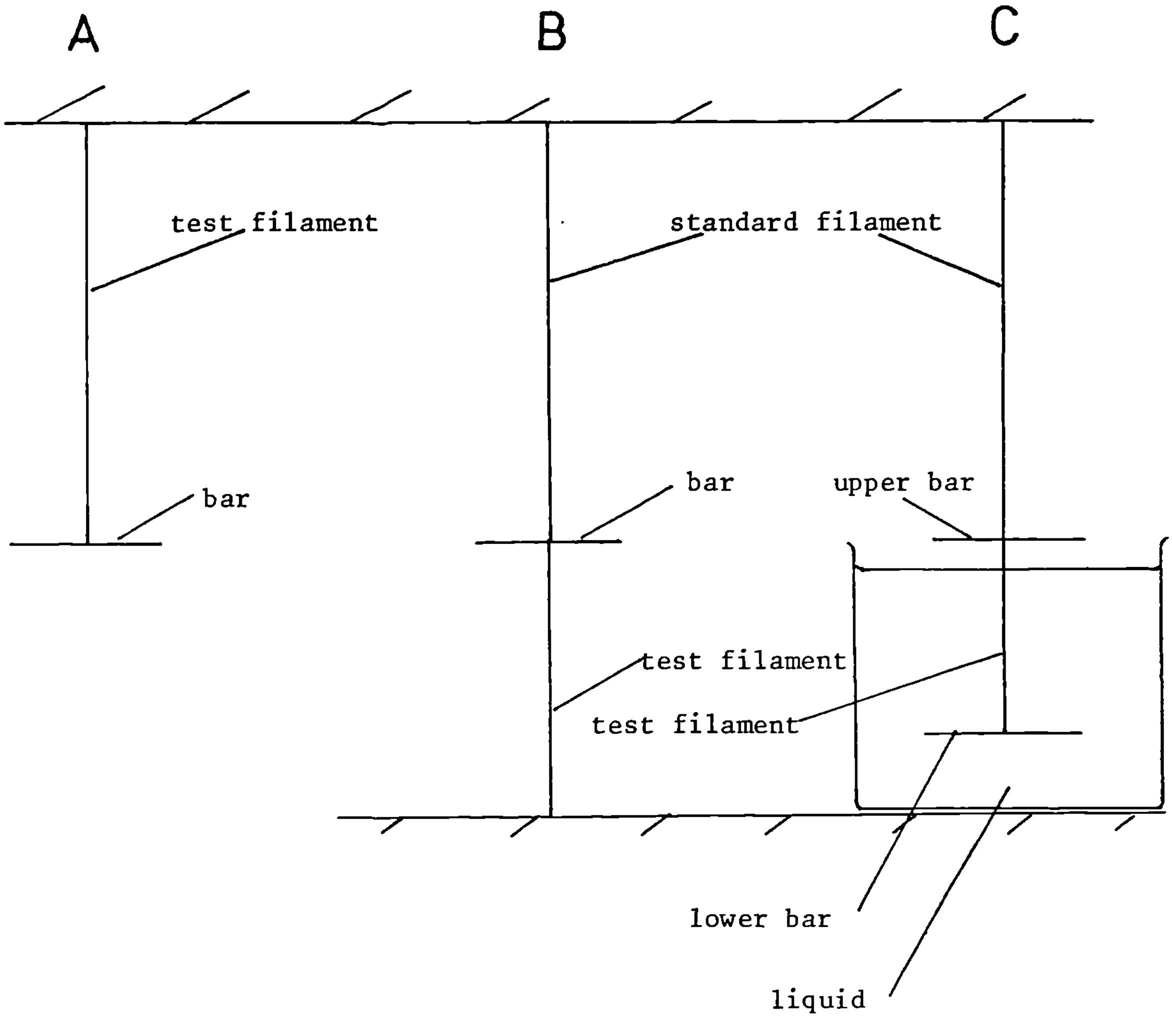


Figure 25. Torsion Pendulum Methods of Yarn and Fibre Torsional Rigidity Determination

A Simple Pendulum

B Compound Pendulum

C Double Pendulum

The double pendulum is of particular use in fibre testing since the test sample is not stressed longitudinally. A compound pendulum is used for testing samples immersed in a fluid. The upper bar is used to counter the high damping effect of the fluid by transmitting energy through the sample to keep the lower bar in motion.

Torsion balance methods[84-89] permit measurement of torsional rigidity for specific torsional strains rather than for the unstrained condition as do corrected pendulum determinations. Figure 26 shows the two most common types in use. A constant velocity drive unit provides the torque, and the angle of rotation of the sample in relation to that of a standard filament is measured either by maintaining the junction of the sample and standard filament fixed or by measuring its angle of rotation using, for instance, an optical lever arrangement.

The viscometer type of test method[90] is, in effect, a variation of the system shown in Figure 26A. A viscous fluid replaces the standard filament so this method is particularly useful for fibre testing where errors would be likely if a torsion balance was used, due to the delicacy of the standard filament which would be required.

A yarn knitted into a fabric is subjected to a range of torsion strains around the loop and, in practice, the strains vary from loop to loop. There is, therefore, little value, in the present work, in determining torsional rigidity at a particular torsional strain.

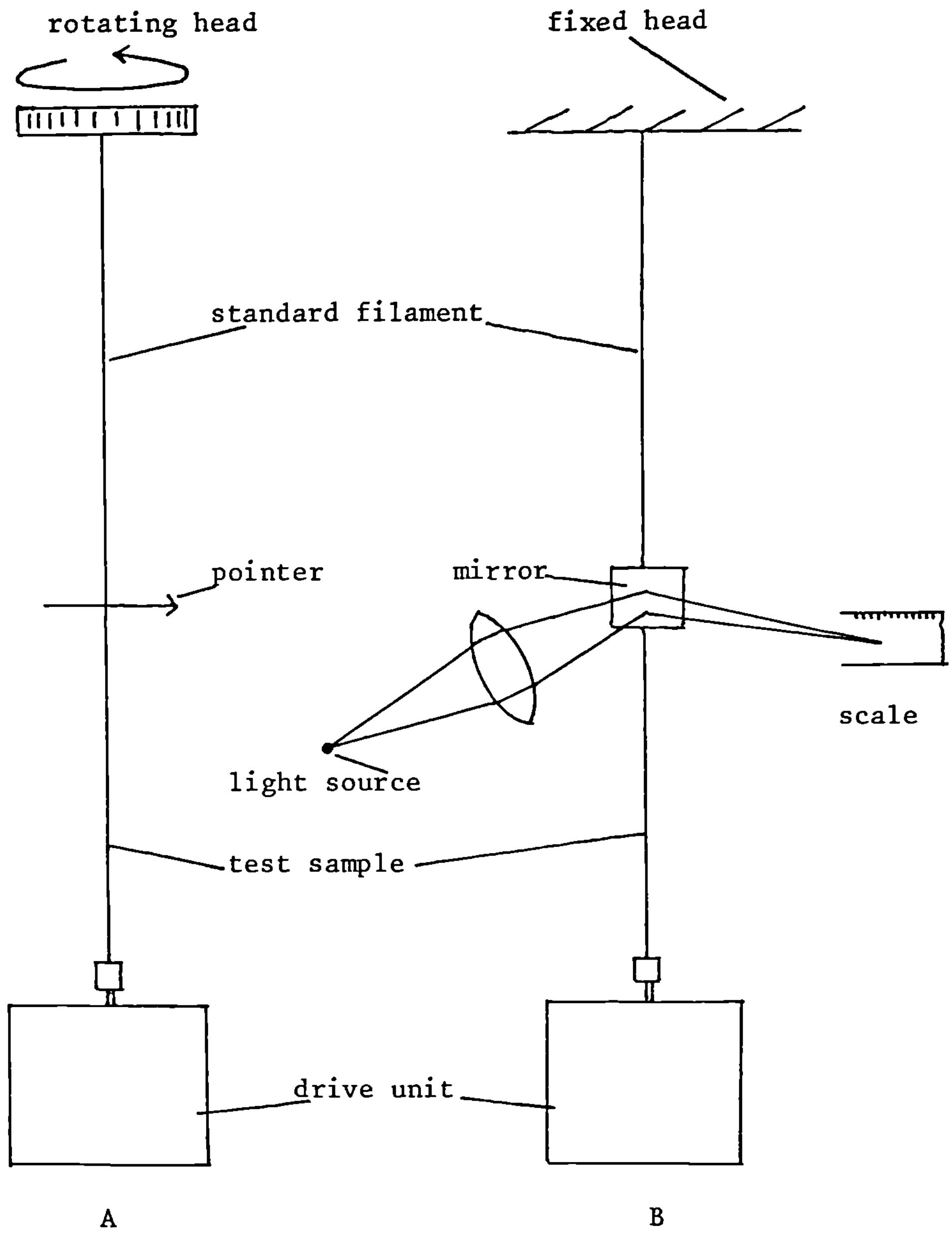


Figure 26 Torsion Balance Methods of Yarn and Fibre Torsional Rigidity Determination

A Rotating Head

B Fixed Head

Rather, we are particularly interested to determine the physical characteristics of the yarn the instant before it forms part of a fabric structure and, therefore, should determine the value in the unstressed condition. A simple pendulum is the ideal method for yarn testing in this instance since the mean stress is zero, provided that certain factors such as the influence of tension and angular deflection on torsional rigidity are taken into account.

5.5.2. Test Method

Figure 27 shows the arrangement of the simple torsion pendulum used for the present work. The test sample length was 500mm under the light tension of a tapered aluminium bar 64mm long, fitted with a small spring clip. The sample was gripped by spring jaws at the top and by the clip at the lower end. A small cylinder engraved with a horizontal mark was used to adjust the sample length. The sprung jaws were opened and the length of the sample adjusted until the top of the clip was against the engraved line. After adjustment, the cylinder was removed from the vicinity of the bar.

The moment of inertia of the bar was measured using fine copper wire of circular cross-section. The diameter of the wire was measured at ten random places using a travelling microscope to give a mean value of 0.180mm. The time for 50 oscillations of each of eight lengths of the wire was recorded when the bar was given a small angular displacement about the axis of the wire. The mean value was 0.946 secs (C.V. 1.63%). Copper has a shear modulus of 4.83×10^{10} $N.m^{-2}$.

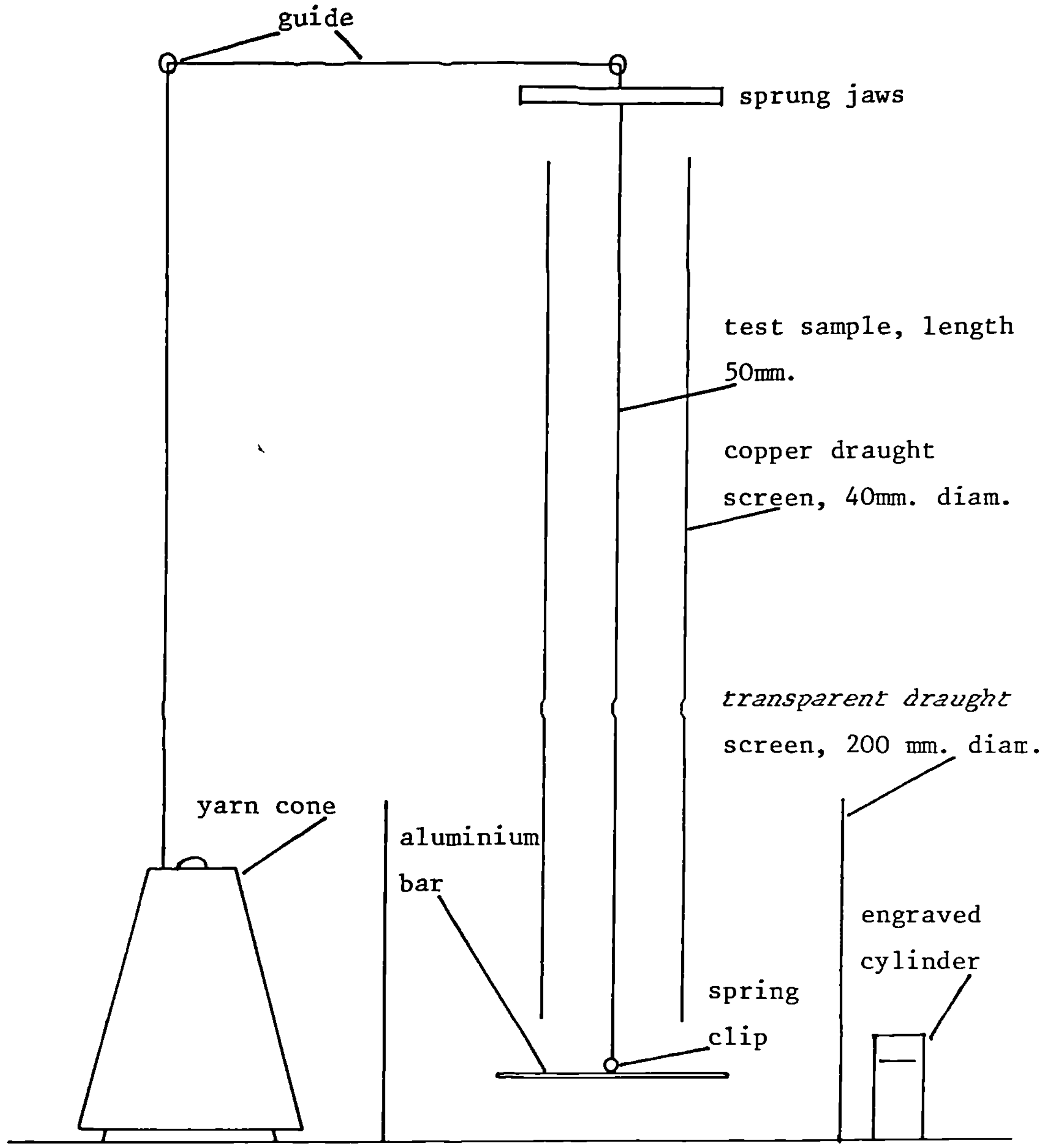


Figure 27 Arrangement of Torsional Pendulum for Determination of Torsional Rigidity

Hence, the moment of inertia of the Bar, I, is given by

$$I = \frac{T.t^2}{8\pi^3.L} = \frac{E.G.s^2.t^2}{8\pi^3.L}$$

Where E = 1 (for circular cross section)
s = π. 9 x 10^{-5}m
t = 0.946 sec
L = 0.5 m

$$\text{Hence } I = \frac{4.83 \times 10^{10} \times (9\times10^{-5})^4 \times\pi^2 \times 9.46^2 \times 10^{-2}}{8\pi^3 \times 0.5}$$

$$= 2.26 \times 10^{-7}\text{kg.m}^2$$

According to theory, the oscillation time period for a simple torsion pendulum of fixed length is independent of the mass of the rod (provided the moment of inertia is fixed) and the magnitude of the oscillations. In practice this is not necessarily the case. Oscillations are damped as a result of air resistance on the bar and internal friction in the filament. If the weight of the bar is increased significantly we could expect the mean cross-sectional area of a yarn to be reduced and internal friction, as the fibres come into closer contact, to be increased.

The weight of the bar and clip chosen for the present work was sufficient to straighten any kinks in a sample without leading to a significant change in cross-sectional area. The weight was 1.4355$\pm$ 0.0005gm, and hence the tension on the yarn was calculated as follows:-

	mean thickness	0.03875 $\pm$0.0003gm/tex
irregular yarn	thin places	0.05814 $\pm$0.0007gm/tex
	thick places	0.02907 $\pm$0.0002gm/tex

Meredith[79] showed that for tensions below 0.2gm/tex the effect of tension on the torsional rigidity of wool fibres was negligible.

Interfibre frictional forces within a yarn tend to zero as the amplitude of oscillations tends to zero. The time period at this state can be obtained by extrapolating the values for successive damped oscillations.

In practice it was found that time periods of very small oscillations could not be measured accurately. This was partly as a result of the difficulty in determining the precise moment when the bar was stationary and partly due to disturbance of the bar by air currents, particularly when measurements were carried out in the conditioning cabinet.

Consequently, all time measurements were made following a standard procedure for all samples:

(i) The bar was allowed to reach a state of rest.

(ii) The bar was rotated three complete clockwise revolutions and then released.

(iii) Timing commenced when the bar reached the maximum amplitude in the anticlockwise direction.

(iv) The time for one complete cycle was measured (rotation clockwise then anticlockwise) and recorded.

(v) The next test sample was prepared. Each sample of 500mm was taken randomly at approximately 3-6 metre intervals along the yarn. Ten measurments were made for each yarn and the mean and coefficient of variation of the time period determined.

Largely because of the interfibre frictional forces during oscillation, the values of torsional rigidity obtained were slightly lower than the true zero-displacement values but since the relative torsional rigidities are the important data it is better to obtain more precise estimates that are slight underestimates than imprecise estimates of unbiassed values.

Figure 24 lists the torsional rigidities of the thirty seven yarn samples calculated from the time period measurements.

5.6 YARN FLEXURAL RIGIDITY

5.6.1. Introduction

Flexural rigidity is defined as the couple required to bend a material to unit curvature.

The bending stiffness of a yarn or fabric may be differentiated into two components: an elastic component and a non-elastic component resulting from internal friction (coercive or frictional couple).

When an applied bending moment is released the frictional residual curvature remaining in the material is a consequence of this non-elastic component. This phenomenon is illustrated by the hysteresis curve shown in Figure 28. The residual curvature is given by OA and the coercive couple by OB. To exclude assymetrical effects these values may be expressed respectively by:

$$\frac{AO + OC}{2} \quad \text{and} \quad \frac{OB + OD}{2}$$

The percentage bending recovery may similarly be expressed as:

$$100.\frac{(AE + CF)}{(OE + OF)}$$

If the bending behaviour of a yarn at small curvatures is to be studied methods such as those devised by Carlene[91] and Pierce[92] may be adequate. However, these methods make the assumption of a linear relationship between curvature and bending moment which is only true for purely elastic materials. Alternative methods are, therefore, required when materials such as yarns, with a significant coercive couple, are bent through large curvatures. Livesey and Owen [93] developed a pure bending (i.e. constant curvature) test method suitable for larger curvatures which was refined by subsequent workers[94-96]. The method relies upon bending a small sample between two sets of jaws, one being attached to a long light arm with its centre of gravity a relatively large distance from the specimen. The couple bending the sample, therefore, remains virtually constant along the sample's length and almost constant curvature along the specimen is maintained as bending takes place.

5.6.2. Test Method

The apparatus used in the present study bends a sample of yarn or

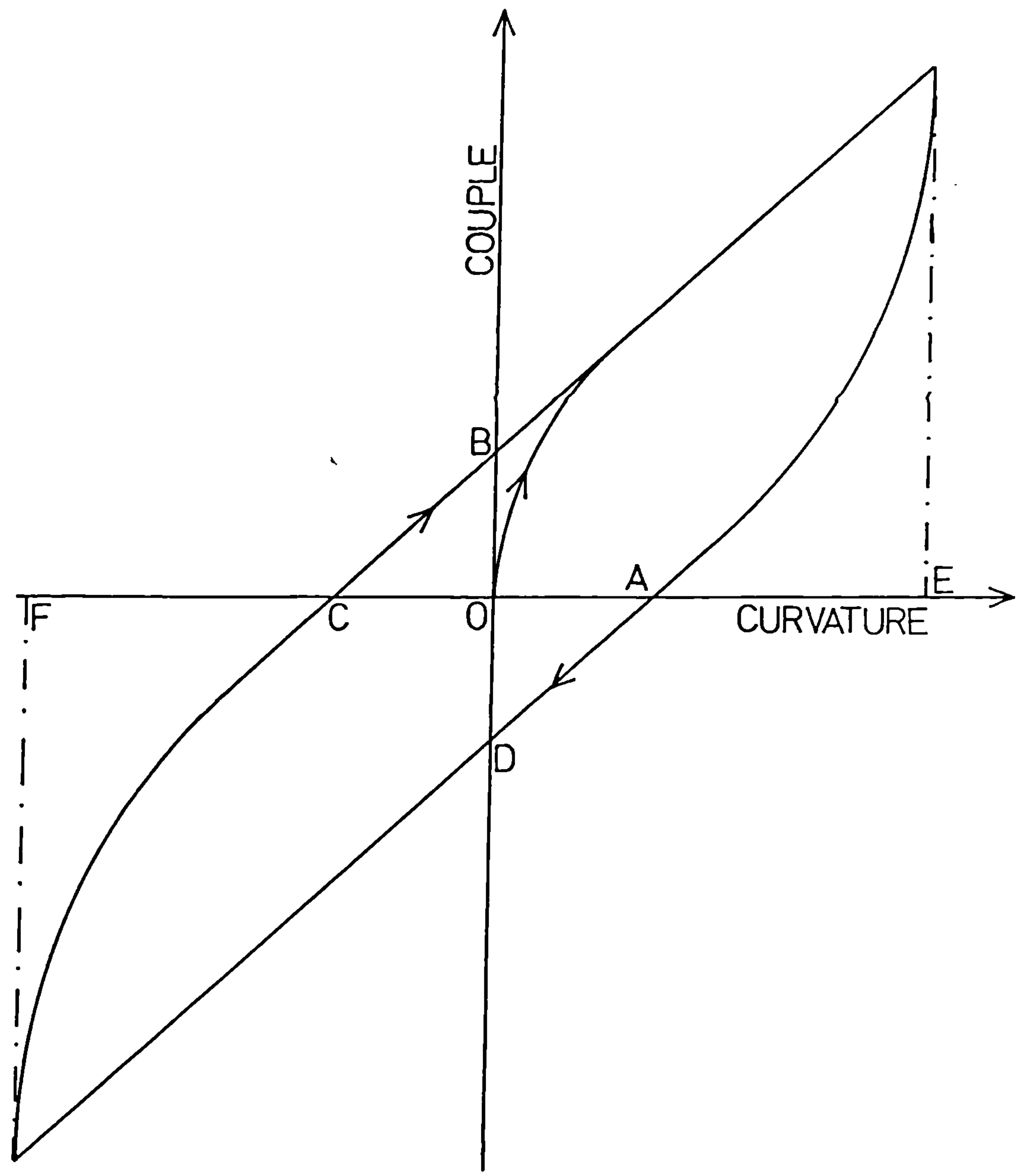


Figure 28. Idealized Bending Hysterisis Curve

fabric whilst maintaining the sample in a circular arc. A different principle to Livesey and Owen's is used to control the relative movement of the jaws.

Referring to Figure 29, the locus of the end of a sample fixed between two sets of jaws O and P is given by:

$$R = \frac{S.\cos\theta}{(\pi/2 - \theta)}$$

Where R = jaw separation (OP')

S = sample length (OP)

$(\pi/2 - \theta)$ = angle through which jaw has moved from initial straight sample position.

Figure 30 gives the derivation of the relationship. Jaws following a path defined by this equation (ⓐ in Figure 29) maintain the sample in a circular arc under pure bending conditions.

If the jaws follow a circular path, centre A, 0.27S along the initial straight configuration (OP) from the fixed jaws, a very close approximation is obtained to curve ⓐ until $\theta \simeq 20^0$ (curve ⓑ, Figure 29). It is necessary for the nip point of the jaws to rotate at a slightly faster speed so as to keep the axis of the jaw collinear with the tangent to the curve of the sample at its end, P'. In Figure 29 the jaw assembly has rotated through $\propto^0$ about A, the axis

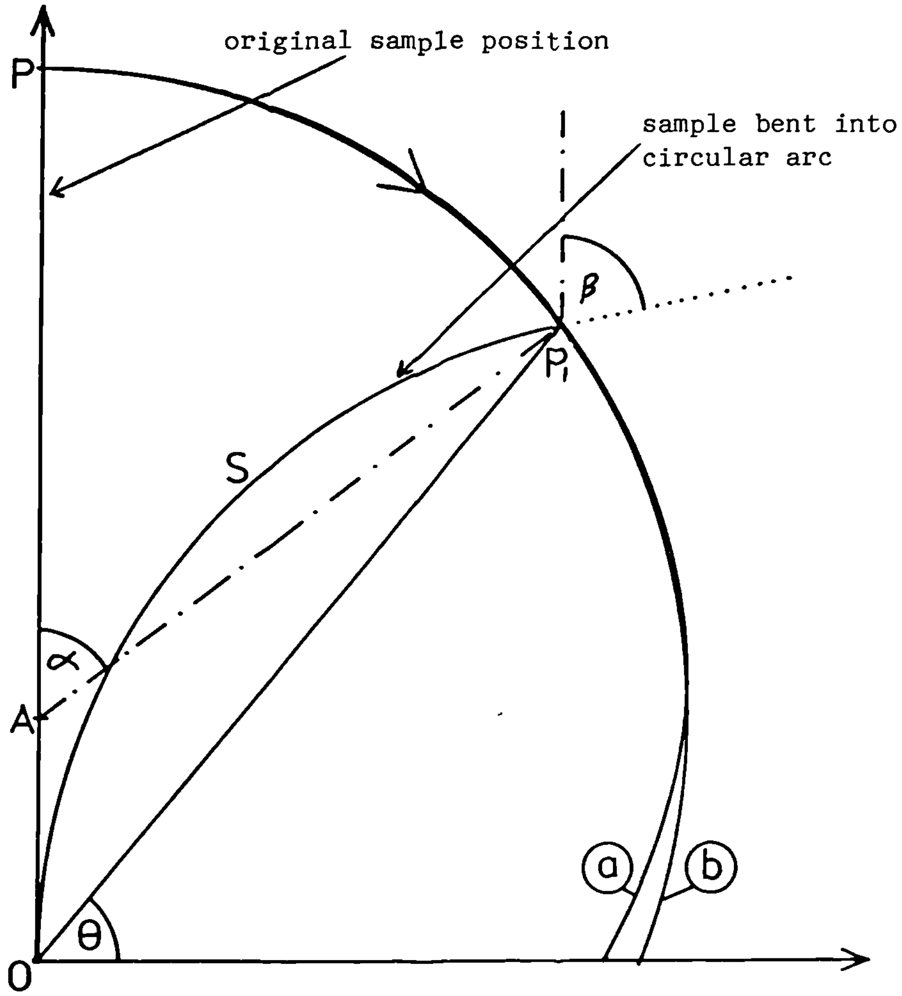
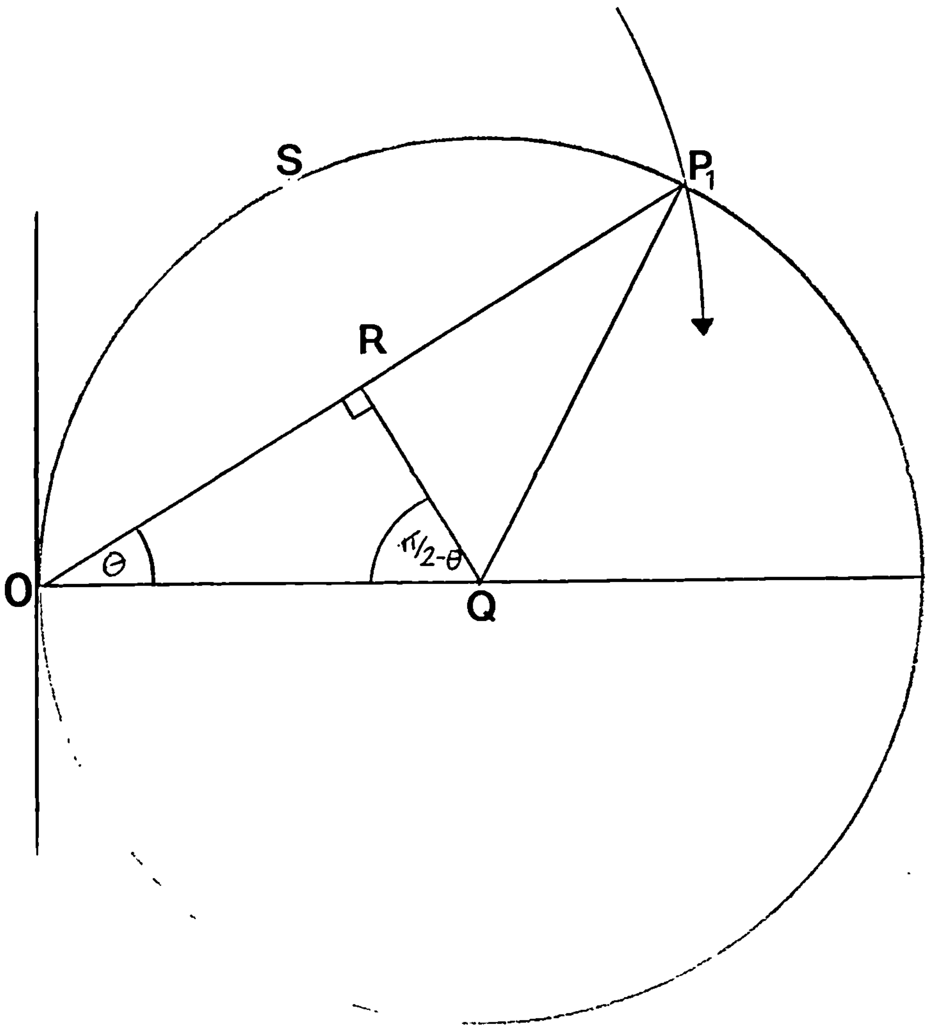


Figure 29. Relative Jaw Movement for Pure Bending



Let circular arc $OP_1 = S$

Then $S = OQ.2(\pi/2 - \theta)$

therefore $OQ = \dfrac{S}{\pi - 2\theta}$

Let chord $OP_1 = R$

then $\cos\theta = \dfrac{R}{2} \cdot \dfrac{1}{OQ}$

$= \dfrac{R}{2} \cdot \dfrac{\pi - 2\theta}{S}$

Therefore $R = \dfrac{S \cdot \cos\theta}{\pi/2 - \theta}$

Figure 30. Derivation of Equation for Moving Jaw Locus in Pure Bending

of the jaw through β^{0} and the sample S is subjected to virtually pure bending conditions.

The apparatus used was the KES-FB Pure Bending Bending Tester (Kato Tekko Co., Ltd., Kyoto, Japan), shown in Figure 31, in which a system of gears and cranks is used to move the jaws along the path closely approximating to the ideal locus. An eccentric gear and crank system adjusts the path closer to ⓐ where divergence occurs at larger curvatures. Figure 32 is a schematic diagram of the bending head mechanism. The driven shaft rotates about the axis AA' (A in Figure 29) so that OA = 0.27 x OP. The line of the nip on the moving jaws, PQ, moves about the axis AA' as the cranked shaft rotates, and the gear train G_1-G_4, moves the jaw head itself about PQ to maintain the required angle β , shown in Figure 29.

The angle of rotation of the head about the fixed nip line (OO') is measured by the output controlled by potentiometer K, axial with OO',and connected mechanicaly to the driven crankshaft. A torque meter (T) measures the couple acting on the test sample. Voltage inputs to the X and Y controls of a chart recorder are controlled by K and T and a curvature:couple curve is plotted as the sample is deformed through a pre-set cycle.

The maximum curvature is 2.5 cm^{-1}. Measurement of curvature and bending moment are made with an accuracy of $\pm 0.2\%$ throughout the ranges.

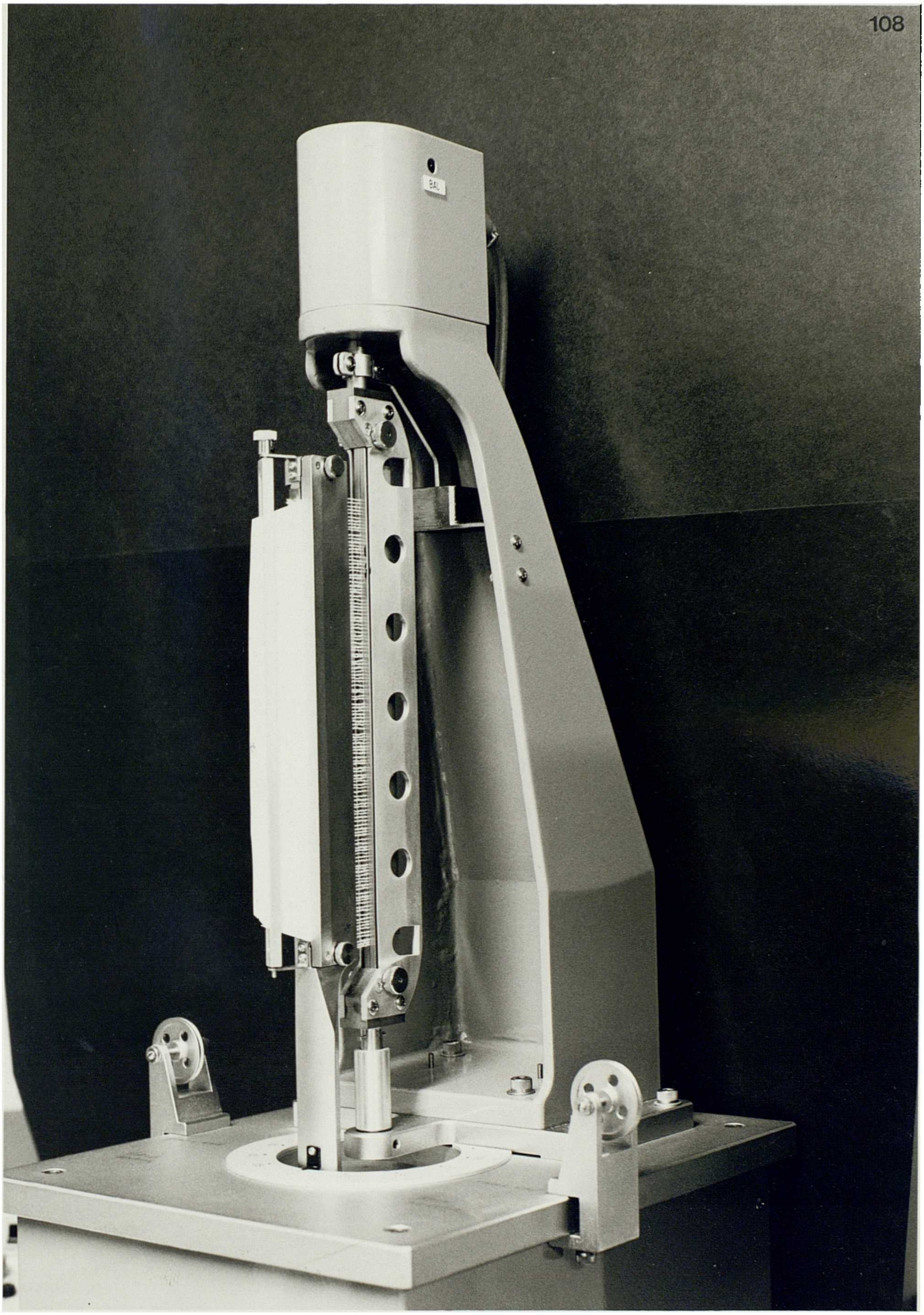


Figure 31 KES-FB Pure Bending Tester

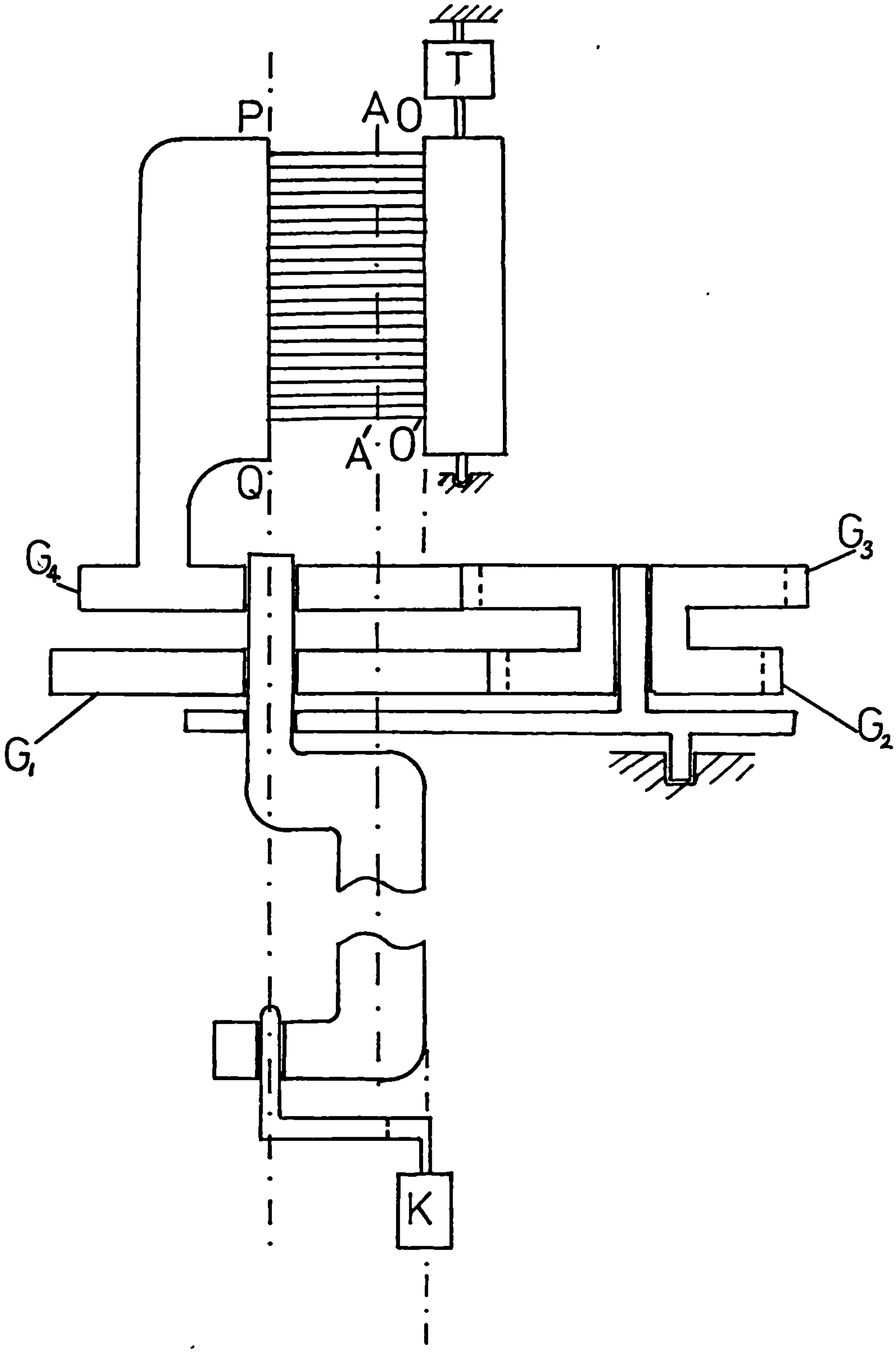
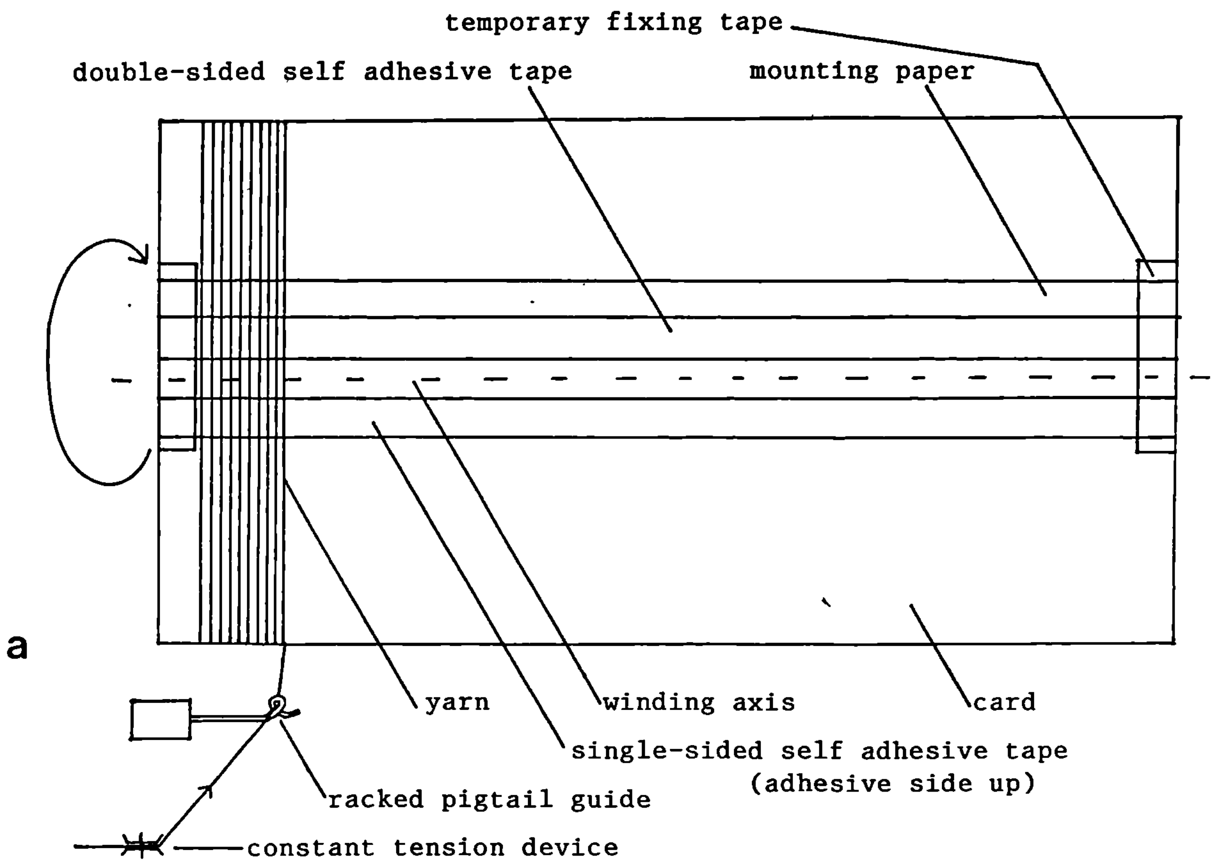


Figure 32. Schematic Diagram of the KES-FB Pure Bending Tester Mechanical Unit

Measurements were made on approximately 125 10mm lengths of yarn on each test. The samples were mounted in parallel 1.5mm apart using a motorised winder comprising a pigtail yarn guide racked by a worm screw and a rotating mounting card. This method actually mounted the samples at an angle theoretically 89.98^0 to the jaws, but the inaccuracy was considered insignificant. Figure 33 shows the stages of assembly of the samples. A card was fitted with a strip of single-sided adhesive tape, adhesive side up, and a strip of paper with a length of double sided adhesive tape alone one edge. The strips were mounted parallel to each other 5mm to either side of the centre line of the card. The card was then fitted to the winder so that the axis of rotation coincided with this centre line. A racked pigtail guided the yarn onto the rotating card as shown in Figure 33. When the card was filled after approximately 130 revolutions, it was removed and strips of single-sided adhesive tape were applied over the strips already fitted to the card. The sample assemblage was then cut from the card at the ends and excess yarn trimmed off to leave approximately 125 samples for testing. The winding arrangement took 10mm test samples at 42cm intervals along the yarn. The mean test results for each assemblage of 125 samples, therefore, represented an estimated value of the mean bending rigidity of a 52.5m length of yarn. Three assemblages were prepared and tested for each of the thirty seven yarns.

It was not possible to use the test equipment at the higher relative humidity in the conditioning cabinet. The assemblages conditioned at the higher humidity were, therefore, removed individually as required



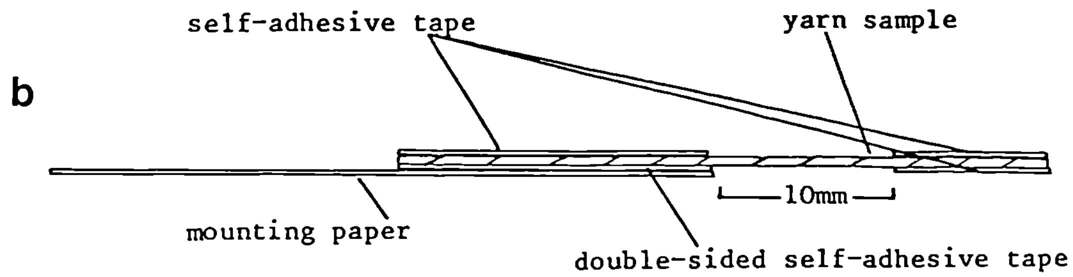


Figure 33 Preparation of Yarn Sample for Bending Test

a) Winding procedure

b) Cross-Section of Assemblage Ready for KES-FB Bending Tester and tested quickly, within 2 minutes, at the standard humidity of 65% r.h. The absolute values of bending stiffness thus obtained may be slightly higher than values obtained at the high humidity of 92.5%; the relative values of the high regain samples are of primary importance, however, and these are not expected to be significantly affected.

The test procedure was carried out automatically when the "start" button was pressed. The sample was bent to a curvature of 2.5 cm^{-1} in one direction, reversed back through the straight position to 2.5 cm^{-1} in the opposite direction and finally back to the unstrained state. The rate of bending was $0.5cm^{-1}sec^{-1}$, so the entire test was completed in 20 seconds. A hysteresis curve, similar to the ideal stress/strain curve shown in Figure 28, was plotted simultaneously. Figure 34 shows examples of two actual plots. Deviations from the ideal curve form resulted from minor unsupressed vibrations (high torque sensitivity is required for yarn testing) and mounting imperfections. The latter anomolies were most apparent at low bending strain when any sample lengths at slightly lower tension were more likely to kink out of the parallel configuration.

Two measurements were made on each stress/strain plot: the bending stiffness of the yarn samples and their hysteresis. The gradients of the increasing curvature slopes were measured between $0.5cm^{-1}$ and $1.5cm^{-1}$ in each direction and the mean taken to give a value of the bending stiffness, after division by the number of yarn samples in the assemblage. Hysteresis, a measure of departure from pure elasticity,

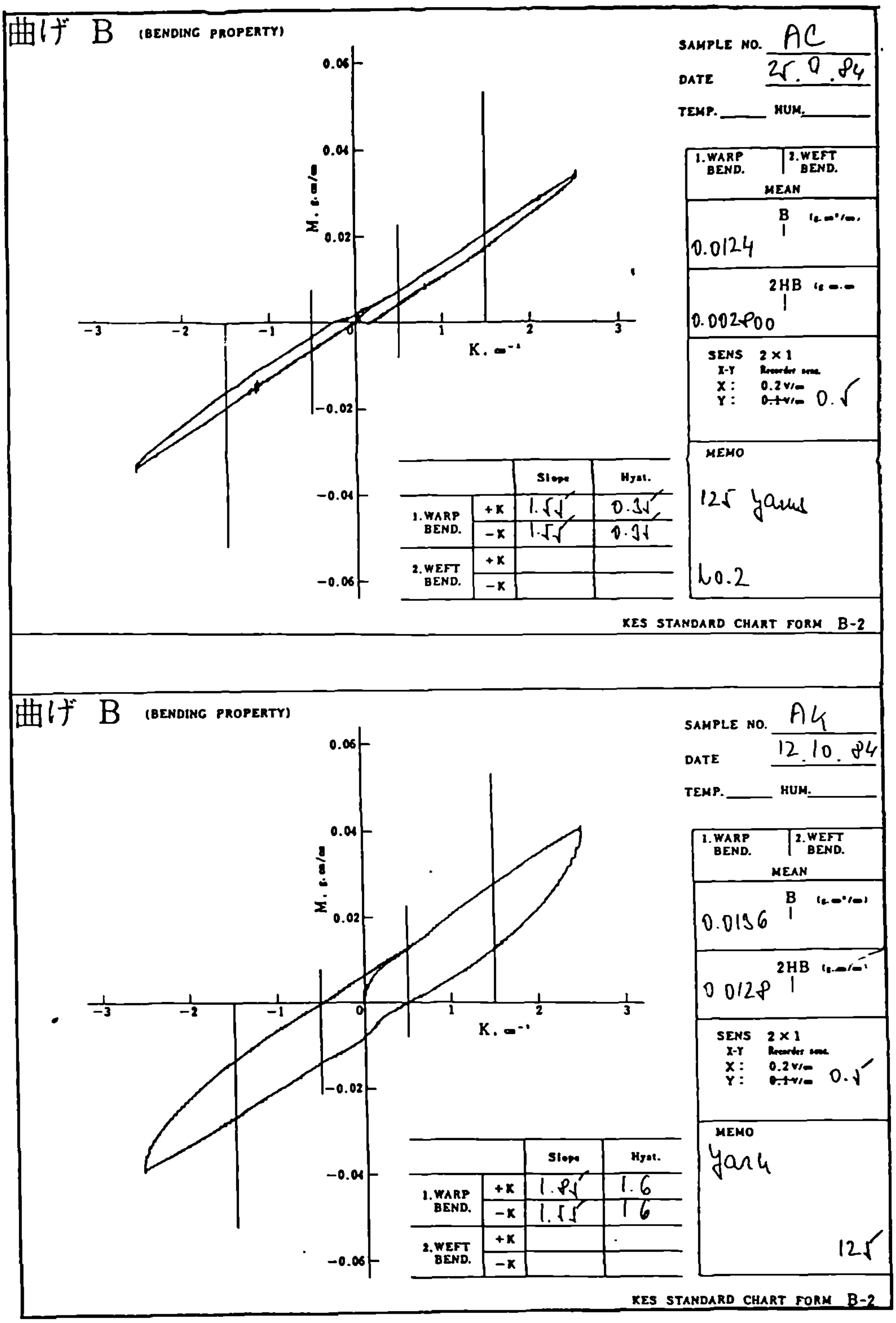


Figure 34. Bending Test Hysterisis Plots

was obtained by measuring the difference in applied moment at $0.5cm^{-1}$ between the increasing and decreasing curvature slopes in both directions, and taking the mean. This value is equivalent to twice the coercive couple of a sample. Values of bending stiffness and hysteresis are given in Figure 24.

A letter was received late in 1986, well after the completion of the experimental work, from the president of Kato Tekko Co., Ltd. This disclosed that the values obtained by the KES-FB bending tester are significantly different to the true values, due to an error in the manufacture of the clamp plates. The effect of this error is to increase the length of the test sample. Kato Tekko Co. Ltd. carried out detailed work subsequently and discovered that true values for flexural rigidity and bending hysteresis are obtained by multiplying the incorrect values in each case by a factor of 1.384. All values for these parameters given in the present work have been corrected by multiplication by this factor.

5.7 FABRIC STITCH DENSITY

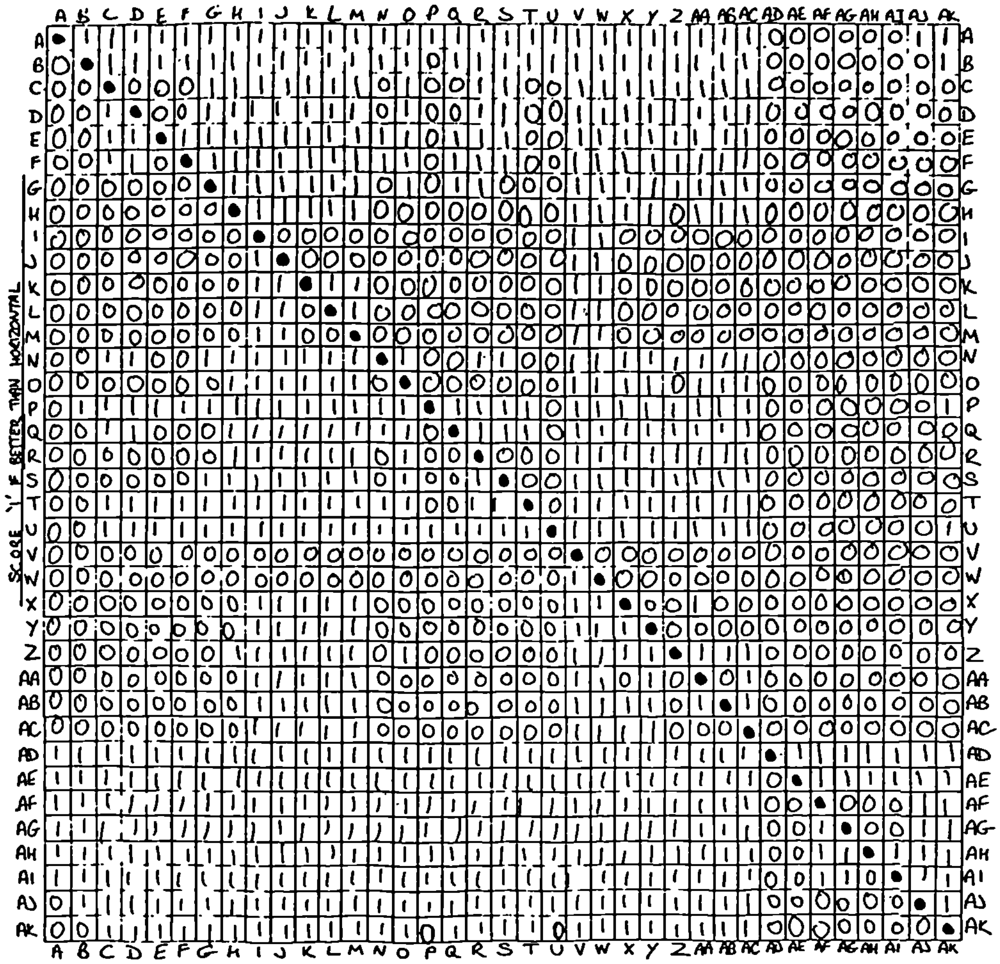
As a check to ensure that complete fabric relaxation had taken place, and that the loop distortion in each sample had developed to its maximum extent, measurements of stitch density were made. A piece glass was used to measure the number of wales and courses per unit length and values of K_1 were calculated as described in Section 1.2. Values for the wool fabrics were in the range 22-23 and for the acrylic fabrics 20.5-21.5. These values suggest that virtually complete relaxation of the structures had occured. The lower value of K_1 for the synthetic yarns was not unexpected, and has previously been accounted for by partial plastic deformation in knitting[8]. Such partial setting, occuring at or soon after knitting, could also account for an acrylic fabric displaying less loop distortion than a wool fabric.

5.8 ASSESSMENT OF LOOP DISTORTION

Photographs of the thirty seven knitted fabrics are shown in Appendix A. The fabrics were assessed by the paired comparison method[53]. Viewing was carried out in diffuse daylight with the samples on a horizontal surface. A piece glass was provided for detailed inspection if required. The judges were asked to determine which sample in each pair had the lower degree of loop distortion, this assessment being a subjective judgement of the degree of unacceptability as a function of the number of distorted loops, the angles of distortion and the distribution of the loops over the fabric surface. The judges were asked to ignore differences in the following factors when making their assessment:

Colour
Degree of milling
Spirality
Yarn count
Creasing

Each sample was approximately 35cm x 40cm in area, equivalent to about 65000 loops. Nine judges were used, each having had previous experience in carrying out this type of assessment. Because of the relatively large number of pairs involved - ((37x37)-37)/2=666 - each judge made the full set of comparisons over four or five sessions to avoid fatigue and a possible lessening of the care taken over judgements. The better sample (i.e. the one with the less distortion) in each pair was awarded one point; the other was awarded zero. When the table for each judge had been completed the row total for each of the thirty seven samples was summed. A typical completed paired comparison table is reproduced in Figure 35. Tied ranks were not permitted. Figure 36 lists the row totals for each of the nine judges. These totals fall within the range 0-36; the equivalent ranks range from 1 to 37 and are found by adding 1 to the row totals. Analysis of the loop distortion assessment results is discussed in the next chapter.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK
A	•	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1
B	0	•	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1
C	0	0	•	0	0	0	1	1	1	1	1	1	1	0	1	0	0	1	1	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
D	0	0	1	•	0	0	1	1	1	1	1	1	1	0	1	0	0	1	1	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
E	0	0	1	1	•	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
F	0	0	1	1	0	•	1	1	1	1	1	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
G	0	0	0	0	0	0	•	1	1	1	1	1	1	0	1	0	1	1	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
H	0	0	0	0	0	0	0	•	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0
I	0	0	0	0	0	0	0	0	•	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
J	0	0	0	0	0	0	0	0	1	•	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K	0	0	0	0	0	0	0	0	1	1	•	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L	0	0	0	0	0	0	0	0	1	1	0	•	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M	0	0	0	0	0	0	0	0	1	1	0	0	•	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N	0	0	1	1	0	0	1	1	1	1	1	1	1	•	1	0	0	1	1	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
O	0	0	0	0	0	0	0	1	1	1	1	1	1	0	•	0	0	0	0	0	0	1	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0
P	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	•	1	1	1	1	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1
Q	0	0	1	1	0	0	0	1	1	1	1	1	1	1	1	0	•	1	1	1	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
R	0	0	0	0	0	0	0	1	1	1	1	1	1	0	1	0	0	•	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
S	0	0	0	0	0	0	1	1	1	1	1	1	1	0	1	0	0	1	•	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
T	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	•	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
U	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	•	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	•	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	•	0	0	0	0	0	0	0	0	0	0	0	0	0	0
X	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	•	0	0	1	0	0	0	0	0	0	0	0	0	0
Y	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	•	0	0	0	0	0	0	0	0	0	0	0	0
Z	0	0	0	0	0	0	0	1	1	1	1	1	1	0	1	0	0	0	0	0	0	1	1	1	1	•	1	1	1	0	0	0	0	0	0	0	0
AA	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	0	1	0	•	0	1	0	0	0	0	0	0	0	0
AB	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	0	1	•	1	0	0	0	0	0	0	0	0
AC	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	•	0	0	0	0	0	0	0	0
AD	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	•	1	1	1	1	1	1	1
AE	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	•	1	1	1	1	1	1
AF	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	•	0	0	0	1	1
AG	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	•	0	0	1	1
AH	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	•	1	1	1
AI	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	0	0	1	1	0	•	1	1
AJ	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	•	1
AK	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	•

Figure 35. One of Nine Paired Comparison Tables Completed During Assessment of Loop Distortion

SAMPLE CODE	JUDGE CODE								
	1	2	3	4	5	6	7	8	9
1	30	32	28	28	31	29	29	34	31
2	18	18	20	22	21	21	22	20	23
3	27	30	26	27	27	22	30	27	26
4	21	17	21	19	19	18	19	20	16
5	14	14	11	13	14	14	14	15	13
6	9	11	6	5	8	7	7	8	7
7	8	10	4	6	6	5	7	6	5
8	8	7	6	6	9	6	4	7	5
9	20	21	17	18	17	19	18	16	18
10	13	18	12	12	12	13	14	11	11
11	0	7	2	1	4	0	1	2	1
12	1	5	1	0	5	5	3	3	2
13	23	26	20	20	21	19	25	25	22
14	27	27	26	22	24	22	29	24	22
15	11	14	8	11	13	10	10	10	13
16	9	8	5	2	9	9	8	7	9
17	15	12	13	15	15	13	16	12	15
18	17	18	15	15	16	16	14	14	17
19	27	28	26	24	26	28	27	28	29
20	36	34	33	36	36	36	36	35	36
21	35	36	36	33	35	34	35	36	35
22	23	24	23	26	28	25	21	24	26
23	22	28	24	25	27	27	24	23	25
24	31	33	35	34	34	35	34	32	32
25	32	35	34	35	33	33	33	33	31
26	34	24	32	31	31	32	32	29	31
27	33	18	29	32	31	31	29	30	30
28	2	2	6	7	1	3	1	3	5
29	3	1	0	4	0	1	2	0	0
30	29	21	30	30	26	30	26	27	25
31	25	27	31	29	23	20	23	27	26
32	5	5	9	9	3	5	8	9	7
33	4	2	9	7	2	5	5	4	4
34	19	20	21	21	21	26	19	19	21
35	17	20	18	18	19	21	19	20	21
36	12	7	15	13	10	16	11	13	15
37	6	6	14	10	9	10	11	13	11

Figure 36. Summary of Loop Distortion Paired Comparison Row Totals - loop distortion decreases as total increases

CHAPTER SIX

ANALYSIS OF RESULTS

6.1. INTRODUCTION

For the purposes of analysis, the data may be divided into three groups as follows:-

(a) Independent Variables

These comprise six sets of data, each in the form of a half factorial design, relating to yarn production and processing variables. Each set of data relates to samples representing treatment combinations nominally at one of two levels or values. Because the variables are independent there is zero correlation between the various treatments in each set.

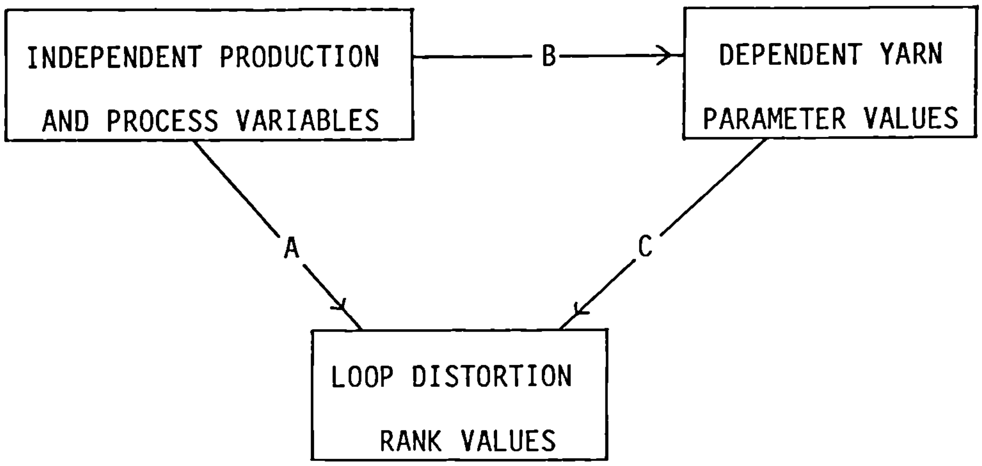
(b) Dependent Yarn Physical Parameters

These variables are likely to be dependent upon the preceding combination of production and processing treatments. One would expect some degree of correlation between the various parameters in this group.

(c) Loop Distortion Assessment Values

This group of dependent variables is in the form of ranked values.

The three groups of data may be inter-related as follows:-



For the knitting yarn spinner, the most important relationship is A, the direct relationship between the yarn production and processing route and the occurrence of loop distortion in the knitted fabric. The analysis of the relationship between treatment combinations in a factorially designed experiment and the dependent variables may be carried out using methods similar to those described by Yates[97]. Ranked data may be treated in the same way as data obtained from quantitative measurements[98], but the values of the estimates obtained will have no significance in terms of their relative magnitude of importance, only in terms of their order.

Having obtained information about the relationships between the various independent variables and their effects on loop distortion, we would then like to understand the mechanisms by which these relationships operate. These mechanisms may be studied by examining the relationships B and C. Loop distortion is presumed to take place as a result of certain physical conditions in the knitting yarns; these, in turn, are dependent upon the original production and processing conditions. Factorial analysis may be used to examine the relationship B. Because of the correlation between the yarn physical parameters, this method may not, however, be used for analysis of relationship C. Instead, the yarn physical parameter values are ranked and each pair of ranked sets of values (loop distortion rank:physical parameter rank) is analysed using Spearman's[99, 100] rank correlation technique.

Initially we shall examine the three groups of data in isolation and then the relationships among them.

6.2. THE INDEPENDENT VARIABLES

The six half replicate factorial designs shown in Figures 18 and 19 include a total of eleven variables, the values of which, within the individual designs, are independent of each other. Two levels of each variable were chosen, the levels being either one of two states, such as treated or untreated, acrylic or wool, etc. or two levels of a variate which is continuously variable. In the latter case the actual values could be distributed about mean values represented by the two nominally fixed levels. The continuous variates included in the group of eleven independent variables are fibre diameter, count, count regularity, twist level and moisture regain.

Fibre diameter measurements are tabulated in Figure 20. The mean "coarse" wool fibre diameter is 35.4 ±0.9 microns and the "fine" diameter 25.2 ±0.7 microns. In both cases the Coefficient of Variation is relatively high (25-26%), as one would expect for a wool fibre blend. The acrylic samples are all nominally "fine", the calculated diameter being 24.7 ±0.8 microns. It is felt that the difference of less than 2% between the "fine" wool and acrylic yarns would not be significant in terms of loop distortion. Figure 37 represents the determinations of the mean fibre diameters with 95% confidence limits.

Regain levels are indicated in Section 4.9. The two independent levels are conditioning relative humidities, not the percentage moisture contents of the fibres. The percentage regain of the wool fibres was about eight times greater than that of the acrylic yarns in the two conditioning atmospheres. The only possible deviation from the two standard conditions would be during the testing of yarn bending rigidity; this was discussed in Section 5.6.2.

Although twist level and regularity were nominally fixed by the settings of the spinning and twisting machines, some dependence on other variables, such as fibre type or diameter, could be expected, especially in the case of count regularity.

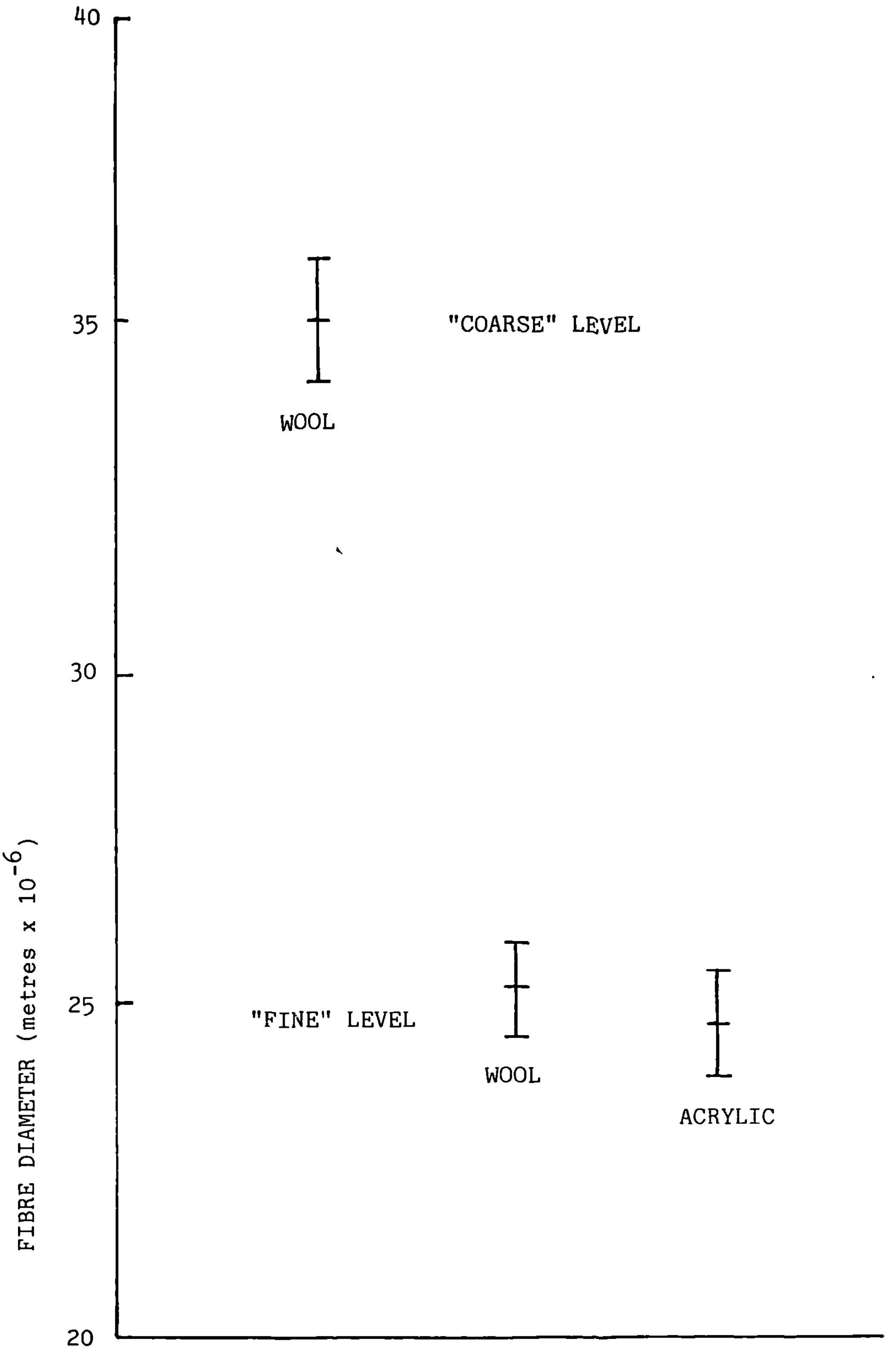


Figure 37 Mean Fibre Diameter Distributions
(showing 95% confidence limits)

Figure 38 shows the distribution of the mean twofold twists of the twenty nine different yarns (the eight samples conditioned to "high" regain, being in other respects equivalent to other "low" regain samples, have not been included). The low twist yarns show a positive skew distribution with the modal value close to the nominal low twist level. The high twists appear to be widely spread (again, "high" regain duplicates have been ommitted from the histogram). Actual mean twist could be included as one of the dependent yarn parameters in the analysis of relationship "B" and this will indicate whether there is a significant correlation between the variable and one of the other independent variables or whether, in fact, the distribution seen is a result of random variations in production and measurement. A similar distribution is also seen for the mean twists of the sixteen singles yarns.

Figure 39 shows the histograms for twofold and singles yarn U% count regularity distribution. Positive skew distributions are seen for both "regular" and "irregular" twofold yarns, with modal values around 10% and 18% respectively. Values for all thirty seven samples are given since, because the count regularity could be influenced by regain, measurements were also made at high regain. It would be interesting to examine the relationships between the actual U% count regularity values and the other independent variables in order to determine whether there are any other significant correlations in addition to that with the nominal level (high or low) of count regularity. Count regularity is expected to influence the short term

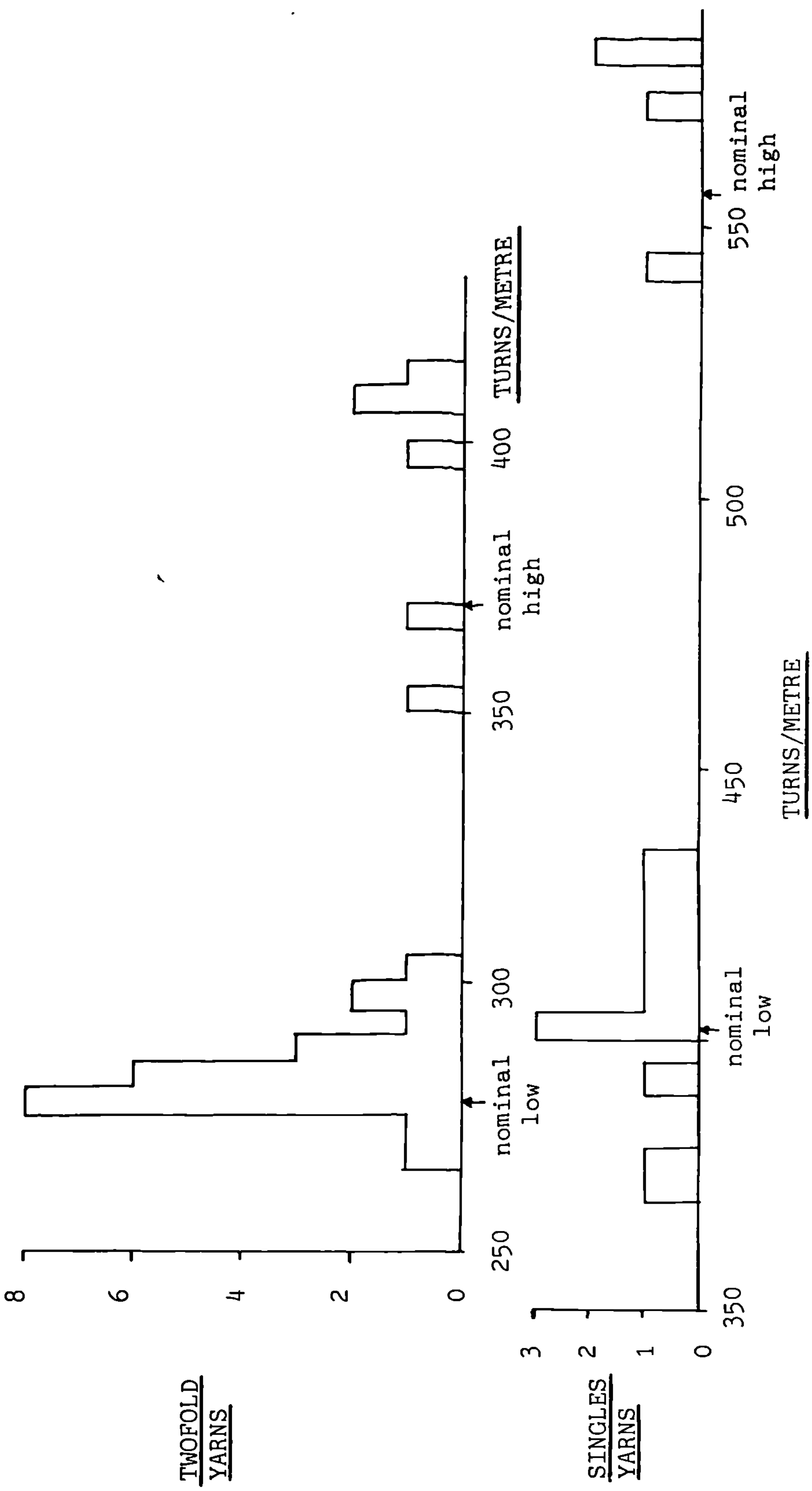


Figure 38 Mean Yarn Twist Distributions

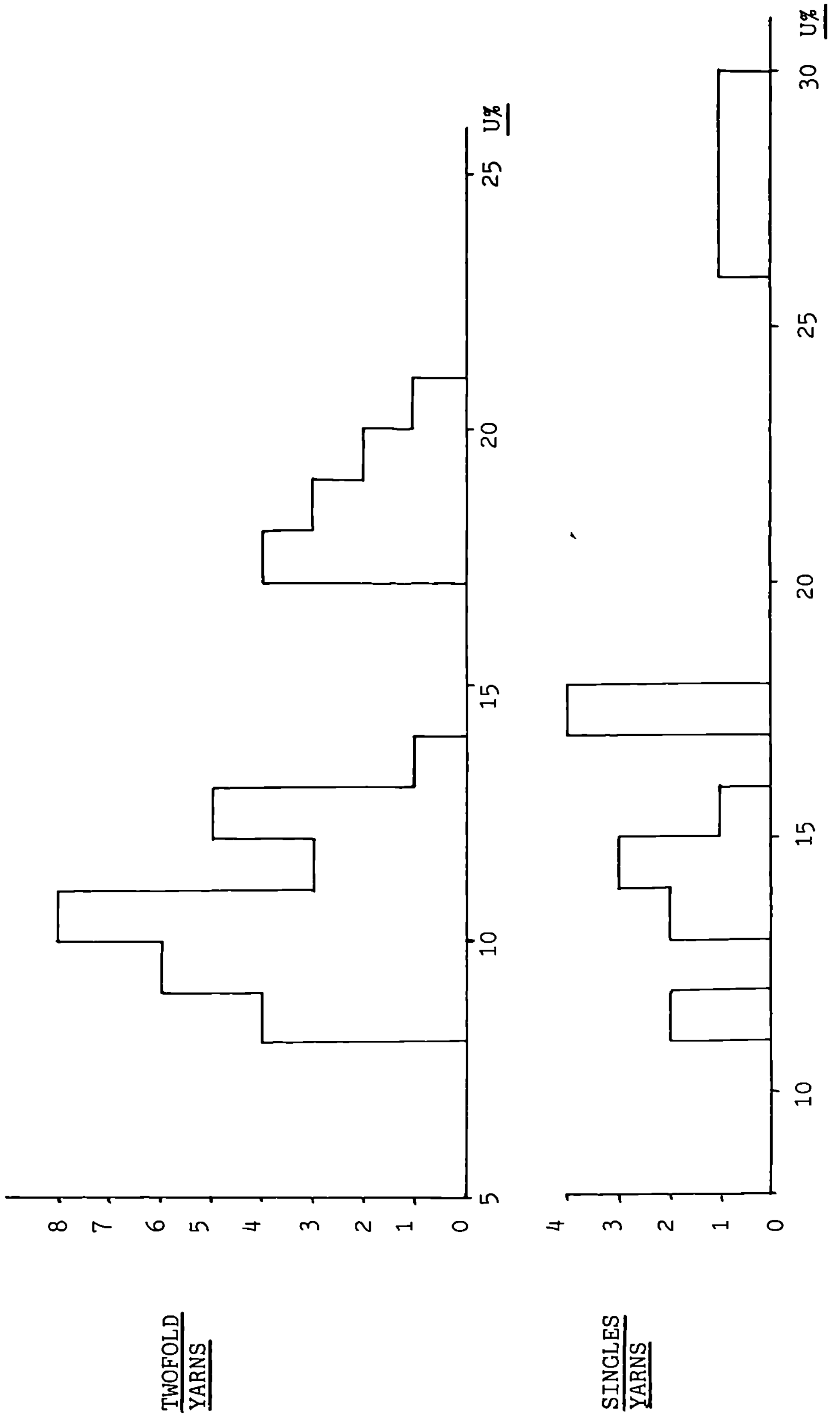


Figure 39 U% Count Regularity Distributions

distribution of twist, (CV%, twist, Figure 23). Scattergrams of count regularity against twist regularity for singles and twofold yarns are given in Figures 40 and 41. When the plot in Figure 41 was examined in detail it was noticed that the autoclave set yarns (the circled points) appeared to have a higher twist irregularity for a given count irregularity than the unset yarns. Analysis revealed the following correlations:-

	Correlation Coefficient (U% count : CV% Twist)
All Yarns (29)	0.901
Autoclave Set Only (15)	0.937
Unset Yarns Only (14)	0.946

For the equation T= aC + b, where T = CV% twist and C = U% count, linear regression analysis gave values for the coefficients as follows:-

	a	b	% FIT
All Yarns	1.70	-2.92	81.1
Autoclave Set Only	2.10	-5.96	87.8
Unset Yarns Only	1.66	-4.02	89.5

These equations have been plotted as lines 1, 2 and 3 respectively in Figure 41. The implication is that more twofold twist iregularity

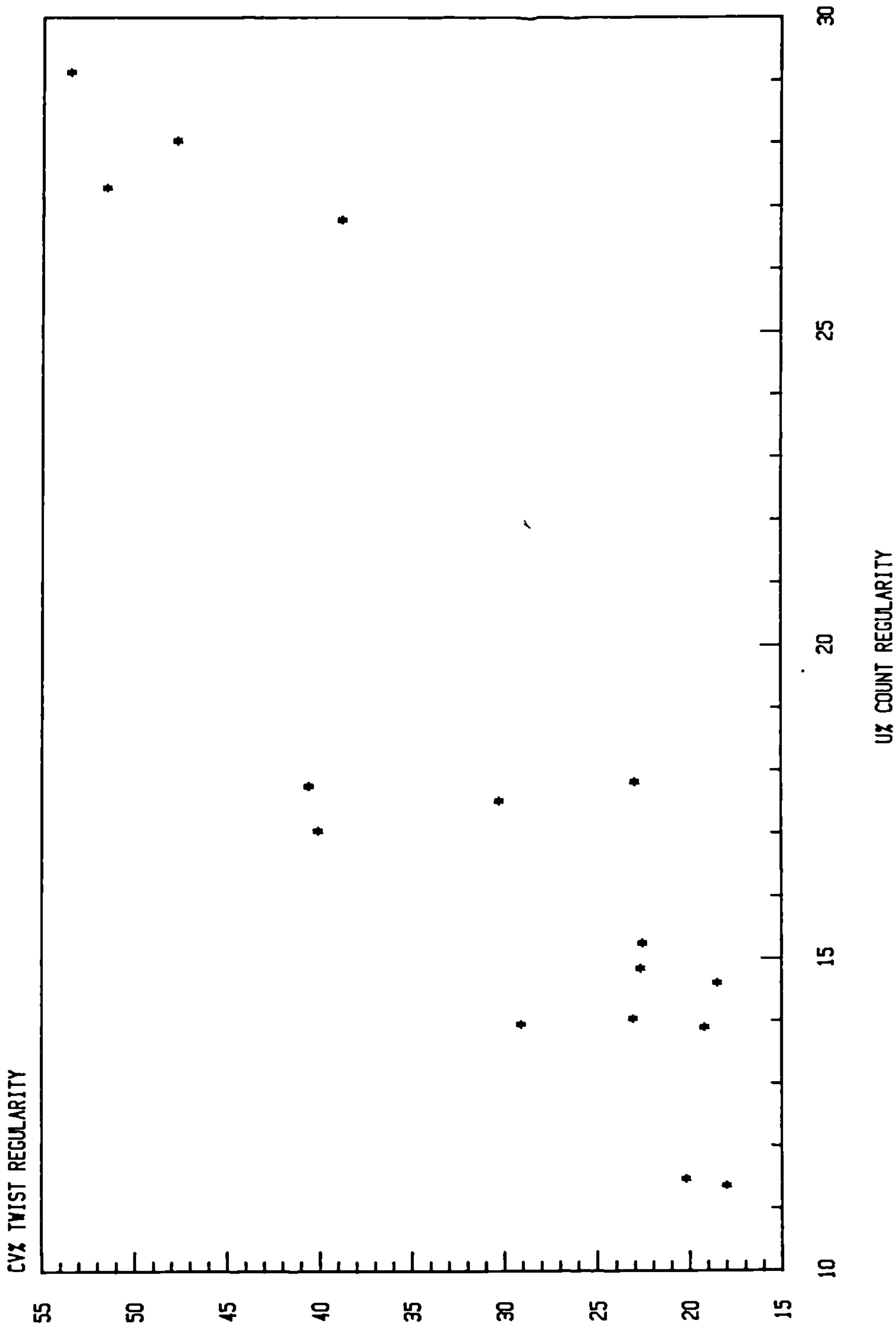


Figure 40 Relationship Between Count and Twist Regularity for Singles Yarns

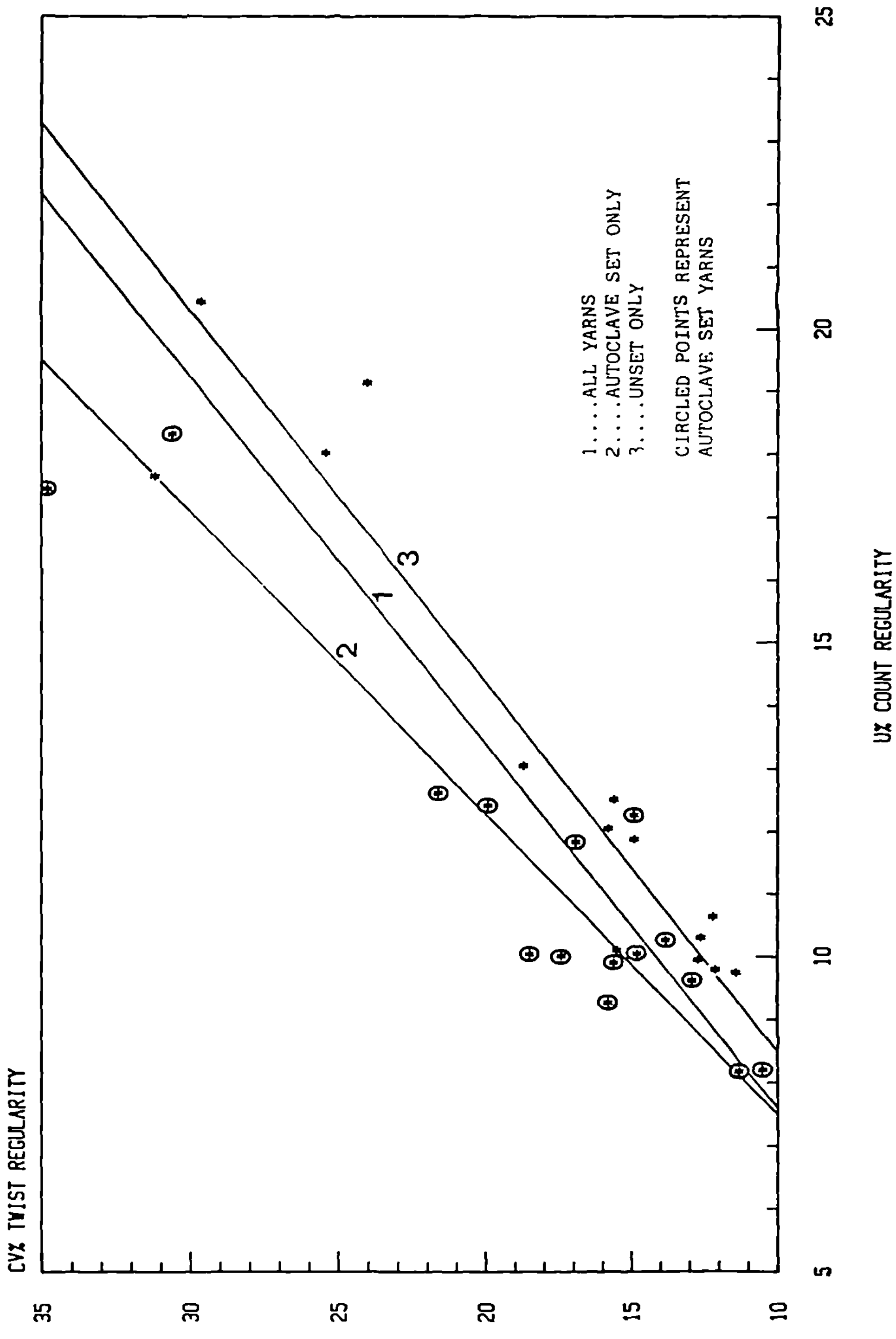


Figure 41 Relationship Between Count Regularity and Twist Regularity for Twofold Yarns

will tend to occur if yarns are autoclave set than if they are left unset. Redistribution of twofold twist would be expected to occur very quickly, probably as soon as the singles yarns have been twisted together on the twisting frame, in other words after singles autoclave setting but before twofold setting.

The following mechanism might be proposed to account for higher twist irregularity in set twofold yarns:-

i) Set singles yarns are assumed to have zero torque along their length, although the count and twist may vary.

ii) Unset singles yarns are assumed to have constant torque along their length (due to twist redistribution).

iii) After twofold twisting to a constant level, torque irregularity is introduced as a result of local count variations.

iv) The mean induced torque/unit folding twist away from an equilibrium (torque-free) balanced state is higher for the set yarns than the unset yarns. This is because the twisting process increases torque in set yarns and decreases torque in unset yarns. In the latter case, if balancing twists have been used, the mean torque should be zero, although count variations will result in a distribution about this value.

v) The higher potential energy of the set yarns results in greater twist irregularity as the energy is released and hence twist redistribution occurs to a greater extent.

vi) The setting of the twofold yarn does not influence twist irregularity but merely stabilises it. However, this setting process could influence the rate of return toward a stable state if further twist redistribution was induced subsequently, e.g. by winding, knitting, etc.,

6.3 DEPENDENT YARN PHYSICAL PARAMETERS

The yarn test results have been tabulated in Figures 23 and 24.

Correlation coefficients for six main physical parameters were calculated as follows using data from all thirty seven samples:-

	Friction	Torsional Rigidity	C.V.% Torsional Rigidity	Flexural Rigidity	Bending Hysteresis	U% Twofold
Friction	1.0					
Torsional Rigidity	-0.592	1.0				
CV% Torsional Rigidity	0.224	0.016	1.0			
Flexural Rigidity	-0.491	0.834	0.067	1.0		
Bending Hysteresis	-0.117	0.435	0.542	0.471	1.0	
U% Twofold	0.186	-0.144	0.295	0.204	0.416	1.0

The significance of these correlations may be determined from tables of Students' "t" distribution where:-

$$t = \frac{r\sqrt{N - 2}}{\sqrt{1 - r^2}}$$

for N - 2 degrees of freedom (in this case 35) when the correlation coefficient is given by r. For 35 degrees of freedom, values of t at the 1% and 0.1% levels are 2.72 and 3.60 respectively. Correlation coefficients must therefore exceed 0.42 for significance at the 1% level and 0.52 for significance at the 0.1% level. The 5% level of significance is represented by a correlation coefficient of 0.32.

Three highly significant correlations are noted: between flexural rigidity and torsional rigidity, between torsional rigidity and friction and between the coefficient of variation of torsional rigidity and bending hysteresis.

One would expect a close relationship between flexural and torsional rigidity. A scattergram of the values for all samples is shown in Figure 42. Closer examination of the actual yarns samples involved shows that the plotted points can be divided into at least 5 distinct groups. These are illustrated in Figure 43. Further analysis of the relationship between the rigidity values and the independent variables is carried out in Section 6.7 but a number of factors are easily appreciated from this graphical representation:-

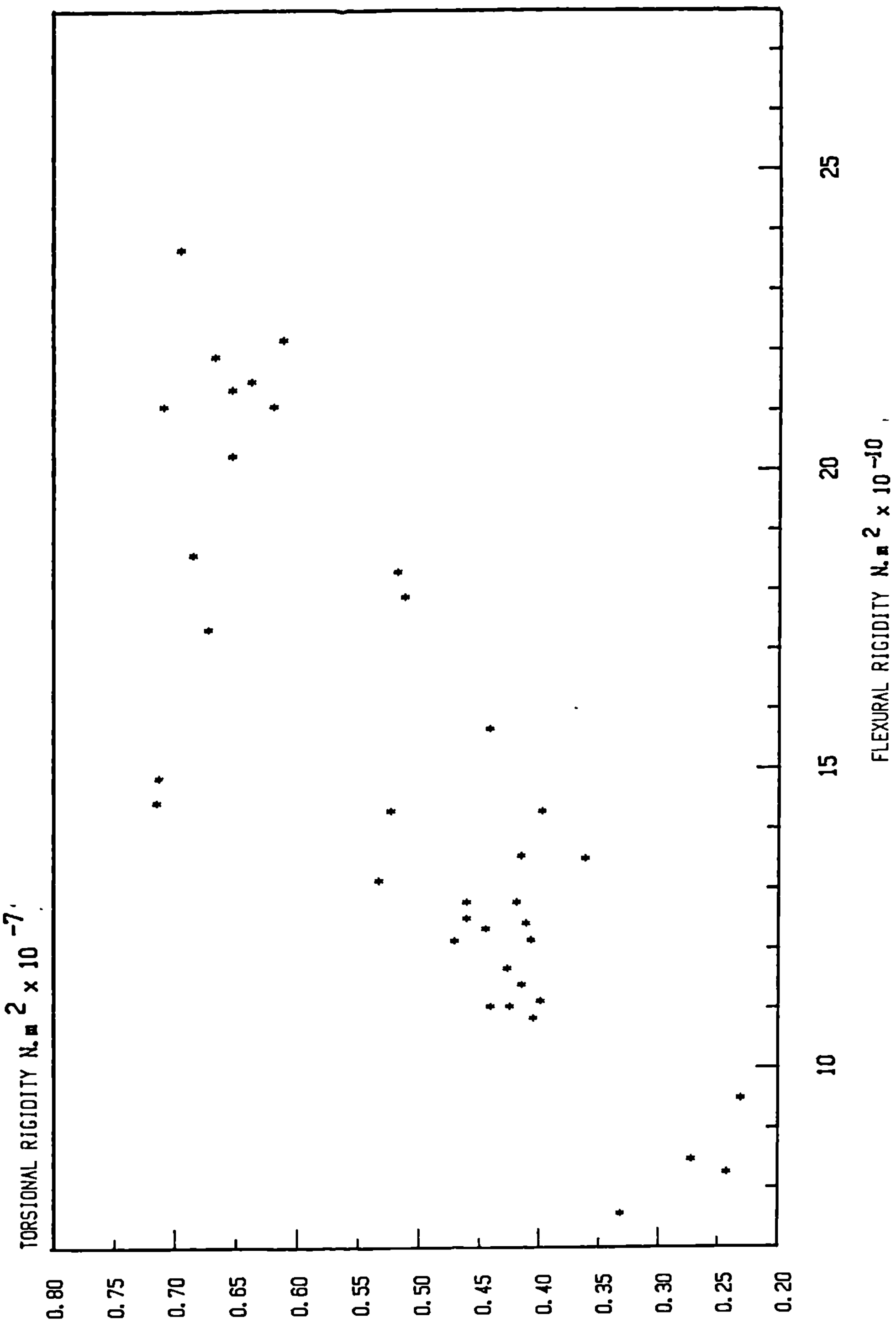


Figure 42 Correlation Between Flexural and Torsional Rigidity for All Yarns

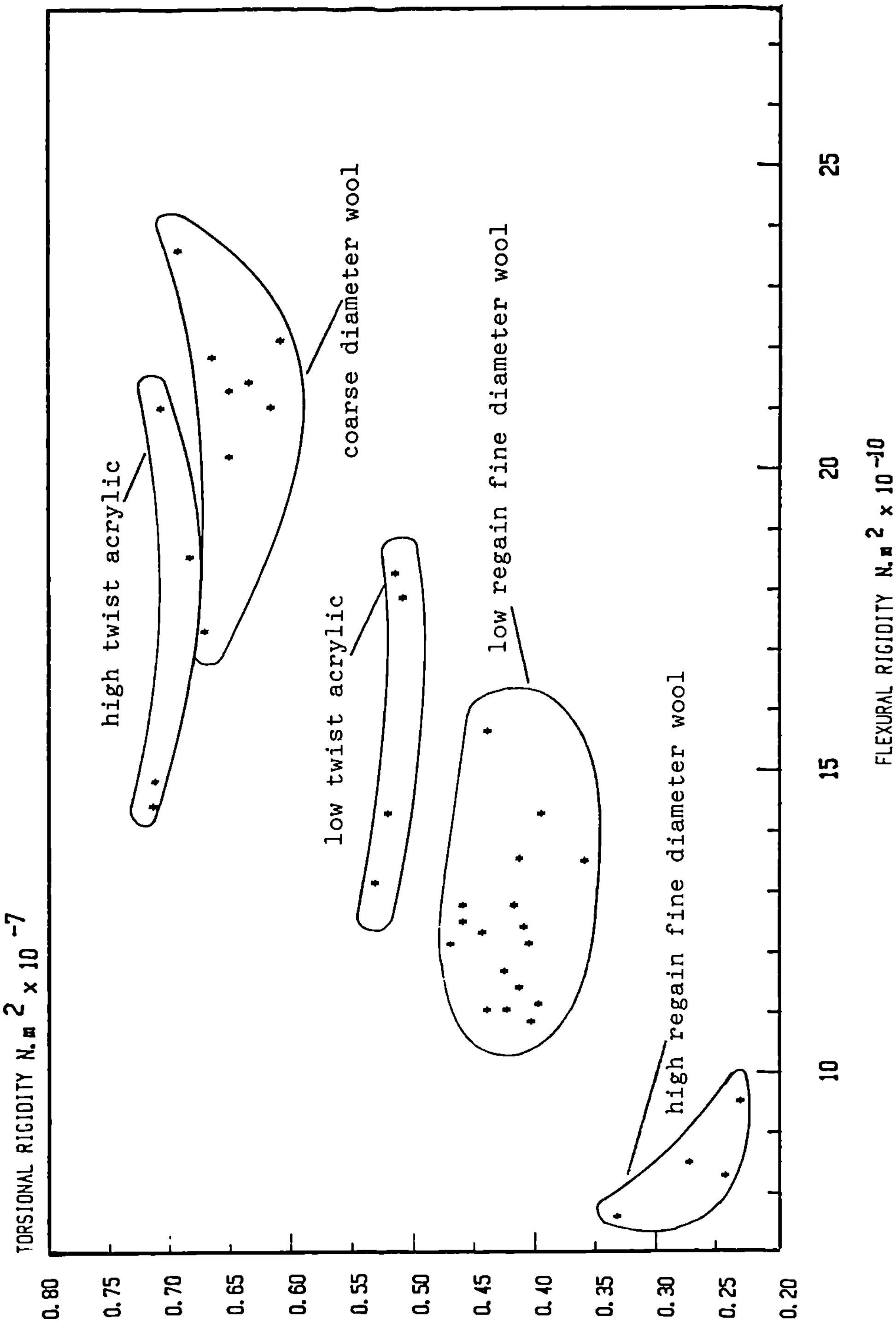


Figure 43 Differentiation of Rigidity Values According to Yarn Type

i) Increasing the regain tends to reduce the rigidity of a wool yarn.

ii) Increasing the fibre diameter tends to increase the rigidity of a wool yarn.

iii) For a given fibre diameter and count, an acrylic yarn tends to have a higher rigidity than a wool yarn.

iv) The torsional rigidity of an acrylic yarn is significantly dependent on twist, the flexural rigidity rather less so.

Figures 44 and 45 show the relationship between the coefficient of friction and flexural and torsional rigidity respectively. Again, the plotted points are composed of a number of discrete groupings. Figure 44 shows that the majority of yarns have a coefficient of friction in the range 0.27-0.31, but that there is an isolated group of high regain yarns with a coefficient of friction of 0.45 or higher. A similar picture is seen in Figure 45; in this case only the high regain wools are an obvious discrete group since flexural rigidity is not such a clear discriminating factor as torsional rigidity.

Both these Figures illustrate that correlation coefficients should not be relied upon too greatly and that a graphical presentation is preferable in many cases for showing relationships between variables. It is only the position of the high regain group that has produced a relatively high correlation coefficient; without this group, friction would be correlated with rigidity at a low level.

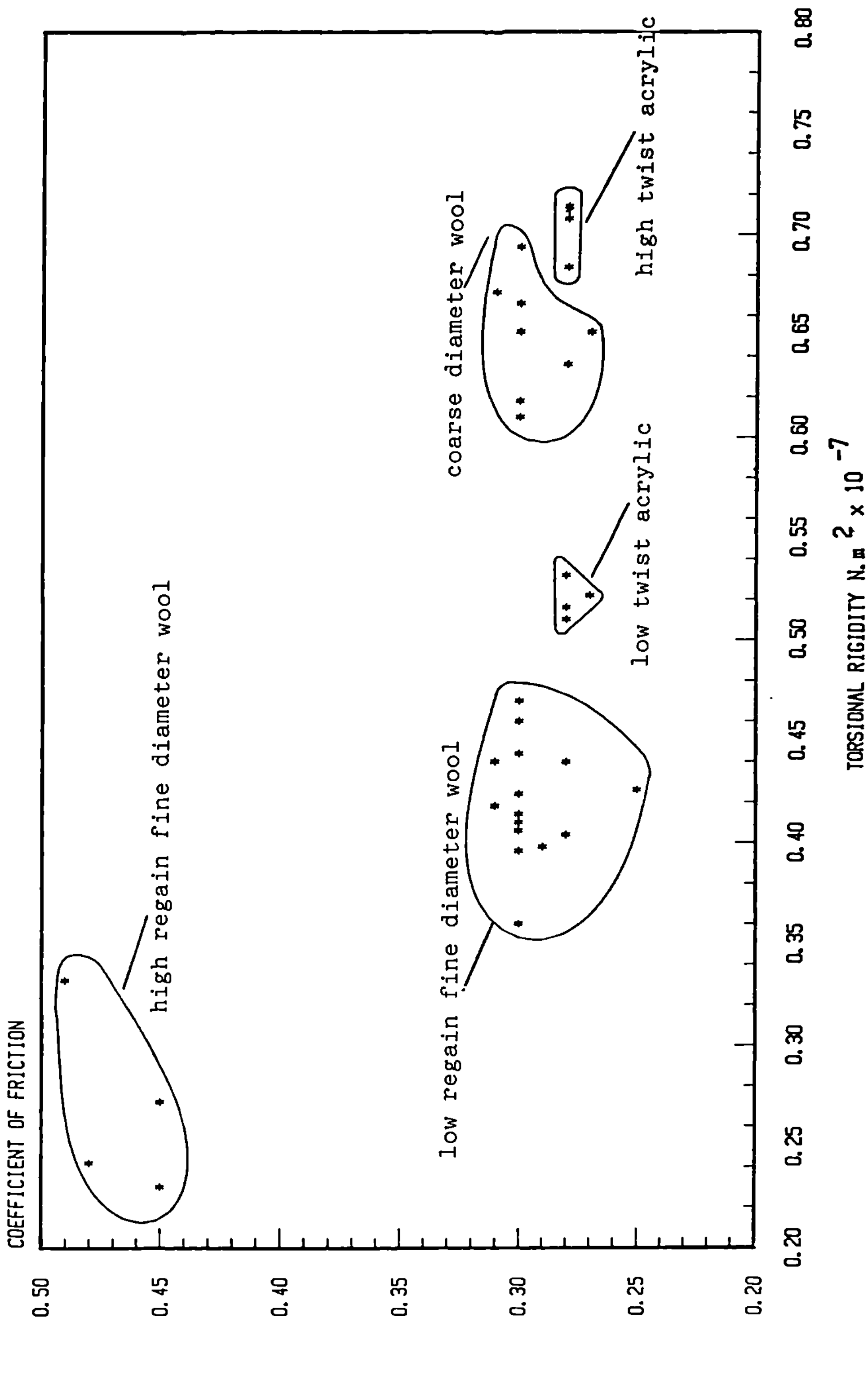


Figure 44 Correlation of Friction with Torsional Rigidity

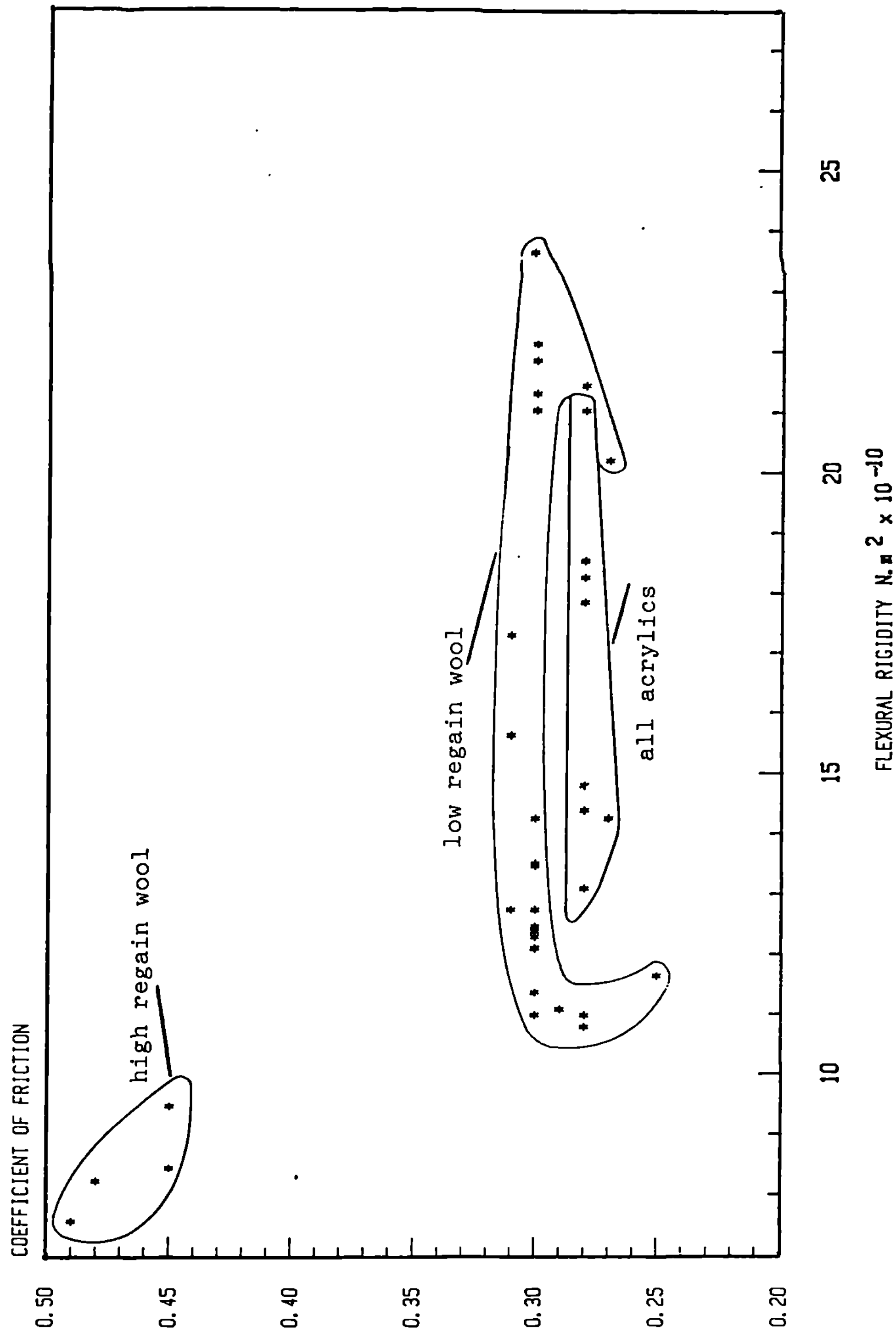


Figure 45 Correlation of Friction with Flexural Rigidity

A highly significant correlation was also noted between the coefficient of variation of the torsional rigidity and the bending hysteresis. This is shown in Figure 46. It is interesting to note that package dyed and top dyed yarns form discrete areas on the scattergram, the top dyed yarns having higher mean values of the two parameters. In fact, analysis of variation for the two groups of six package dyed and six top dyed samples showed that the differences between the means was significant at a level exceeding 0.1%. The acrylic yarns fall in an area with yet higher values of the parameters. Although it may be rather early in the analysis to consider such relationships, it is of interest to remember from the results of previous studies that top dyed wool yarns usually result in less loop distortion than package dyed wool yarns and that acrylic yarns are usually freer of loop distortion than wool yarns.

When twist redistribution occurs within a yarn, torsional variations are reduced. There is, therefore, no reason to suppose that there should be a high degree of correlation between the coefficient of variation of the torsional rigidity and the count and twist irregularity of the yarn. This is borne out by the insignificant correlation coefficients of 0.295 and 0.246 for correlation with count and twist regularity respectively.

Setting processes such as autoclave steaming or package dyeing take place after there has been an opportunity for much of the twist redistribution to take place. One would not, therefore, expect a

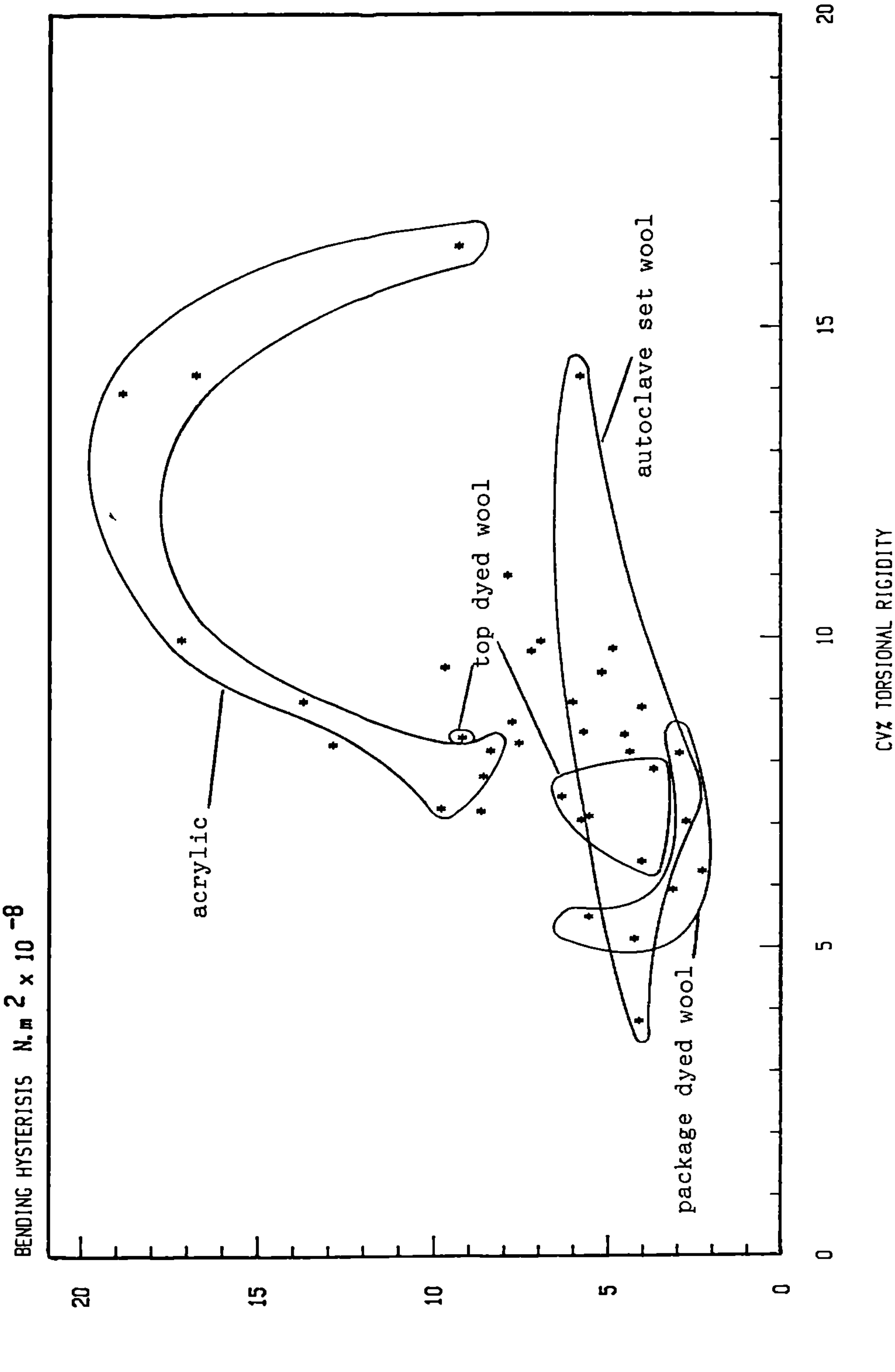


Figure 46 Correlation of Bending Hysterisis with CV% Torsional Rigidity

great difference in torsional rigidity regularity between set and unset yarns. Such yarn treatments might, however, be expected to manifest themselves more clearly in differences in bending hysteresis. These effects are seen in the table below:-

Yarn Group	Mean Bending Hysteresis ($N.m \times 10^{-8}$)	Standard deviation	Mean CV% torsional rigidity	Standard deviation
Acrylic	12.72	4.31	10.81	3.47
Unset* wool	8.10	1.92	8.68	1.25
Top Dyed Wool	5.70	1.96	7.38	0.69
Autoclaved Wool	4.46	1.00	8.13	2.32
Package Dyed Wool	3.43	1.20	6.33	1.10

* Not set by autoclave steaming or package dyeing

Relationships between loop distortion and these values will be examined later as will the results of analysis of the dependent yarn variables in terms of the full range of processing and production variables.

Finally, bearing in mind its theoretical significance in the determining the three dimensional configuration of a loop[18], we should look at the ratio

$$\frac{\text{flexural rigidity}}{\text{torsional rigidity}}$$

This value was calculated for the full set of yarns (column 7, Figure 24), and its correlation with other dependant variables determined. Correlation at a significance level better than 0.1% was found against count regularity (0.694). The scattergram of the values of the two variables is shown in Figure 47. This plot shows, not suprisingly, that the points fall into two groups depending upon whether the yarns were spun with "high" or "low" irregularity. But within each of the two groups there also appears to be a positive correlation. Analysis of the two groups separately gave rise to the following data:-

	"Low" Irregularity (27 yarns)	"High" Irregularity (10 yarns)
Correlation Coefficient U% regularity:B/T	0.785	0.722
Significance level %	<0.01	<2.0

Closer examination of the "low" irregularity yarns, where there was an extremely significant level of correlation, showed an interesting further subdivision based on fibre type and diameter. Three groups, "fine" acrylic, "fine" wool and "coarse" wool were clearly distinguished. As might be expected, the three groups spun to a progressively more irregular yarn, although they were all nominally at a single "low" level. However, within each group, the range of U% was quite narrow, irrespective of other production or processing variables. It was also apparent that each group had a successively higher mean value of flexural/torsional rigidity. In other words, if fine wool is substituted for acrylic, or coarse wool is substituted for fine wool, then the bending stiffness increases more quickly than the torsional stiffness. Fibre type and diameter are already suspected to be important factors in terms of loop distortion. The suggestion from this plot is that their connection with loop distortion may be something more than simply the influence that these factors have on count regularity, particularly when one remembers, for instance, that a wool yarn still distorts more than an acrylic yarn even when both have the same count regularity. Further analysis may show the relative importance of the different variables dependent upon fibre type and diameter in terms of loop distortion.

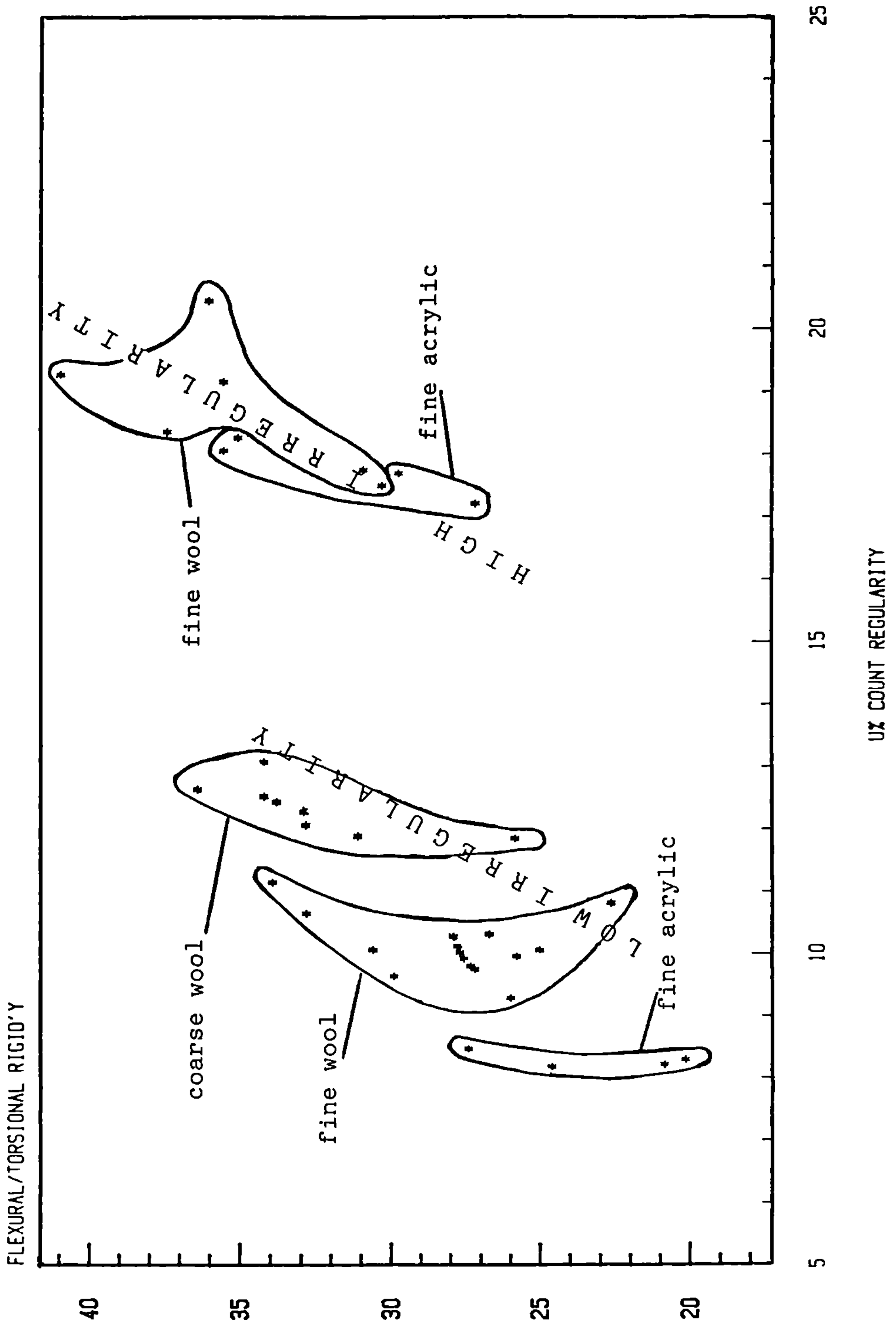


Figure 47 Correlation of Flexural/Torsional Rigidity with U% Count Regularity

6.4. LOOP DISTORTION ASSESSMENT VALUES

The procedure for assessing the thirty seven fabrics in terms of loop distortion was discussed in Section 5.8. and a summary of the row totals for each fabric tabulated in Figure 36. Analysis of the results tabulated in Figure 36 was facilitated by the use of the Interactive Software for Econometric Analysis (ISEA) computer programme package designed for the Hewlett-Packard HP3000 computer. The ISEA package was also used for other work such as rank correlation, regression analysis etc. where required in subsequent analysis.

The first stage of the loop distortion assessment analysis was:

(a) Convert the row totals to ranks (1-37), using mean values for tied ranks, for each of the nine judges.

(b) Sum the ranks for each sample to obtain a consensus rank sum.

(c) Sort all values in order of the consensus rank sum and print out the results.

However, before arriving at a consensus ranking for the fabrics it is necessary to examine the reliability, or consistency, of each individual judge and the degree of agreement which existed within the panel of judges.

The consistency of an individual judge may be determined by finding the proportion of contradictory judgements, or "inconsistent triads", in his complete assessment. A triad, a group of three assessed samples, has been judged inconsistently if scores are awarded in the form $A < B < C < A$. Referring to the example shown in Figure 35, it is seen that "B" was judged better than "U" (and hence scored 1 point), that "U" was judged better than "P" and "P" was judged better than "B". This represents an inconsistent triad. The Coefficient of Consistency of a judge is defined as

$$K = 1 - \frac{\text{actual number of inconsistent triads}}{\text{maximum possible number of inconsistent triads}}$$

It can be shown[100] that the maximum possible number of inconsistent triads is: $d_{max} = (n^3 - n)/24$ for an odd number of samples

or $d_{max} = (n^3 - 4n)/24$ for an even number of samples.

Where n is the number of samples.

The actual number of inconsistent triads is calculated from the row totals of the paired comparison table and is given by:

$$d = n(n - 1)(2n - 1)/12 - 1/2 \sum a_i^2$$

where a_i are the row totals.

The results for the nine judges were as follows:-

Judge Code	No. of Inconsistent Triads*	Coefficient of Consistency
1	10	0.995
2	166	0.921
3	21	0.990
4	28	0.987
5	18	0.992
6	41	0.981
7	29	0.986
8	70	0.967
9	103	0.951

* Maximum possible number of inconsistent triads is 2109

Over half the judges were, therefore, more than 98% consistent. None of the judges assessments was eliminated through being considered too unreliable for inclusion in the analysis.

The credibility of the final consensus rank depends not only upon the consistency of the individual judges but upon the degree of agreement between them as a group. The Coefficient of Agreement, A, is a measure of how closely the judges concur. Taking a table such as that shown in Figure 35, a value may be written into each cell, related to each paired comparison, equal to the number of judges having that preference. For instance, if seven of the nine judges prefered sample "A" to sample "B", then the first cell on the top row would contain the value 7. For n samples there are nC2 = n(n - 1)/2 paired comparisons and therefore, if there was perfect agreement between m judges, nC2 cells would contain the value 0 and nC2 cells the value m. In practice we are likely to find that there is not complete agreement for a preference, and that only j judges are in agreement. Between these j judges we have jC2 pairs of agreement. We can add up the number of pairs of agreement for all nC2 paired comparisons to get the total number of agreements between pairs of judges for the complete assessment:

$$J = \sum jC2$$

The maximum possible number of agreements between the judges is given by :

$$K = mC2.nC2$$

The Coefficient of Agreement is then defined as:

$$A = 2J/K - 1$$

which takes its maximum value of 1 for total agreement. In the present assessment the maximum possible number of agreements is:

$$((37^2 - 37)(9^2 - 9)/4 = 23976$$

and the total number of actual agreements was as follows:

number of judges indicating a preference	jC2	Total nuber of cells with this number of agreeing judges	Total number of agreeing pairs
9	36	486	17496
8	28	79	2212
7	21	45	945
6	15	33	495
5	10	23	230
4	6	23	138
3	3	33	99
2	1	45	45
1	0	79	0
0	0	486	0
		TOTAL 1332*	21660

* i.e. $37^2 - 37$

Hence the Coefficient of Agreement is given by:

$$A = 43320/23976 - 1 = 0.81$$

The significance of this value is obtained by considering what the distribution would have been if the preferences had been allotted at random. For large values of n and j the χ^2distribution is adequate. We define χ^2 and ν (degrees of freedom) in the following terms[100]:

$$\chi^2 = \frac{4}{j - 2}\left\{ J - (nC2)(jC2).\frac{(j - 3)}{j - 2}\right\}$$

$$\nu = (nC2)(j^2 - j)/(j - 2)^2$$

so, for j=9, n=37 we have

$$\chi^2 = 6505 \quad \text{and} \quad \nu = 978.6$$

Published tables of χ do not extend to 978.6 degrees of freedom. However, $\sqrt{2\chi^2}$ is distributed about a mean of $\sqrt{2\nu -1}$ with unit standard deviation. In this case the mean is 44.2 with a value of $\sqrt{2\chi^2}$ of 114.06. The difference, of about 70 standard errors, is clearly of extremely high significance and we can be in no doubt that the judges preferences were in close accord.

Figure 48 gives the ranked results, the yarn samples being listed in order from most(1) to least(37) loop distortion according to the rank sums shown in the last column of the table. The next stage is to consider the significance of the consensus rank sums. For instance, samples 2 and 34 have rank sums of 194 and 194.5 respectively. Is there any real difference in the loop distortion of these samples? The procedure used was based upon tables originally devised by Kramer[101] and subsequently revised and expanded [102, 103].

Essentially, the method tests the probability of a particular rank sum deviating from the mean value in a set of ranked data. Tables are published for probabilities of 0.05 and 0.01. For a particular number of samples and replicates (judges) two numerical ranks are given. Only rank sums falling outside these ranges can be considered to be significantly different from the mean. The first, narrower, range of values applies when the full set of values is treated equally, the intention being to determine whether any of the values is significantly different to the rest. The second, wider, range applies when one particular value is set aside first, with the intention of finding out, for instance, whether a particular treatment has a significant effect on the ranked parameter. In the present work the full set of data is analysed without prejudice in favour of any particular value, so the narrower range of values is used. The published tables only go up to a maximum of twenty samples. It was, therefore, necessary to extrapolate the values up to thirty seven samples.

SAMPLE CODE	JUDGE CODE 1	2	3	4	5	6	7	8	9	RANK SUM
29.000	4.000	1.000	1.000	4.000	1.000	2.000	3.000	1.000	1.000	18.00
11.000	1.000	8.000	3.000	2.000	5.000	1.000	1.500	2.000	2.000	25.50
12.000	2.000	4.500	2.000	1.000	6.000	5.500	4.000	3.500	3.000	31.50
28.000	3.000	2.500	7.000	8.500	2.000	3.000	1.500	3.500	6.000	37.00
33.000	5.000	2.500	10.500	8.500	3.000	5.500	6.000	5.000	4.000	50.00
7.000	8.500	11.000	4.000	6.500	7.000	5.500	7.500	6.000	6.000	62.00
8.000	8.500	8.000	7.000	6.500	10.000	8.000	5.000	7.500	6.000	66.50
32.000	6.000	4.500	10.500	10.000	4.000	5.500	9.500	10.000	8.500	68.50
16.000	10.500	10.000	5.000	3.000	10.000	10.000	9.500	7.500	10.000	75.50
6.000	10.500	12.000	7.000	5.000	8.000	9.000	7.500	9.000	8.500	76.50
37.000	7.000	6.000	15.000	11.000	10.000	11.500	12.500	14.500	11.500	99.00
15.000	12.000	14.500	9.000	12.000	14.000	11.500	11.000	11.000	13.500	108.50
36.000	13.000	8.000	16.500	14.500	12.000	16.500	12.500	14.500	15.500	123.00
10.000	14.000	18.500	13.000	13.000	13.000	13.500	15.000	12.000	11.500	123.50
5.000	15.000	14.500	12.000	14.500	15.000	15.000	15.000	17.000	13.500	131.50
17.000	16.000	13.000	14.000	16.500	16.000	13.500	17.000	13.000	15.500	134.50
18.000	17.500	18.500	16.500	16.500	17.000	16.500	15.000	16.000	18.000	151.50
9.000	21.000	23.500	18.000	18.500	18.000	19.500	18.000	18.000	19.000	173.50
4.000	22.000	16.000	22.500	20.000	19.500	18.000	20.000	21.000	17.000	176.00
35.000	17.500	21.500	19.000	18.500	19.500	22.500	20.000	21.000	20.500	180.00
2.000	19.000	18.500	20.500	23.500	22.000	22.500	23.000	21.000	24.000	194.00
34.000	20.000	21.500	22.500	22.000	22.000	27.000	20.000	19.000	20.500	194.50
13.000	24.500	27.000	20.500	21.000	22.000	19.500	26.000	26.000	22.500	209.00
22.000	24.500	25.500	24.000	27.000	30.000	26.000	22.000	24.500	28.000	231.50
14.000	28.000	28.500	27.000	23.500	25.000	24.500	30.000	24.500	22.500	233.50
23.000	23.000	30.500	25.000	26.000	28.500	28.000	25.000	23.000	25.500	234.50
31.000	26.000	28.500	32.000	30.000	24.000	21.000	24.000	28.000	28.000	241.50
30.000	30.000	23.500	31.000	31.000	26.500	31.000	27.000	28.000	25.500	253.50
19.000	28.000	30.500	27.000	25.000	26.500	29.000	28.000	30.000	30.000	254.00
3.000	28.000	32.000	27.000	28.000	28.500	24.500	32.000	28.000	28.000	256.00
27.000	34.000	18.500	30.000	33.000	32.000	32.000	30.000	32.000	31.000	272.50
1.000	31.000	33.000	29.000	29.000	32.000	30.000	30.000	35.000	33.000	282.00
26.000	35.000	25.500	33.000	32.000	32.000	33.000	33.000	31.000	33.000	287.50
25.000	33.000	36.000	35.000	36.000	34.000	34.000	34.000	34.000	33.000	309.00
24.000	32.000	34.000	36.000	35.000	35.000	36.000	35.000	33.000	35.000	311.00
21.000	36.000	37.000	37.000	34.000	36.000	35.000	36.000	37.000	36.000	324.00
20.000	37.000	35.000	34.000	37.000	37.000	37.000	37.000	36.000	37.000	327.00

Figure 48 Samples in Order of Rank Sum (Most to Least Loop Distortion) and Individual Judge Rankings

From Figures 49 and 50 it is seen that the first ten and the last seven loop distortion rank sums are significantly different to the mean value and merit reranking into separate groups. Likewise, the central group of twenty samples is also reranked. Each of the three groups was reranked in isolation using the appropriate original values of the row totals of the nine judges. By carrying out this procedure on the first group of ten samples, for instance, we arrive at the rank sums 18 to 73.5 shown in the third column of Figure 50. By referring to Figure 49 for ten samples we see that values below 28 and above 71 are beyond the range where we could consider that their difference from the group mean was insignificant. Hence a further subdivision is carried out, indicated by the broken lines above 31.5 and below 67.5. In the fourth column, these further three groups are again treated in isolation. The first of these groups consists of only two samples which yield rank sums of 13 and 14 respectively. From Figure 49 we see that any values from 11 to 15 inclusive are not significantly different. Hence the two samples cannot be statistically distinguished. Figure 50 demonstrates the analysis of the whole original group of thirty seven samples step by step to an ultimate division into fourteen significantly different levels of loop distortion. The final list of significant ranks is given in Figure 51, with mean values taken for tied ranks.

Number of Samples	Lowest Insignificant Rank Sum	Highest Insignificant Rank Sum
2	11	16
3	13	23
4	15	30
5	17	37
6	19	44
7	22	50
8	24	57
9	26	64
10	28	71
11	30	78
12	32	85
13	34	92
14	36	99
15	38	106
16	40	113
17	42	120
18	44	127
19	45	135
20	47	142
21	49	148
22	51	155
23	53	162
24	55	169
25	57	176
26	59	183
27	61	190
28	64	197
29	66	204
30	68	211
31	70	218
32	72	225
33	74	232
34	76	239
35	78	246
36	80	253
37	82	260

Figure 49. Rank Totals Required for Significance at the 5% Level Using Nine Judges

SAMPLE CODE	RANK SUMS				
29	18	18	13		
11	25.5	24	14		
12	31.5	31.5	18.5		
28	37	37	20	15.5	
33	50	49	29	22.5	15.5
7	62	59	37.5	29	23.5
8	66.5	63.5	40.5	31.5	23.5
32	68.5	67.5	43.5	36.5	27.5
16	75.5	72	13.5		
6	76.5	73.5	13.5		
37	99	19	19		
15	108.5	20.5	20.5		
36	123	31	36		
10	123.5	33	30.5		
5	131.5	41.5	40		
17	134.5	44.5	43		
18	151.5	61	12		
9	173.5	82.5	28	19	
4	176	86	33	26	
35	180	89	34	25.5	
2	194	103.5	49	38	
34	194.5	103.5	47.5	36.5	
13	209	117	58	44	
22	231.5	140	71	13.5	
14	233.5	140.5	72.5	13.5	
23	234.5	142.5	19.5		
31	241.5	146.5	22.5		
30	253.5	158.5	30		
19	254	162	31		
3	256	162	32		
27	272.5	18.5	14		
1	282	18.5	13		
26	287	24	11.5		
25	309	39	20.5	13	
24	311	41	22	14	
21	324	54	12		
20	327	57	15		

Figure 50. Division of Samples into Groups with Loop Distortion Significantly Different at the 5% Level Using Rank Sums

Sample Codes	Consensus Rank Significance at 5% Level.
29, 11	1.5
12,	3
28	4
33, 7, 8, 32	6.5
16, 6	9.5
37, 15, 36, 10, 5, 17	13.5
18	17
9, 4, 35, 2, 34, 13	20.5
22, 14	24.5
23, 31, 30, 19, 3	28
27, 1	31.5
26	33
25, 24	34.5
21, 20	36.5

Figure 51. The Significant Levels of Loop Distortion Consensus Ranks. Higher ranks indicate lower loop distortion.

6.5. THE RELATIONSHIP BETWEEN INDEPENDENT PRODUCTION AND PROCESS VARIABLES AND LOOP DISTORTION RANKED VALUES

6.5.1. Introduction

Before beginning an analysis of the results we should first consider the applicability of ranked, rather than absolute, values as a measure of the effect in the framework of a factorial design. Although it is usual to calculate the estimates of treatment combinations using actual measured values of the effect, Duckworth[98] has shown that ranked data, transformed if necessary to homogenize the variance throughout the range of samples, "can be analysed with confidence by the usual technique". No assumptions concerning linearity, or any other function, are made about the rank values with respect to the "true" degree of loop distortion; merely that if two samples have different rank values, then that with the higher value has less loop distortion. We would not be justified in saying by how much a particular treatment is better or worse than another. The individual experiments are self-contained and estimates obtained in one design cannot be related to those in another. The particular samples chosen for each design from the total group of thirty seven must be re-ranked. In order to obtain an estimate of the error (variance within treatments) it is necessary to consider the rankings of all judges individually, rather than the consensus ranks listed in Figure 51. The consensus rankings for all samples together are used later in Spearman Rank Correlation with the measured yarn variables.

6.5.2. Design Matrices 1-4

These four half factorial designs are shown in Figure 18. Figures 52-55 summarise the analyses of the experiments in terms of the estimates of loop distortion rankings. The procedure used was as follows:-

(a) The individual ranks, based on the paired comparison row totals for the nine judges, were tabulated for the particular set of eight samples in the design. The range (maximum-minimum rank) for each sample was calculated to ensure that there was no apparent correlation between the variance and the rank total. A homogenizing transformation of the rank totals would be required before calculation of the effect estimates if the variance was found to be a function of the rank.

(b) The rank totals were calculated and arranged in order along with their respective range values. Any trend in the value of the range with the rank order would be apparent. The rank totals were divided into groups significantly different at the 5% level using the method previously described. The significant rank totals allocated were the mean values for the samples within each group, before correction. For instance, in Figure 52, we see that there is no significant difference between samples 7,8 and 6. Therefore the significant rank total allocated was 18, the mean of the rank totals for the three individual samples.

Sample Code	JUDGE CODE									Range	Total
	1	2	3	4	5	6	7	8	9		
1	8	8	8	8	8	8	8	7	8	1	71
2	5	6	5	6	6	6	6	5.5	6	1	51.5
3	7	7	7	7	7	7	7	8	7	1	64
4	6	5	6	5	5	5	5	5.5	5	1	47.5
5	4	4	4	4	4	4	4	4	4	0	36
6	3	3	2.5	1	2	3	2.5	3	3	2	23
7	1.5	2	1	2.5	1	1	2.5	1	1.5	1.5	14
8	1.5	1	2.5	2.5	3	2	1	2	1.5	2	17

Sample Code	7	8	6	5	4	2	3	1
Rank Total	14	17	23	36	47.5	51.5	64	71
Range	1.5	2	2	0	1	1	1	1
Significant Rank Total	18			36	49.5		64	71

Effect	Estimate	Sum of Squares	Degrees of Freedom	Mean Square
D(TC)	-144	288.00	1	288.00
T(DC)	-25	8.68	1	8.68
C(TD)	11	1.68	1	1.68
A(DATC)	-54	40.50	1	40.50
DA(ATC)	18	4.50	1	4.50
TA(DAC)	25	8.68	1	8.68
CA(DAT)	-11	1.68	1	1.68
Source of Variation	(Between treatments	353.72	7	
	(Within treatments	21.28	64	0.3325
	TOTAL	375.00	71	

Key
D Fibre Diameter
T Top Dye
C Top Chlorination
A Autoclave Set

Figure 52 Design 1: Derivation of Estimates and Analysis of Variance

Sample Code	JUDGE CODE 1	2	3	4	5	6	7	8	9	Range	Total
1	8	8	8	8	8	8	8	8	8	0	72
2	6	5.5	7	7	7	7	7	7	7	1.5	60.5
9	7	7	6	6	6	6	6	6	6	1	56
10	4	5.5	5	4	4	4	4.5	4	4	1.5	39
5	5	4	4	5	5	5	4.5	5	5	1	42.5
6	3	3	3	3	3	3	3	3	3	0	27
11	1	2	2	2	1	1	1	1	1	1	12
12	2	1	1	1	2	2	2	2	2	1	15

Sample Code	11	12	6	10	5	9	2	1
Rank Total	12	15	27	39	42.5	56	60.5	72
Range	1	1	0	1.5	1	1	1.5	0
Significant Rank Total	13.5		27	40.75		56	60.5	72

Effect	Estimate	Sum of Squares	Degrees of Freedom	Mean Square
DC(PC)	-134.50	251.25	1	251.25
P(DC)	- 76.50	82.28	1	81.28
C(PD)	5.00	0.35	1	0.35
A(DAPC)	- 40.50	22.78	1	22.78
DA(APC)	7.00	0.68	1	0.68
PA(DAC)	10.00	1.39	1	1.39
CA(DAP)	- 17.50	4.25	1	4.25
Source of Variation	(Between treatments	361.98	7	
	(Within treatments	15.02	64	0.2347
	TOTAL	377.00	71	

Key D Fibre Diameter; P Package Dye; C Top Chlorination; A Autoclave Set

Figure 53 Design 2: Derivation of Estimates and Analysis of Variance

Sample Code	JUDGE CODE									Range	Total
	1	2	3	4	5	6	7	8	9		
1	8	8	8	8	8	8	7.5	8	8	0.5	71.5
2	5	5	5.5	6.5	5.5	6	5	5	7	2	50.5
13	6	6	5.5	5	5.5	5	6	7	5.5	2	51.5
14	7	7	7	6.5	7	7	7.5	6	5.5	2	60.5
15	4	4	4	4	4	4	4	4	4	0	36
16	3	2	2	1	2.5	3	3	2.5	3	2	22
7	1.5	3	1	2.5	1	1	2	1	1.5	2	14.5
8	1.5	1	3	2.5	2.5	2	1	2.5	1.5	2	17.5

Sample Code	7	8	16	15	2	13	14	1
Rank Total	14.5	17.5	22	36	50.5	51.5	60.5	71.5
Range	2	2	2	0	2	2	2	0.5
Significant Rank Total	18			36	51		60.5	71.5

Effect	Estimate	Sum of Squares	Degrees of Freedom	Mean Square
D(TH)	-144	288.50	1	288.00
T(DH)	- 29	11.68	1	11.68
H(TD)	5	0.35	1	0.35
A(DATH)	- 29	11.68	1	11.68
DA(ATH)	- 5	0.35	1	0.35
TA(DAH)	48	32.00	1	32.00
HA(DAT)	12	2.00	1	2.00
Source of Variation	(Between treatments	346.06	7	
	(Within treatments	26.94	64	0.4209
	TOTAL	373.00	71	

Key D Fibre Diameter H Hercosett Treatment
T Top Dye A Autoclave Set

Figure 54 Design 3: Derivation of Estimates and Analysis of Variance

Sample Code	JUDGE CODE									Range	Total
	1	2	3	4	5	6	7	8	9		
1	8	8	8	8	8	8	8	8	8	0	72
2	7	6.5	7	7	7	7	7	7	7	0.5	62.5
17	5	4	5	5.5	5	5	6	5	5	2	45.5
18	6	6.5	6	5.5	6	6	5	6	6	1.5	53
15	4	5	4	4	4	4	4	4	4	1	37
16	3	3	3	3	3	3	3	3	3	0	27
11	1	2	2	2	1	1	1	1	1	1	12
12	2	1	1	1	2	2	2	2	2	1	15

Sample Code	11	12	16	15	17	18	2	1
Rank Total	12	15	27	37	45.5	53	62.5	72
Range	1	1	0	1	2	1.5	0.5	0
Significant Rank Total	13.5		27	37	45.5	53	62.5	72

Effect	Estimate	Sum of Squares	Degrees of Freedom	Mean Square
D(PH)	-142	280.06	1	280.06
P(DH)	- 73	74.01	1	74.01
H(PD)	1	0.01	1	0.01
A(DAPH)	- 12	2.00	1	2.00
DA(APH)	- 8	0.89	1	0.89
PA(DAH)	27	10.13	1	10.13
HA(DAP)	7	0.68	1	0.68
Source of Variation	(Between treatments	367.78	7	
	(Within treatments	9.22	64	0.1441
	TOTAL	377.00	71	

Key D Fibre Diameter H Hercosett Treatment
P Package Dye A Autoclave Set

Figure 55 Design 4: Derivation of Estimates and Analysis of Variance

(c) The effect of the different treatments and interactions was calculated using the corrected rank totals by adding or subtracting the values as indicated in the original experimental design. As an example, we obtain an estimate of -144 for Fibre Diameter (D) in Design 1 as follows. Referring to Figure 18 we see that samples 1-4 have a low level (-) value of fibre diameter and samples 5-8 have a high level value (+). The estimate of the influence of fibre diameter on loop distortion is then obtained by signing the significant rank totals appropriately, thus:

$$-71-49.5-64-49.5+36+18+18+18 = -144$$

(d) Analysis of Variance was carried out using these effect estimates and the ranking given by the individual judges for the eight samples. "Between Treatments" variation was the total of the Sums of the Squares for the individual treatments and interactions. The Sums of the Squares were obtained by dividing the squares of the total effect estimates by 72 (i.e. 36 individual results contributing to each half of the effect multiplied by $(1^2 + 1^2)$ for linear components). The "Within Treatments", or variation due to error, component was obtained by subtracting the "Between Treatments" component from the total Sum of the Squares. The total Sum of the Squares was derived from the original individual rank values and is given by:

$$T = \sum x^2 - [(\sum x)^2/n]$$

for each rank value of x over n (72) observations. Further details of this procedure are described by Duckworth[98].

(e) By using the "Within Treatments" value of the mean square as an estimate of the error, the significance of the various treatments and interactions was assessed from F-Distribution tables for $\emptyset_1 = 1$ degree of freedom and $\emptyset_2 = 64$ degrees of freedom.

The first point of note regarding the analysis of the four experiments is that the range of individual rank values did not appear in any case to relate to the order of the rank totals. Because the variance appeared to be homogenous, or random, there was no need to transform the rank totals. The high degree of concordance between the judges has already been demonstrated. This fact, and the relatively large number of judges used, has resulted in a low value for the mean square of the "within treatment" variance. Consequently, the mean square values of the various treatments are relatively highly significant in most cases. Looking only at estimates with mean squares of a significance of 1% or better, the following relationships were derived, in order of magnitude of the mean squares:

Design 1

1. D (Fibre Diameter) - coarser wool fibres increase loop distortion.
2. A (Autoclave Setting) - setting increases loop distortion.
3. T (Top Dyeing) - top dyeing increases loop distortion.
3. TA (Top Dyeing/Autoclave) - interaction*.
4. DA (Fibre Diameter/Autoclave) - interaction*.

Design 2

1. D (Fibre Diameter) - coarser wool fibres increase loop distortion.
2. P (Package Dyeing) - package dyeing increases loop distortion.

3. A (Autoclave Setting) - setting increases loop distortion.

4. CA (Chlorination/Autoclave) - interaction*.

Design 3

1. D (Fibre Diameter) - coarser wool fibres increase loop distortion.

2. TA (Top Dyeing/Autoclave) - interaction*.

3. A (Autoclave Setting) - setting increases loop distortion.

3. T (Top Dyeing) - dyeing increases loop distortion.

Design 4

1. D (Fibre Diameter) - coarser wool fibres increase loop distortion.

2. P (Package Dyeing) - package dyeing increases loop distortion.

3. PA (Package Dyeing/Autoclave) - interaction*.

4. A (Autoclave Setting) - autoclave setting increases loop distortion.

* Note. At this stage we have merely noted that an interaction is apparently significant. The meaning of the interaction is discussed in more detail subsequently.

The following treatments were found to produce no significant effect on loop distortion:-

(a) Top chlorination

(b) Hercosett treatment

By examining the order of magnitude of the mean squares from all designs together, an overall picture can be appreciated:-

	Design 1	Design 2	Design 3	Design 4
Increasing ↑ Influence on Loop Distortion	D A T TA DA	D P A {CA}	D {TA} A T	D P PA A
Insignificant Effect	C	C	H	H

The insignificant interactions have been omitted from the diagram. The only anomalous result is the position of the interaction TA, which occurs <u>below</u> A in Design 1 but <u>above</u> A in Design 3. The relative positions of the interactions TA in Design 3 and CA in Design 2 cannot be exactly located relative to independent variables in other designs. For instance, although TA has a greater effect on loop distortion than A but less than D in Design 3, we cannot say whether its effect is greater or less than, for instance, P which also has an effect intermediate between A and D. This uncertainty is indicated in the table above by the wavy lines. "T" was included only in Designs 1 and 3, and "P" only in Designs 2 and 4. The rankings for all four designs were therefore consistent in terms of all the main effects and the ranks may be summarised thus:

Increasing ↑ Influence on Loop Distortion	D P A T
Insignificant	C, H

Hence, at this stage in the analysis, it is apparent that, for the levels of independent variables chosen, wool fibre diameter has the most important influence on loop distortion; the shrink resist treatments of chlorination or chlorine/Hercosett treatment have no significant influence; package dyeing leads to more loop distortion than top dyeing and autoclave setting causes loop distortion, but not as badly as package dyeing.

Turning again to the interactions, two were ranked above autoclaving: "TA" in Design 3 and "PA" in Design 4. These are both the experiments including Hercosett treatment. Remembering the anomally of the relative positions of the TA interactions in Designs 1 and 3, we could replace the interactions TA and PA in Designs 3 and 4 by their aliases. In both cases this is the single second order interaction DAH. Hence the revised ranking table would be:-

	Design 1	Design 2	Design 3	Design 4
Increasing ↑	D	D	D	D
Influence		P		P
on			DAH	DAH
Loop	A	A	A	A
Distortion	T TA	{ CA }	T	
	DA			
Insignificent Effect	C	C	H	H

The substitution of this interaction has a number of logical advantages - it avoids the anomaly with the findings from Design 1, it is feasible in that it involves possible chemical changes, which are commonly associated with interactive effects, and it involves only a single interaction above autoclaving, rather than two, which can be positioned relative to other main effects (between package dyeing and autoclaving). We may tabulate the loop distortion estimates from the two designs as follows:-

		Fine Diameter Unset	Fine Diameter Set	Coarse Diameter Unset	Coarse Diameter Set
Design 3	Untreated	71.5 ↖	51	18	18
	Hercosett Treated	51	↖ 60.5	36 ←	18
Design 4	Untreated	72 ⤡	62.5	13.5 ⤡	13.5
	Hercosett Treated	45.5	53	37	37

(Arrows indicate decreasing loop distortion)

The second order interaction is seen for both designs but most clearly for Design 4. The diagonal effects of decreasing loop distortion are reversed when the fibre diameter is changed.

6.5.3. Design Matrix 5

The method of analysis used here was very similar to that employed for the first four designs. Design 5, shown in Figure 19, includes five main effects, however, and requires sixteen treatment combinations for the half factorial design. Figure 56 shows the individual judges' ranks, rank totals and ranges. It will be seen that there is some tendency for the range to increase towards the middle of the ranks; these samples were apparently found to be a little more difficult to judge than the obviously "good" and "bad" ones at the ends of the rankings. In serious cases the individual ranks would be transformed by substituting $\sin^{-1}r$, where r is the rank proportion; for instance a rank of "4" would be transformed to $\sin^{-1}$ (4/16) = 14.5^{o} and the angular values would replace the ranks. It was felt, however, that the relatively low degree of bias in range magnitude towards the centre of the rankings did not justify the transformation since the error used in the untransformed data would only be small. Also, the range values are not symmetrical about the centre since values towards the higher ranks are greater than those at the lower end, so that even the transformed values would not be completely homogenous.

SAMPLE CODE	JUDGE CODE 1	2	3	4	5	6	7	8	9	RANGE	TOTAL
1	10	12	8	8	11	9	10.5	14	12	6	94.5
19	8	10.5	7	5	6.5	8	9	9	9	5.5	72.0
20	16	14	13	16	16	16	16	15	16	3	138
21	15	16	16	13	15	14	15	16	15	3	135
22	6	7.5	5	7	9	6	5	6	7.5	4	59
23	5	10.5	6	6	8	7	7	5	5.5	5.5	60
24	11	13	15	14	14	15	14	12	14	4	122
25	12	15	14	15	13	13	13	13	12	3	120
26	14	7.5	12	11	11	12	12	10	12	6.5	101.5
27	13	5	9	12	11	11	10.5	11	10	8	92.5
28	1	2.5	2	2.5	2	2	1	2	3	2	18
29	2	1	1	1	1	1	2	1	1	1	11
30	9	6	10	10	6.5	10	8	7.5	5.5	4.5	72.5
31	7	9	11	9	5	5	6	7.5	7.5	6	67
32	4	4	3.5	4	4	3.5	4	4	4	0.5	35
33	3	2.5	3.5	2.5	3	3.5	3	3	2	1.5	26

SAMPLE CODE	RANK TOTAL	RANGE	SIGNIFICANT RANK TOTAL
29	11	1	11
28	18	2	18
33	26	1.5	26
32	35	0.5	35
22	59	4	59.5
23	60	5.5	
31	67	6	70.5
19	72	5.5	
30	72.5	4.5	
27	92.5	8	93.5
1	94.5	6	
26	101.5	6.5	101.5
25	120	3	121
24	122	4	
21	135	3	136.5
20	138	3	

Figure 56 Design 5 - Loop Distortion Ranks and Ranges

Correction of the rank totals into groups significantly different at the 5% level resulted in differentiation of the samples into ten discrete levels of loop distortion.

Designs 1-4 included all the possible different combinations of variable levels, excluding the aliases. Interactions not shown are aliases of either main effects or those interactions listed along the top row. A total of fifteen different main effects and combinations are possible in Design 5, each consisting of an alias pair. These are listed in Figure 57. The estimates were calculated using a short computer programme, shown in Figure 58. This programme was used for all calculations of estimates, on all designs, both for ranked loop distortion values and dependent yarn variables discussed later. The "within treatments" error term was calculated from the individual ranks, as discussed previously.

At a significance level of 1% or higher, the following main effects and interactions were important:

1. F (Fibre Type) - wool distorts more than acrylic.
2. R (Count Regularity) - increasing irregularity increases loop distortion.
3. AS (Twist Level/Autoclave) - interaction.
4. S (Twist Level) - higher twist increases loop distortion.
5. FS (Fibre Type/Twist Level) - interaction.
6. RS (Count Regularity/Twist Level) - interaction.
7. M (Moisture Regain) - higher moisture regain increases loop distortion.

EFFECT	ESTIMATE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
F (RA)	478	1586.69	1	1586.69
R (AF)	-372	961.00	1	961.00
S (RSAF)	-98	66.69	1	66.69
A (RF)	-14	1.36	1	1.36
M (RAMF)	-47	15.34	1	15.34
FM (RAM)	31	6.67	1	6.67
RM (AFM)	-1	0.01	1	0.01
SM (RASMF)	29	5.84	1	5.84
AM (RFM)	15	1.56	1	1.56
RS (ASF)	54	20.25	1	20.25
SA (RSF)	100	69.44	1	69.44
FS RAS)	-72	36.00	1	36.00
RSM (AFSM)	-17	2.01	1	2.01
FSM (RASM)	-13	1.17	1	1.17
SAM (RSMF)	-33	7.56	1	7.56
SOURCE OF VARIATION: between treatments		2781.59	7	
within treatments		268.91	136	1.98
total		3050.50	143	

KEY

F fibre type
R count regularity
S twist level
A autoclave set
M moisture regain

Figure 57 Design 5 - Analysis of Variance of Loop Distortion Ranks

```
10 PRINT:PRINT:PRINT:PRINT:PRINT:PRINT
20 INPUT "HOW MANY EFFECTS AND INTERACTIONS";V
30 INPUT "HOW MANY TREATMENTS";T
40 PRINT:PRINT:PRINT:PRINT
50 DIM A(V,T)
60 FOR K=1 TO V
70 PRINT "EFFECT ";K:PRINT
80 FOR J= 1 TO T
90 PRINT "TREATMENT";J;
100 INPUT A(K,J)
110 NEXT J
120 PRINT
130 INPUT "              ALL CORRECT";Q$
140 IF Q$<>"Y" GOTO 80
150 NEXT K
160 LPRINT "MATRIX AS FOLLOWS:-":LPRINT:FOR K=1 TO V:LPRINT K;:NEXT K:LPRINT
170 PRINT "MATRIX AS FOLLOWS:-":PRINT:FOR K=1 TO V:PRINT K;:NEXT K:PRINT
180 PRINT:FOR J=1 TO T:FOR K=1 TO V:PRINT A(K,J);:NEXT K:PRINT:NEXT J:PRINT
190 LPRINT:FOR J=1 TO T:FOR K=1 TO V:LPRINT A(K,J);:NEXT K
200 LPRINT:NEXT J:LPRINT
210 DIM R(T)
220 INPUT "NAME OF RESPONSE";R$
230 PRINT
240 FOR J= 1 TO T
250 PRINT "TREATMENT";J;
260 INPUT R(J)
270 NEXT J
280 PRINT:PRINT:LPRINT:LPRINT:PRINT"          ";R$:LPRINT"          ";R$
290 PRINT
300 FOR K= 1 TO V
310 C=0
320 FOR J= 1 TO T
330 C=C+R(J)*A(K,J)
340 NEXT J
350 PRINT "ESTIMATE FOR VARIABLE ";K;"=";2*C/T
360 LPRINT "ESTIMATE FOR VARIABLE ";K;"=";2*C/T
370 NEXT K
380 INPUT "ANOTHER RESPONSE";Q$
390 PRINT:PRINT:PRINT:PRINT:PRINT:PRINT
400 IF Q$="Y" GOTO 220
```

```
HOW MANY EFFECTS AND INTERACTIONS? 3
HOW MANY TREATMENTS? 4



EFFECT  1

TREATMENT 1 ? 1
TREATMENT 2 ? 1
TREATMENT 3 ? -1
TREATMENT 4 ? -1

              ALL CORRECT? Y
EFFECT  2

TREATMENT 1 ? 1
TREATMENT 2 ? -1
TREATMENT 3 ? 1
TREATMENT 4 ? -1

              ALL CORRECT? Y
EFFECT  3

TREATMENT 1 ? -1
TREATMENT 2 ? 1
TREATMENT 3 ? 1
TREATMENT 4 ? -1

              ALL CORRECT? Y
MATRIX AS FOLLOWS:-

 1  2  3

 1  1 -1
 1 -1  1
-1  1  1
-1 -1 -1

NAME OF RESPONSE? LOOP DISTORTION

TREATMENT 1 ? 14.6
TREATMENT 2 ? 13.1
TREATMENT 3 ? 8.2
TREATMENT 4 ? 5.8

          LOOP DISTORTION

ESTIMATE FOR VARIABLE  1 = 6.85
ESTIMATE FOR VARIABLE  2 = 1.95
ESTIMATE FOR VARIABLE  3 = .45
ANOTHER RESPONSE? N
```

Figure 58 Above: Programme for the Calculation of Estimates of Responses in Factorially Designed Experiments.

Right: A Simple Example

Fibre type and regularity were expected to be important in terms of loop distortion, and it is not surprising to find these two main effects at the top of the list. The absence of autoclave setting is notable, in view of the results from the previous four experimental designs. Examination of the rank totals in terms of the autoclave set samples shows that, in fact, the lowest four places are all occupied by autoclave set wool samples. However, the autoclave set acrylic samples occupy the top four places. The two groups have, therefore, apparently cancelled each other out; there is an interaction between fibre type and autoclave setting:

MEAN SIGNIFICANT RANK TOTALS

	Wool only	Acrylic only	Both fibres
Unset	70.75	84	77.375
Autoclave set	22.5	128.75	75.625

Unfortunately, this is not shown in the Analysis of Variance table because the effect AF is the alias of the main effect "count regularity" (R). This effect is the second most important listed. Clearly, the design is weak from this aspect; we cannot be certain which part of the variance is attributable to the count regularity and which part to the interaction between fibre type and autoclave setting. Experimental Design 6 may clear up some uncertainty since here regularity is included with autoclave setting on wool only samples.

Twist level appears either as a main effect or a first order interaction in four of the seven significant treatments. The aliases are all interactions between three, four or five main effects.

Higher twist is seen to increase loop distortion:

	MEAN SIGNIFICANT RANK TOTAL	
	low twist	high twist
	82.625	70.375

However, an examination of the interaction AS shows that this conclusion may be misleading:

	MEAN SIGNIFICANT RANK TOTAL	
	low twist	high twist
Unset	89.75	65
Autoclave set	75.5	75.75

Hence the effect of twist is seen to be real only for unset yarns. However, further differentiation into fibre type is required for the true situation to be appreciated:

	MEAN SIGNIFICANT RANK TOTAL			
	low twist		high twist	
	wool only	acrylic only	wool only	acrylic only
Unset	82	97.5	59.5	70.5
Autoclave set	14.5	136.5	30.5	121

So, for both low and high twist yarns, the relationship is similar to that shown in the AF table described earlier; setting apparently increases distortion in wool yarns and improves it in acrylic yarns. There is some evidence for a second order interaction ASF. Both low twist and high twist acrylic yarns have a similar response to setting. However, in the case of wool, the deterioration is much more marked for low twist yarns so that, whereas they were better than their high twist counterparts in the unset state, they were significantly worse after setting.

ASF is, in fact, aliased with RS which is also listed as being of significant importance. The problems of using a half factorial design when many interactions are possible is becoming apparent. Wool and acrylic fibres behave quite differently in their response to steam, application of torque, moisture regain etc., so that interactions can become quite complex if any of the other main effects also interact. A full factorial design would have been better when acrylic was introduced as an independent variable.

Nevertheless, if we disregard at this stage elements of uncertainty and concentrate on the main effects, we reach the following conclusion:

Increasing	↑	Fibre Type
Influence	│	Count Regularity + Autoclave/Fibre Type
on Loop	│	Twist Level
Distortion	│	Moisture Regain

6.5.4. Design Matrix 6

Design 6 (See Figure 19) is concerned only with fine fibre diameter wool. The new variable of twist method (ring or two-for-one twisting) is included. The results are summarised in Figure 59. There was a particularly high degree of agreement between the judges in this group and this is seen in the fact that every rank total is significantly different from every other at the 5% level. The mean

SAMPLE CODE	JUDGE CODE 1	2	3	4	5	6	7	8	9	RANGE	TOTAL
1	8	8	8	8	8	8	8	8	8	0	72
34	6	5.5	6	6	6	7	5.5	5.5	5.5	1.5	52.5
22	7	7	7	7	7	6	7	7	7	1	62
35	5	5.5	5	5	5	5	5.5	6	5.5	1	47.5
36	4	4	4	4	4	4	3.5	3.5	4	0.5	35
28	1	1	1	1	1	1	1	1	1	0	9
37	3	3	3	3	3	3	3.5	3.5	3	0.5	28
32	2	2	2	2	2	2	2	2	2	0	18

SAMPLE CODE	28	32	37	36	35	34	22	1
RANK TOTAL	9	18	28	35	47.5	52.5	62	72
RANGE	0	0	0.5	0.5	1	1.5	1	0
SIG. RANK TOTAL	9	18	28	35	47.5	52.5	62	72

EFFECT	ESTIMATE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
R (AX)	-144	288.00	1	288.00
S (RAXS)	-13	2.35	1	2.35
A (RX)	-70	68.06	1	68.06
X (RA)	2	0.06	1	0.06
RS (AXS)	9	1.13	1	1.13
AS (RXS)	21	6.13	1	6.13
XS (RAS)	-11	1.68	1	1.68
SOURCE OF VAR'N	between t'ments	367.41	7	
	within t'ments	8.09	64	0.1264
	total	375.50	71	

KEY

R Count regularity
S Twist level
A Autoclave set
X Twist method

Figure 59 Design 6 : Derivation of Estimates and Analysis of Variance range is low, only 0.5, but a relationship between rank level and range can be seen, with a maximum about two-thirds of the way along the placings. A transformation could be applied to the individual ranks to homogenise the ranges, but since the maximum range is only 1.5 this is hardly justified.

Applying the values for the mean squares in the Analysis of Variance table to F-distribution tables, all treatments are shown to be significant at the 1% level except the method of twisting. In order of importance, the treatments are:

1. R (Regularity) - loop distortion increases with irregularity.
2. A (Autoclave Setting) - setting increases loop distortion.
3. AS (Autoclave/Twist Level) - interaction
4. S (Twist Level) - loop distortion increases with twist.
5. XS (Twist Method/Twist Level) - interaction.
6. RS (Regularity/Twist Level) - interaction.

Regularity (R) is aliassed with AX. The likelihood of this interaction being significant is minimal; there is no logical reason why autoclave setting should interact with a purely mechanical variable such as the choice of twisting method. Interactions are the result of an effect which requires two (or more) components to be operable, such as a chemical reaction. This is seen in many of the significant interactions encountered so far, where one component might be a particular material (e.g. acrylic fibre, shrink resist resin, etc.) and the other a treatment upon it (e.g. steam setting, dyeing treatment, etc.) which may bring about a chemical change within the material. Rejecting the interaction AX helps to clarify the results from the previous design where R was aliassed with an interaction which was likely to be important. We can now be fairly certain that count irregularity is a major factor in loop distortion in wool yarns independent of irregularity related to fibre diameter.

Autoclave setting is again found to be a prime factor when only wool yarns are considered. The autoclave/twist level interaction appeared in Design 5 as the most important factor after fabric type and regularity and again it appears, this time in the third position. The mean significant rank totals were as follows (sample codes in brackets):

	MEAN SIGNIFICANT RANK TOTAL	
	Low Twist	High Twist
Unset	53.5 (1,36)	45 (22,37)
Autoclave set	30.75 (28,34)	32.75 (32,35)

Again, we see that lower twist wool yarns appear to be more susceptible to the detrimental effects of steam setting than higher twist yarns. In the unset state they were significantly better than high twist yarns; after setting the position was reversed. The trends above are similar to those of the wool yarns already described from Design 5 (it should be mentioned that four of the samples are present in both designs):

	MEAN SIGNIFICANT RANK TOTAL	
	Low Twist	High Twist
Unset	82 (1,19)	59.5 (22,23)
Autoclave set	14.5 (28,29)	30.5 (32,33)

The mechanics of the interaction may become clearer when it is examined in terms of estimates of dependent yarn parameters such as rigidity.

High twist as a main effect has a lesser, but significant role (its alias RAXS can be ignored). As in Design 5, its importance as a factor influencing loop disortion follows that of the interation AS. Finally we have two interactions with twist level which, although just significant at the 1% level, are probably of no great importance in practical terms.

6.5.5. Summary

Figure 60 is a compilation of the results from the six experiments and indicates the overall relative importance of the independent production and processing variables.

Although the table only applies to the particular levels or values chosen for the six designs it puts into relative perspective the various yarn production parameters and highlights areas of particular concern. For all-wool yarns, fibre diameter is clearly a very important factor, but package dyeing is also a serious cause of distortion and would warrant more detailed investigation, particularly in view of the modern trend towards dyeing at this stage.

Autoclave setting consistently produced increased loop distortion,

INCREASING INFLUENCE ON LOOP DISTORTION →

DESIGN 2	DESIGN 1	DESIGN 3	DESIGN 4	DESIGN 6	DESIGN 5
-D	-D	-D	-D		
-P			-P		+F
		-[DAH]	-[DAH]	-R	-R
-A	-A	-A	-A	-A	+[AF?]
-CA	-T, +[TA]	-T		+[AS]	+[AS]
	+[DA]			-S	-S
				-[XS]	
				+[RS]	+[RS]
					-M
	1% SIGNIFICANCE LEVEL				
C	C	H	H		

Notes

a) Horizontal comparisons may only be made when they are not separated by a bold line. E.g. -[XS] is more important than -M, but no conclusions can be drawn regarding the relative importance of -T and -S.

b) A key to the effect codes is given in Figures 52-55, 57 and 59.

c) A minus sign before a code letter indicates that the low level of the variable or interaction produces less loop distortion, a plus sign the reverse.

Figure 60 Order of Influence of Main Effects and Interactions on Loop Distortion though less than package dyeing. The five most important main effects are autoclave setting, package dyeing, fibre type, yarn regularity and fibre diameter. The first two are linked in that they both have the effect of setting the yarn on the package and the last two are related since fibre diameter influences regularity (although fibre diameter probably influences loop distortion by other mechanisms as well). Acrylic behaves quite differently to wool in the presence of heat and moisture; any physical changes which occur do not apparently cause loop distortion during subsequent knitting to anywhere like the same extent as with wool. Moisture regain was very low in the order of factors influencing loop distortion (although if the assessments had been carried out before full relaxation it would probably have rated more highly).

Also of interest in the table are main effects which do not significantly influence loop distortion. There was no evidence to suggest that 2-for-1 twisting causes more loop distortion than ring twisting. Chlorination and chlorine/Hercosett treatment seem not to affect loop distortion to a significant extent although there is a suggestion that they could interact with other variables if the yarns are autoclave set. Of particular interest is the hypothetical interaction between autoclave setting, Hercosett treatment and fibre diameter which could have significant commercial implications. This is another area which may be worth studying in more detail.

6.6. THE RELATIONSHIP BETWEEN DEPENDENT YARN VARIABLES AND LOOP DISTORTION RANKED VALUES

For these correlations there is no longer the restriction of a number of small factorial designs; all thirty seven samples may be compared as a single group. The consensus rank totals are those significantly different at the 5% level, listed in Figure 51. These were correlated with with the following dependent yarn physical parameters:

- CV% two-fold twist
- U% two-fold count regularity
- Coefficient of friction
- Torsional rigidity
- CV% torsional rigidity
- Flexural rigidity
- Bending hysteresis
- Flexural rigidity/torsional rigidity

The values of these eight parameters were first ranked, prior to correlation with the loop distortion assessments using Spearman's method. Figure 61 lists the rankings of the measured values of the dependent yarn variables for all thirty-seven samples. From this complete set, smaller groups were extracted and ranked. The loop distortion ranks were recalculated for the smaller groups from the original row totals of the individual judges and differentiated into significantly different levels by the method previously described. This was equally necessary for the smaller groups as for the original full set. Even when only a few samples are ranked, if two or more

CODE	CV% TWST	FRICTION	U% COUNT	TORS RIG	CV% TORS	FLEX RIG	BEND HYS	FLX/TORS	LD RANK
29.000	32.500	34.500	36.000	1.000	35.500	4.000	18.000	37.000	1.50
11.000	15.500	2.500	21.000	29.500	3.000	30.000	14.500	23.000	1.50
12.000	26.000	8.500	24.000	28.000	2.000	34.000	9.000	27.000	3.00
28.000	32.500	22.500	34.000	5.000	30.000	19.000	12.000	36.000	4.00
8.000	15.500	22.500	23.000	31.000	9.000	35.000	14.500	26.000	6.50
7.000	20.500	22.500	22.000	29.500	20.000	33.000	29.000	24.500	6.50
32.000	36.500	22.500	29.000	10.000	1.000	14.000	8.000	20.000	6.50
33.000	36.500	34.500	31.000	3.000	22.000	3.000	16.000	22.000	6.50
16.000	22.000	32.000	20.000	32.000	24.000	26.000	6.500	7.000	9.50
6.000	27.000	22.500	26.000	26.000	25.500	36.000	19.000	35.000	9.50
15.000	18.500	22.500	25.000	27.000	33.000	31.500	25.000	29.500	13.50
17.000	6.000	1.000	8.000	15.000	4.000	10.000	4.000	12.000	13.50
37.000	28.000	32.000	35.000	16.500	28.000	25.000	31.000	32.500	13.50
5.000	25.000	22.500	27.000	34.000	18.000	37.000	33.000	29.500	13.50
36.000	31.000	22.500	37.000	6.000	23.000	21.500	24.000	34.000	13.50
10.000	13.000	14.000	15.000	7.000	15.000	8.000	3.000	17.000	13.50
18.000	14.000	8.500	12.500	16.500	7.000	6.500	2.000	5.000	17.00
13.000	5.000	22.500	7.000	19.500	12.000	15.000	20.000	10.500	20.50
2.000	18.500	22.500	9.000	11.500	21.000	9.000	11.000	14.000	20.50
4.000	23.000	22.500	11.000	18.000	14.000	13.000	5.000	15.000	20.50
34.000	12.000	22.500	6.000	9.000	27.000	12.000	13.000	19.000	20.50
9.000	9.000	8.500	16.000	8.000	5.000	5.000	1.000	9.000	20.50
35.000	20.500	22.500	5.000	14.000	16.000	6.500	10.000	8.000	20.50
14.000	24.000	32.000	12.500	13.000	6.000	16.500	6.500	21.000	24.50
22.000	10.500	22.500	10.000	21.000	10.000	11.000	28.000	6.000	24.50
30.000	34.500	8.500	30.000	35.000	34.000	31.500	37.000	18.000	28.00
31.000	34.500	8.500	28.000	33.000	35.500	29.000	35.000	10.500	28.00
23.000	10.500	37.000	18.000	4.000	29.000	1.000	22.000	3.000	28.00
19.000	7.500	36.000	19.000	2.000	31.500	2.000	21.000	28.000	28.00
3.000	17.000	22.500	14.000	19.500	8.000	16.500	17.000	16.000	28.00
27.000	29.500	8.500	33.000	22.000	25.500	27.000	34.000	31.000	31.50
1.000	7.500	22.500	17.000	11.500	19.000	20.000	23.000	24.500	31.50
26.000	29.500	8.500	32.000	23.000	31.500	28.000	36.000	32.500	33.00
25.000	1.500	8.500	3.000	37.000	17.000	23.000	26.000	1.000	34.50
24.000	1.500	8.500	2.000	36.000	13.000	24.000	27.000	2.000	34.50
21.000	3.500	2.500	4.000	24.000	37.000	21.500	30.000	13.000	36.50
20.000	3.500	8.500	1.000	25.000	11.000	18.000	32.000	4.000	36.50

Figure 61 Ranked Values of Dependent Yarn Variables

rank sums are close together in value we cannot necessarily assume that there is any significant difference between them. The smaller groups were:-

(a) All-wool only.

(b) All-acrylic only.

(c) "Low" regain wool only.

(d) "Low" regain, "fine" diameter wool only.

(e) "Low" regain "coarse" diameter wool only.

The significant ranks for the five groups are given in Figures 62-66. Wool and acrylic were separated primarily because of the different responses of the two fibres to processing treatments. It was felt that separate examination could reveal a difference in the cause of distortion for the two fibre types and show why wool is much more susceptible to distortion than acrylic. The high regain wools were then eliminated because regain is an independent variable of low importance in terms of loop distortion but does have an important bearing on the rigidity characteristics of the yarn at the time of knitting. It was felt that the inclusion of high regain yarns could mask any contribution that rigidity of the yarn in the finished fabric makes towards the development of distortion. Finally, the coarse wool yarns were separated from the fine wool yarns since fibre diameter is known to have an overriding influence and so, by removing it, the different mechanisms by which fibre diameter and other treatments affect distortion may be differentiated.

SAMPLE CODE	RANK SUM (9 JUDGES)	SIGNIFICANT RANK
29	18.0	1.5
11	25.5	1.5
12	31.5	3
28	37.0	4
33	50.0	6.5
7	62.0	6.5
8	66.5	6.5
32	68.5	6.5
16	75.5	9.5
6	76.5	9.5
37	99.0	13.5
15	108.5	13.5
36	123.0	13.5
10	123.0	13.5
5	131.5	13.5
17	134.5	13.5
18	151.0	17
9	172.0	20.5
4	176.0	20.5
35	178.0	20.5
2	192.5	20.5
34	192.5	20.5
13	205.0	20.5
22	224.5	25
14	224.5	25
23	226.0	25
19	240.5	27.5
3	242.5	27.5
1	259.5	29

Figure 62 Significant Loop Distortion Ranks for Wool-only Samples

SAMPLE CODE	RANK SUM (9 JUDGES)	SIGNIFICANT RANK
31	15.5	1.5
30	16.5	1.5
27	27.5	3
26	35.0	4
25	49.5	5.5
24	51.0	5.5
21	63.0	7.5
20	66.0	7.5

Figure 63 Significant Loop Distortion Ranks for Acrylic-only Samples

SAMPLE CODE	RANK SUM (9 JUDGES)	SIGNIFICANT RANK
11	18.5	1
12	22.0	2
28	28.0	3
7	46.5	5
8	51.5	5
32	51.5	5
16	60.5	7.5
6	60.5	7.5
37	81.0	11.5
15	91.5	11.5
36	105.0	11.5
10	105.0	11.5
5	113.5	11.5
17	116.5	11.5
18	133.0	15
9	154.0	18
4	158.0	18
35	160.0	18
2	174.5	18
34	174.5	18
13	184.0	21
22	199.5	22.5
14	200.5	22.5
3	212.0	24
1	223.5	25

Figure 64 Significant Loop Distortion Ranks for "Low Regain" Wool-only Samples

SAMPLE CODE	RANK SUM (9 JUDGES)	SIGNIFICANT RANK
28	11.0	1
32	25.0	2
37	42.0	4.5
36	52.0	4.5
10	49.0	4.5
17	55.0	4.5
18	68.5	7
9	89.0	10
35	97.5	10
4	99.0	10
2	108.5	10
34	111.0	10
13	124.5	13
22	136.0	14.5
14	140.0	14.5
3	151.5	16
1	168.5	17

Figure 65 Significant Loop Distortion Ranks for "Low Regain","Fine" Fibre Diameter Wool-only Samples

SAMPLE CODE	RANK SUM (9 JUDGES)	SIGNIFICANT RANK
11	10.5	1
12	16.5	2
7	29.5	3.5
8	34.0	3.5
6	48.5	5.5
16	48.0	5.5
15	61.0	7
5	76	8

Figure 66 Significant Loop Distortion ranks for "Coarse" Fibre Diameter Wool-only Samples

Figure 67 lists the Spearman rank correlation coefficients and their significance for the six groups of samples. Twist and count regularity were most often highly correlated with loop distortion. Because these two variables are themselves highly correlated one cannot always be certain which is active in the development of loop distortion; however it is interesting to note that in two of the groups where fibre diameter was kept constant ("acrylic" only and "low regain fine wool") that twist variation was more highly correlated with loop distortion than count variation.

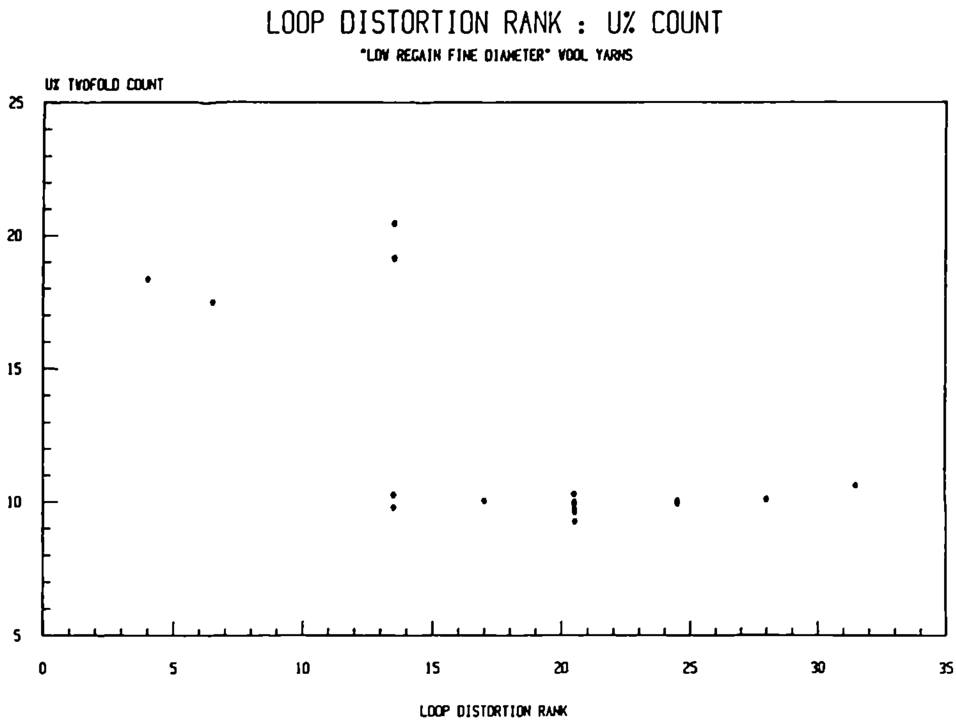
We have seen previously (e.g. Figures 44 and 45) that it is desirable to examine graphically relationships between significantly correlated variables. Figure 68 shows the loop distortion ranks of the "low regain fine wool" group in terms of twist and count regularity. The count regularity is seen to be virtually at two levels, as designed, with the highly irregular yarns occupying the "distorted" end of the rank range. Variations within each of the two groups is due to other processing factors. A similar picture is seen for twist regularity, although here the two levels of regularity are not quite so clear-cut. A very similar situation occurs with the acrylic yarns, which were also spun to two nominal levels of regularity.

The extraction of the coarse wools from the "low regain wool" group did not greatly alter the dependence of loop distortion on CV% twist but it <u>did</u> apparently reduce the dependence on count regularity. Therefore, coarser wools would seem to influence loop distortion at least partly through their effect on count regularity. In the

VARIABLE	ALL SAMPLES		WOOL ONLY		ACRYLIC ONLY		LOW REGAIN WOOL		LOW REGAIN FINE WOOL		LOW REGAIN COARSE WOOL	
	CORR. COEFF.	T	CORR. COEFF.	T	CORR. COEFF.	T	CORR. COEFF.	T	CORR. COEFF.	T	CORR. COEFF.	T
CV% TWIST	-0.464	3.10	-0.588	3.78	-0.887	4.70	-0.477	2.61	-0.487	2.16	0.333	0.87
U% COUNT	-0.484	3.27	-0.628	4.19	-0.732	2.63	-0.619	3.78	-0.382	1.60	0.595	1.81
FLEXURAL RIG.	-0.106	0.63	-0.378	2.12	-0.994	22.35	-0.520	2.92	0.013	0.05	0.345	0.90
TORSIONAL RIG.	0.178	1.07	-0.189	1.00	-0.042	0.10	-0.281	1.40	0.524	2.38	0.190	0.48
FLEX/TORS RIG.	-0.472	3.17	-0.473	2.79	-0.470	1.31	-0.474	2.58	-0.296	1.20	0.530	1.53
BENDING HYST.	0.464	3.10	0.069	0.36	-0.744	2.73	-0.001	0.01	0.237	0.95	0.524	1.51
CV% TORS RIG.	0.197	1.19	0.013	0.07	-0.423	1.14	0.006	0.03	-0.143	0.56	0.714	2.50
COEFF. FRICT.	-0.211	1.28	0.248	1.33	-0.077	0.19	0.323	1.64	0.329	1.35	0.655	2.12
T-VALUE FOR 5% SIGNIF'NCE	-	1.96	-	2.05	-	2.45	-	2.07	-	2.13	-	2.45
T-VALUE FOR 1% SIGNIF'NCE	-	2.58	-	2.77	-	3.71	-	2.81	-	2.95	-	3.71

KEY · SIGNIFICANCE AT 1% LEVEL   SIGNIFICANCE AT 5% LEVEL

Figure 67 Rank Correlation Between Loop Distortion Assessment Values and Dependent Yarn Physical Parameters



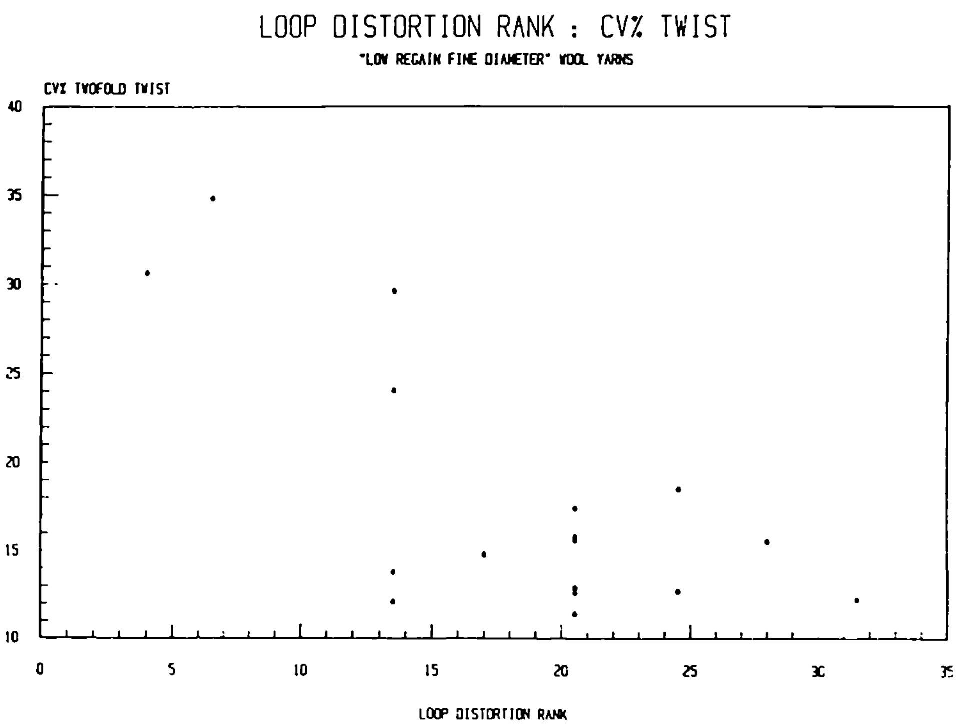


Figure 68 Relationship Between Loop Distortion and Count and Twist Regularity

"coarse wools" group neither twist nor count regularity appeared significant according to the rank correlation coefficients. None of these yarns were spun intentionally irregularly and so the range of irregularity was low in comparison to the fine wool yarns which included samples of abnormally high irregularity.

Flexural rigidity appeared to be another important factor for both wool and acrylic. For acrylic, the bending stiffness of the yarn appears to be the most important parameter determining the development of loop distortion. It was also very important for "low" regain wools; however, when the fibre diameter is fixed, as in the "low regain fine wools" group, bending stiffness is of lesser importance. Consequently, we might assume that another reason for the high dependence of loop distortion on fibre diameter in the case of wool is that coarser fibres are stiffer, and stiffness causes loop distortion. It will be recalled that there was no significant correlation between count regularity and flexural and torsional rigidity for the sample yarns. It seems likely that fibre diameter influences loop distortion by at least two independent mechanisms.

In Figure 69, loop distortion ranks have been plotted against flexural rigidity, omitting samples spun irregularly and conditioned at high humidity. We already know that irregular yarns rate poorly and their inclusion would mask any influence of mean flexural rigidity on loop distortion. Similarly, we expect regain to influence yarn stiffness significantly, particularly in the case of wool, but in fact, during and after the fabric finishing process, all fabrics are subjected to

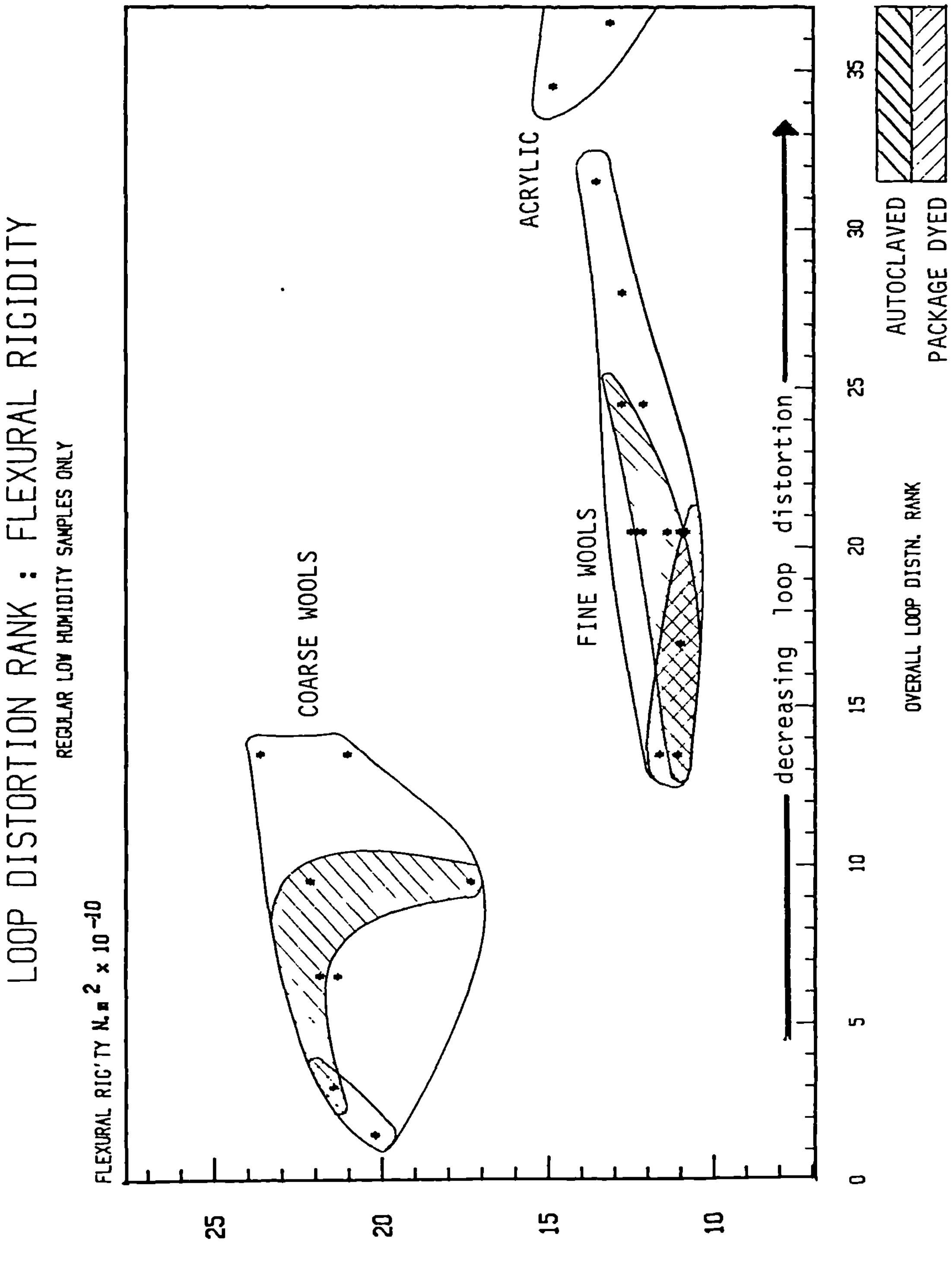


Figure 69 Loop Distortion Rank : Flexural Rigidity

identical conditions. Results suggest that regain at the time of knitting is irrelevant in terms of loop distortion in the fully relaxed state and the inclusion of high regain samples would obscure the true picture.

Coarse and fine wools are clearly differentiated in terms of flexural rigidity and this suggests that coarser wools distort more because they are stiffer. This is only a fraction of the picture, though, since acrylic yarns have virtually the same flexural rigidity as wool yarns of the same fibre diameter and yet they are much freer of loop distortion. Furthermore, processing treatments such as package dyeing and autoclave setting of wool yarns clearly lead to distortion problems without affecting flexural rigidity significantly. Figure 70 shows a very similar picture for torsional rigidity except here the difference between wool and acrylic is even more marked. Although the acrylic yarns have roughly the same torsional stiffness as the coarse wool yarns, they are freer of distortion than the fine wool yarns. There is apparently a significant correlation between torsional rigidity and loop distortion for low regain fine wools (see Figure 67), but Figure 70 shows that in reality the torsional rigidity merely remains approximately constant with varying loop distortion level. In Figure 71 the ratio of flexural to torsional stiffness against loop distortion has been plotted. In this case one might detect a trend of increasing loop distortion with an increasing value of the ratio, although the relationship is much distorted by different processing treatments within the three major fibre groups. Figure 72 plots flexural rigidity against loop distortion for all eight acrylic

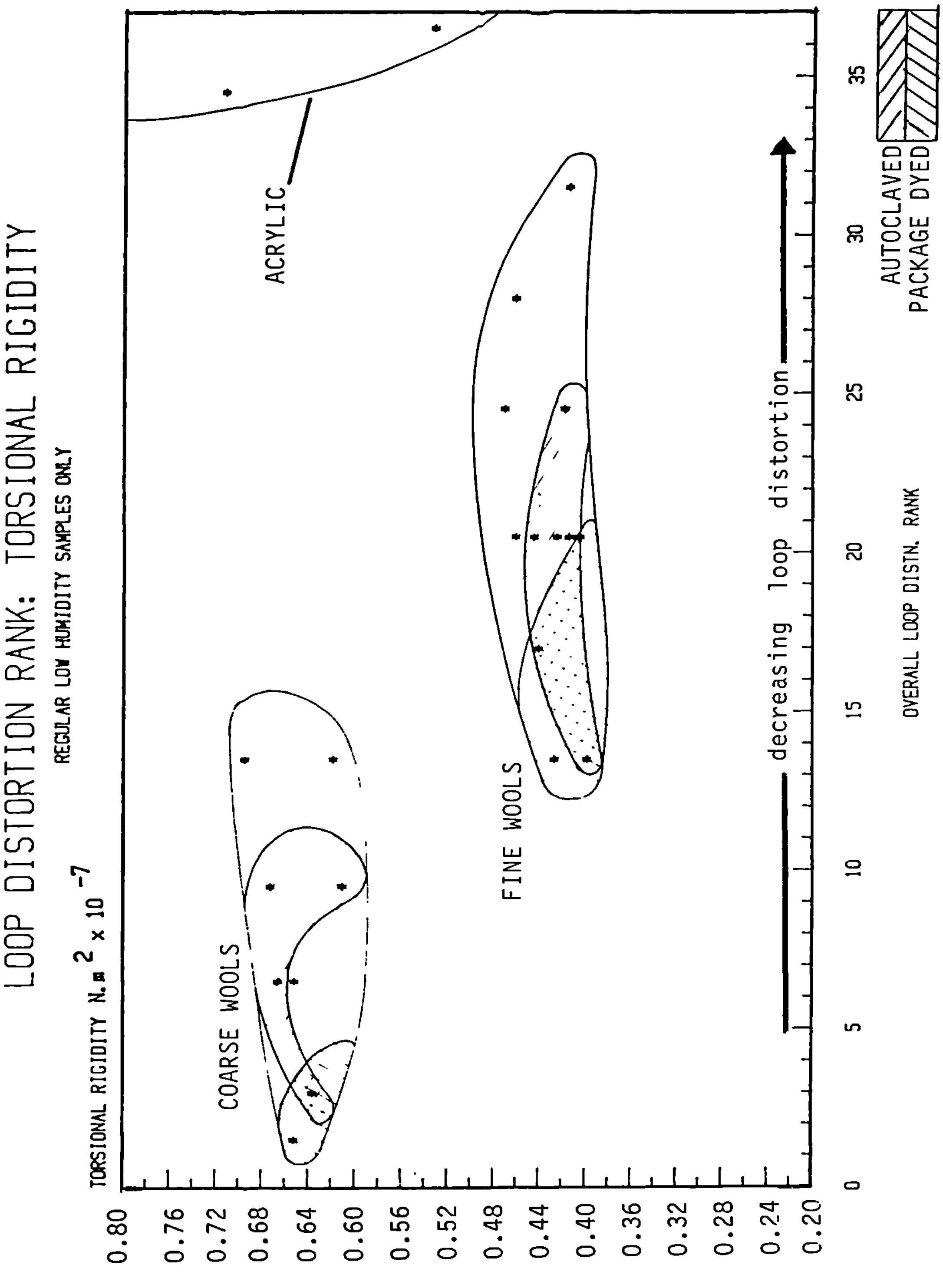


Figure 70 Loop Distortion : Torsional Rigidity

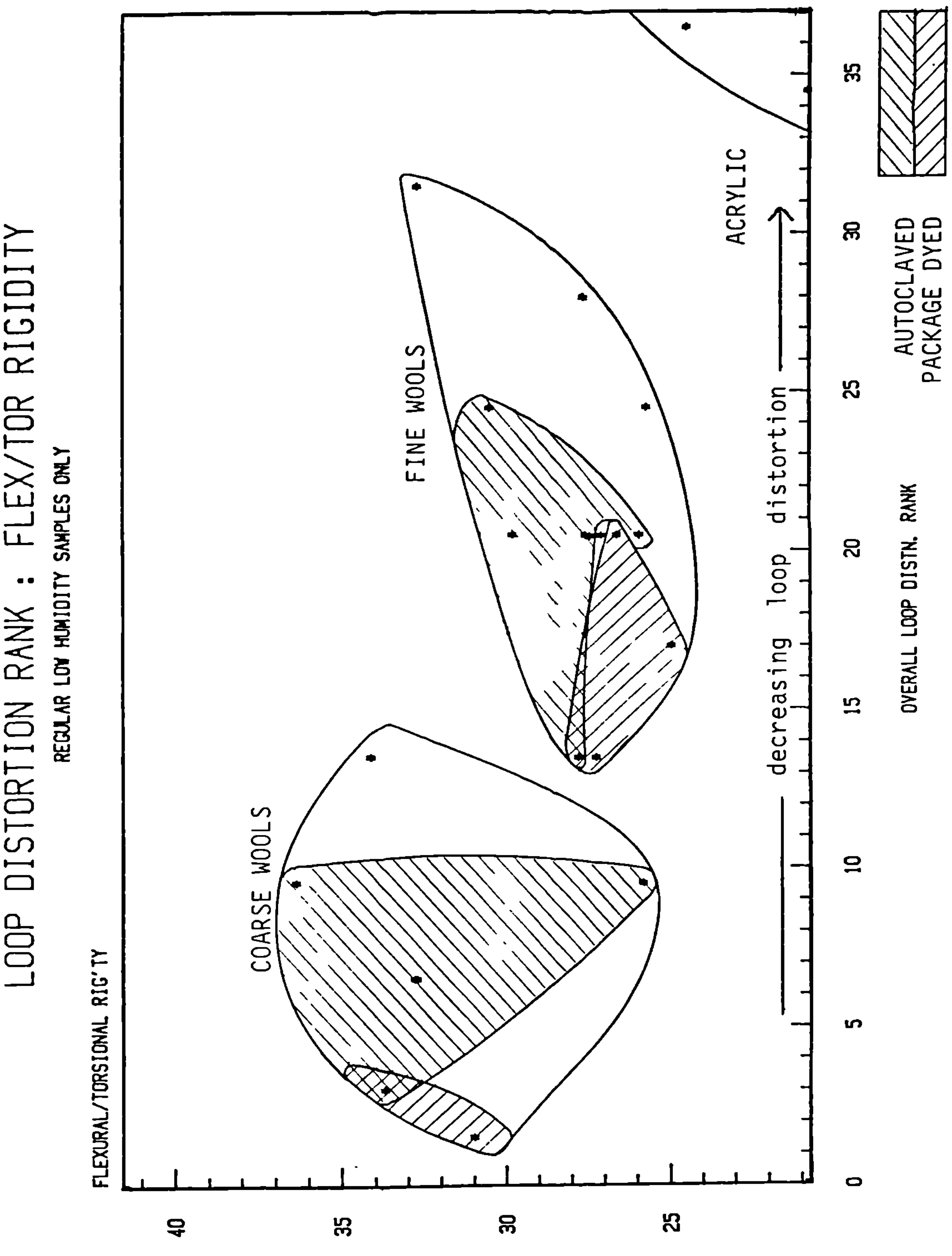


Figure 71 Loop Distortion Rank : Flexural/Torsional Rigidity

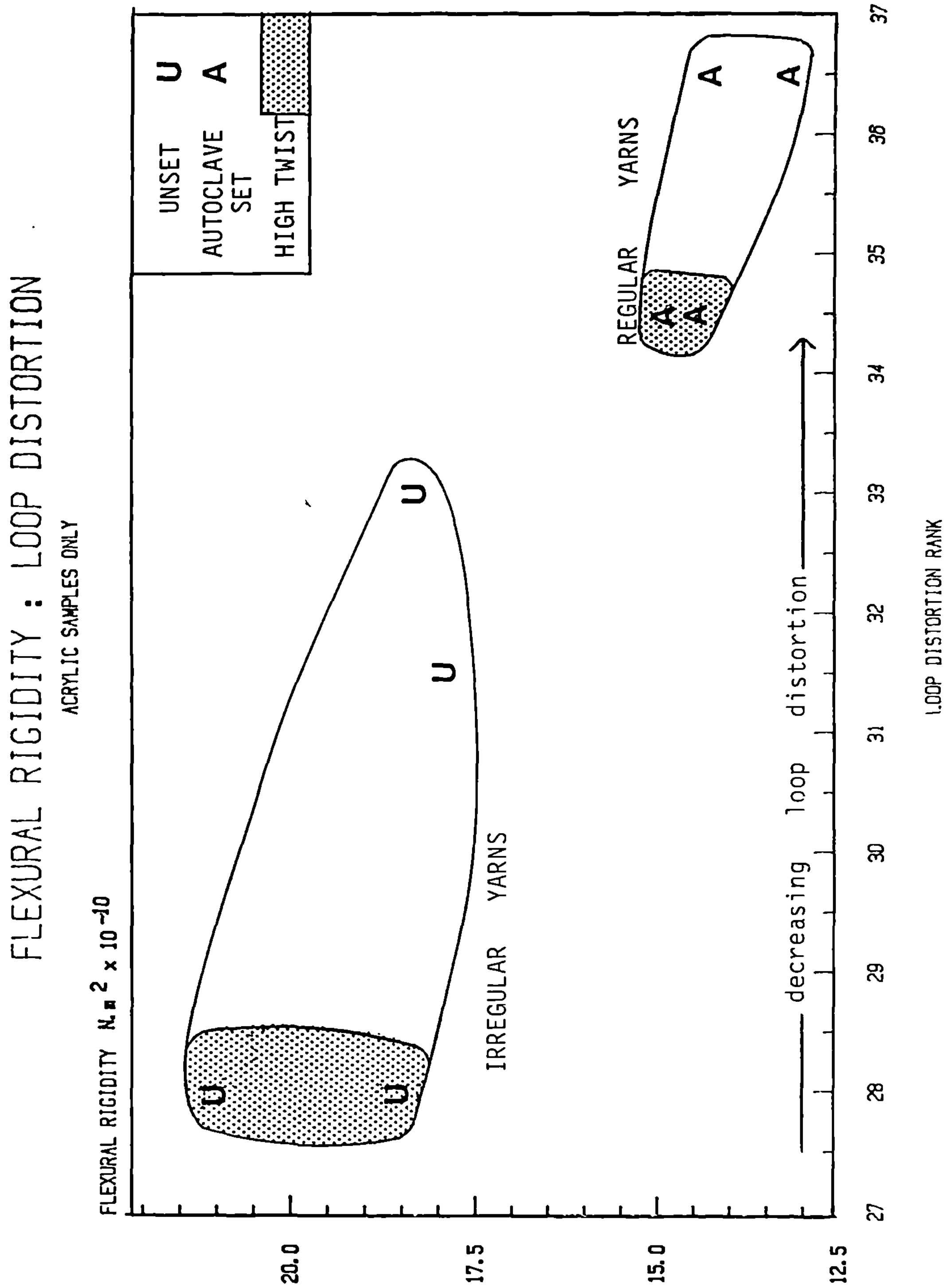


Figure 72 Flexural Rigidity : Loop Distortion
(Acrylic Samples Only)

yarns. Unlike wool, the stiffness characteristics of an acrylic yarn are hardly affected by moisture:-

	Low Humidity		High Humidity	
	Torsional Rigidity Nm^2x10^{-7}	Flexural Rigidity Nm^2x10^{-10}	Torsional Rigidity Nm^2x10^{-7}	Flexural Rigidity Nm^2x10^{-10}
Autoclaved, low twist	0.533	13.1	0.523	14.2
Autoclaved, high twist	0.712	14.8	0.714	14.4
Irregular, low twist	0.515	18.3	0.510	17.9
Irregular, high twist	0.709	21.0	0.685	18.5

Torsional irregularity is apparently influenced only by twist level, but for flexural rigidity the relationship is a little more complicated. Figure 72 illustrates the apparent influence of flexural rigidity on loop distortion. The following points are of note:-

(i) The yarns with the higher flexural rigidity are the more distorted.

(ii) Because of the limitations of the experimental design, the four yarns with a high flexural rigidity are both irregular and unset and the four yarns with a low flexural rigidity are both regular and autoclave set.

(iii) The difference in mean flexural rigidity between the two groups may be assigned either to count regularity or to autoclave setting. The second hypothesis seems the more likely; the influence of setting on the stiffness of acrylic yarn is discussed in more detail in Section 6.7.4.

(iv) Within each of the two groups, twist has an effect on stiffness, the higher twist yarns being stiffer and more distorted in the fabric.

(v) Although regularity may not directly influence flexural rigidity, it almost certainly is important in terms of loop distortion. One cannot necessarily, therefore, assign the difference between the two groups in terms of loop distortion purely to flexural rigidity. However, the twist effect within the groups suggests that flexural rigidity does have at least some part to play.

We have seen in Figure 68 that a rough division into "good" and "bad" loop distortion can be made on the basis of yarn regularity and from Figure 69 that, taking the regular yarns only, a division can be made on the basis of flexural rigidity.

Finer differentiation has been made for the acrylic yarns in terms, again, of flexural rigidity, so that the reasons for different process treatments on loop distortion can be accounted for. But so far we have been unable to account for the differences within the two major wool groups "fine regular wools" and "coarse regular wools". We have seen clearly in Figures 69 and 70, and from the results in Section 6.4, that in both groups the package dyed samples tend to be worse, followed closely by the autoclaved samples, but this has not yet been accounted for in physical terms.

Turning to the bending hysteresis values, however, we see here evidence for the mechanism through which these treatments might influence loop distortion. Rank correlation gives significant values only for all samples together and acrylic only, and virtually zero correlation for the "low regain fine wool" group. But if we plot the actual values of all the regular yarns, as shown in Figure 73, (since we know that the irregular yarns will be worse than otherwise equivalent regular yarns with the same mean bending hysteresis) then we see that the correlation values can be a little misleading. Both coarse and fine fibres follow similar trends of bending hysteresis against loop distortion. The acrylic samples, having the same mean fibre as the fine wool samples, may be grouped with them to demonstrate a possible reason why acrylic yarns apparently distort significantly less than wool, i.e. because they have a higher bending hysteresis. We may now be approaching an understanding of the physical parameters of a yarn which influence loop distortion. Firstly we have count (and twist) regularity and flexural rigidity. For given values of these parameters, loop distortion appears to improve with increasing bending hysteresis. So, although a particular wool yarn may yield objectionably distorted fabric, an acrylic yarn of similar stiffness and irregularity could well be acceptable as a result of its greater bending hysteresis.

But what of the actual production and processing treatments which influence these yarn physical characteristics? We already know a good deal from analyses of the plotted values, but a more formal analysis of the factorial experiments will be useful, and this forms the subject of the next section.

Mention should finally be made of the last two variables in Figure 67: CV% torsional rigidity and coefficient of friction. The former variable appears to be of no significant importance for any group except the coarse wools, and even here the correlation must be regarded as rather suspect. The implication is that as the short-

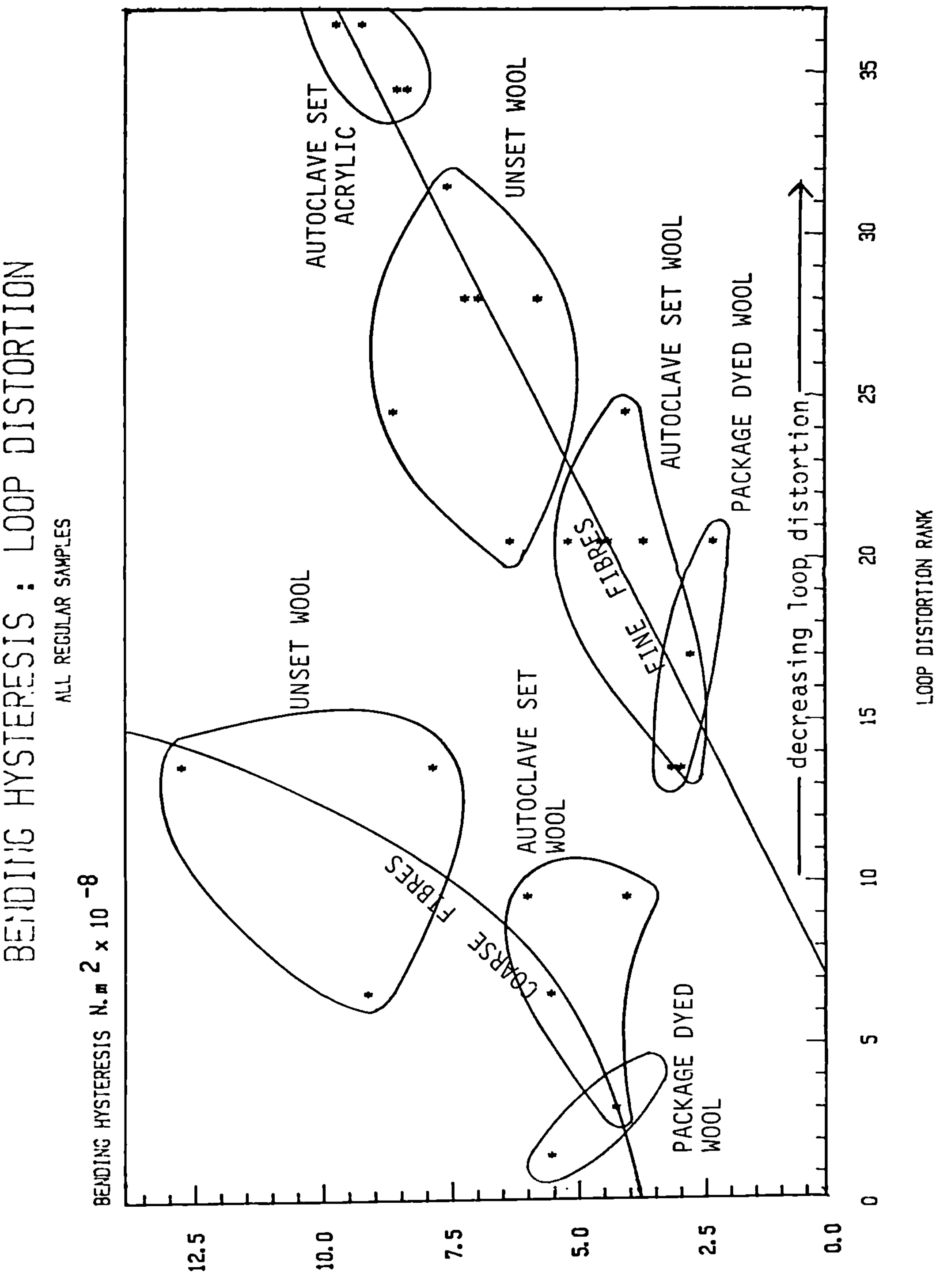


Figure 73   Bending Hysterisis : Loop Distortion

term variation in torsional rigidity increases, loop distortion decreases. This seems very unlikely; one might, in fact, expect the opposite effect if one were to assume a positive correlation between CV% torsional rigidity and count regularity. (Although this is the case for the full sample set, the level is not significant). The frictional values of all acrylic and low regain wool samples were within the narrow range of about 0.27 - 0.31, only the high regain wools being exceptionally beyond this range (≥0.45) and we have already seen that regain level at the time of knitting has little effect on loop distortion. Not surprisingly, therefore, no significant role of friction in the development of loop distortion was detected.

6.7 THE RELATIONSHIP BETWEEN INDEPENDENT PRODUCTION AND PROCESS VARIABLES AND DEPENDENT YARN VARIABLES

6.7.1. Introduction

At this stage in the analysis we have a good indication as to which independent production and processing variables have an effect on the development of loop distortion. We are also fairly clear as to which yarn physical parameters are important in the development. It, therefore, remains to assign particular independent variables to yarn physical characteristics so that we can understand by what mechanism they are likely to operate. Although we can already make a well informed guess at how some of the independent variables operate, a more formal analysis will be a useful confirmation of the graphical representations which have already been discussed. In addition, there are likely to be more subtle effects, possibly interactions, which are not easily appreciated purely by the examination of plotted values.

It would be desirable to obtain an estimate of the error variance when the half factorial experiments are analysed. When the loop distortion ranks were being estimated, the variation between individual judges was used to derive a value for the "Within Treatments" or error variation. This will not be possible for estimates of the yarn physical parameters. Also, there is no previous experience which will give reliable values for likely errors of the various dependent variables. One could only make the assumption that certain interactions are actually insignificant and that any estimate assigned to them is due to error, although this method is rather insensitive for a factorial design, particularly for a small number of treatments and interactions.

In fact, it has already been suggested that certain interactions may be likely to affect loop distortion (chlorination/autoclave setting, etc), so an assumption that the estimates for such interactions are due to error is not really justified. For five of the six experimental designs there would be very few degrees of freedom left for a worthwhile estimate of error variance even if interactions not suspected to influence loop distortion were assigned to error estimation.

However, Design 5 does permit some estimate of the size of error to be calculated. There is a total of ten alias pairs in which each of the two effects is an interaction. One would be fairly safe in assigning estimates for the second order interactions (RSM, etc) to error. Additionally, first order interactions with relative humidity are unlikely to produce real effects with the possible exception of its interaction with fibre type on stiffness characteristics (see Figures 76 and 77). None of the interactions was seen to have any significant influence on loop distortion, even at the 5% level (see Figure 57 in which the 5% significance level is represented by a mean square value of 9.0). Consequently, in all except the first of the analysis of variance tables to be discussed (Figures 74 - 79), the interactions with "moisture regain" in Design 5 have been used to obtain an estimate of the size of error for the dependent yarn parameters. The estimate obtained is applicable to all six experimental designs.

We already know that certain yarn parameters have no significant influence on loop distortion, and it would be fruitless to include these in the analysis. Only the following dependent variables, therefore, were included:-

CV% Twofold Twist (twist regularity)
U% Twofold Count (count regularity)
Flexural Rigidity
Torsional Rigidity
Flexural Rigidity/Torsional Rigidity
Bending Hysteresis

6.7.2. CV% Twofold Twist

Figure 74 summarises the mean square of the estimates for CV% two-fold twist from the six experiments. Count regularity, and hence twist regularity (Figures 40 and 41), was one of the main independent effects so, as expected, in Designs 5 and 6 which included count regularity as a main effect, this was overwhelmingly predominant and accounted for 94% and 88% of the variance respectively. Where count regularity was not included (Designs 1-4) other variables became relatively important, primarily fibre diameter and autoclave setting. Fibre diameter is important partly because it determines the mean number of fibres in the yarn cross-section, which in turn determines the count regularity and hence the twist regularity. The relationship between twist regularity and autoclave setting has already been demonstrated graphically in Figure 41 and a mechanism was proposed to explain the phenomenon in Section 6.2.

DESIGN 1			DESIGN 2			DESIGN 3			DESIGN 4			DESIGN 5			DESIGN 6		
Effect	Est.	Mn. Sq.	Effect	Est.	Mn. Sq.	Effect	Est.	Mn. Sq.	Effect	Est.	Mn. Sq.	Effect	Est.	Mn. Sq.	Effect	Est.	Mn. Sq.
C(TD)	14.7	27.01	D(PC)	20.9	54.60	A(DATH)	10.9	14.85	D(PH)	12.6	19.85	R(AF)	150.7	1420.16	R(AX)	65.4	534.65
D(TC)	10.3	13.26	A(DAPC)	12.5	19.53	DA(ATH)	-10.1	12.75	A(DAPH)	12.4	19.22	F(RA)	-23.9	35.82	A(RX)	15.6	30.42
A(DATC)	7.3	6.66	P(DC)	-6.9	5.95	HA(DAT)	5.9	4.35	HA(DAP)	-4.4	2.24	RS(SAF)	20.7	26.88	AS(RXS)	12.2	18.61
TA(DAC)	5.3	3.51	CA(DAP)	-4.3	2.31	D(TH)	5.5	3.78	H(PD)	-3.2	1.28	S(RAFS)	19.5	23.86	X(RA)	-8.0	8.00
T(DC)	-4.5	2.53	C(PD)	4.1	2.10	H(TD)	3.9	1.90	PA(DAH)	3.0	1.12	A(RF)	11.5	8.32	XS(RAS)	-7.4	6.85
DA(ATC)	-3.3	1.36	DA(APC)	3.3	1.36	TA(DAH)	1.5	0.28	P(DH)	1.4	0.25	SA(RFS)	-5.7	2.00	RS(AXS)	-4.8	2.88
CA(DAT)	2.3	0.66	PA(DAC)	-0.1	0	T(DH)	0.3	0.01	DA(APH)	0.2	0.01	FS(RAS)	0.5	0.01	S(RAXS)	2.0	0.50
	TOTAL	54.99		TOTAL	85.85		TOTAL	37.92		TOTAL	45.56		TOTAL	1517.05		TOTAL	601.91

KEY

D	FIBRE DIAMETER	F	FIBRE TYPE
T	TOP DYE	R	COUNT REGULARITY
C	TOP CHLORINATION	S	TWIST LEVEL
A	AUTOCLAVE SET	X	TWIST METHOD
P	PACKAGE DYE		
H	HERCOSETT TREATMENT		

Figure 74 Source of Variation for CV% Twofold Twist

Package dyeing, which is also a yarn setting process, would not be expected to influence twist regularity because it is only carried out in the twofold yarn, after twist redistribution has taken place.

The dependent variable "CV% twofold twist" was the only parameter for which it was not possible to make an estimate of the error variance. This was because twist variation measurements were only carried out at "low" relative humidity, for technical reasons. In fact, it is unlikely that further significant twist redistribution would take place if a yarn was conditioned at a higher relative humidity.

6.7.3. U% Twofold Count

The analyses of variance for U% twofold count are shown in Figure 75. Using the seven moisture interactions in Design 5 for error estimation, we find that a mean square value must exceed 0.55 for significance at the 5% level and 1.21 at the 1% level. We see, therefore, that when all samples are nominally spun to the same regularity, as in Designs 1-4, only fibre diameter has a significant influence on the U% count variation. The "PA" interaction in Design 4 is also apparently just significant but, since the error estimate is only approximate, this result must be viewed with some caution. Autoclave setting does not rate as an important factor in terms of count regularity, as it did for twist regularity, and one would not expect it to do so if the proposed mechanism for the influence of autoclave setting on twist regularity actually operates.

DESIGN 1			DESIGN 2			DESIGN 3			DESIGN 4			DESIGN 5			DESIGN 6		
Effect	Est.	Mn. Sq.	Effect	Est.	Mn. Sq.	Effect	Est.	Mn. Sq.	Effect	Est.	Mn. Sq.	Effect	Est.	Mn. Sq.	Effect	Est.	Mn. Sq.
D(TC)	9.33	10.88	D(PC)	8.88	9.86	D(TH)	8.34	8.69	D(PH)	8.27	8.55	R(AF)	63.85	254.80	R(AX)	35.94	161.46
T(DC)	-1.79	0.40	PA(DAC)	1.66	0.34	TA(DAH)	1.91	0.46	PA(AHD)	2.19	0.60	F(RA)	-11.05	7.63	A(RX)	-5.44	3.70
TA(DAC)	1.27	0.20	C(PD)	1.40	0.24	A(DATH)	-0.87	0.10	P(HD)	-0.75	0.07	A(RF)	-7.70	3.77	S(RAXS)	-3.20	1.28
A(DATC)	-1.05	0.14	P(DC)	-1.36	0.23	T(DH)	-0.79	0.08	H(PD)	-0.65	0.05	S(RAFS)	-4.97	1.54	X(RA)	2.06	0.53
C(TD)	0.95	0.11	DA(APC)	0.86	0.09	H(TD)	-0.71	0.06	A(PHDA)	-0.59	0.04	RS(SAF)	-2.63	0.43	RS(AXS)	1.14	0.16
DA(ATC)	0.59	0.04	A(DAPC)	-0.66	0.05	HA(DAT)	0.15	0	DA(PHA)	0.33	0.01	M(RAFM)	2.61	0.43	AS(RXS)	0.74	0.07
CA(DAT)	-0.03	0	CA(DAP)	-0.30	0.01	DA(ATH)	-0.05	0	HA(PDA)	-0.23	0.01	FS(RAS)	1.85	0.21	XS(RAS)	-0.10	0
	TOTAL	11.77		TOTAL	10.82		TOTAL	9.35		TOTAL	9.33	SA(RFS)	-0.11	0		TOTAL	167.20
												FM	-2.41	0.36			
												RSM	-1.47	0.14			
												SM	-1.21	0.09			
												RM	-0.85	0.05			
												FSM	-0.59	0.02	} 0.099		
												SAM	-0.51	0.02			
												AM	0.43	0.01			
													TOTAL	269.50			

KEY

D	FIBRE DIAMETER	F	FIBRE TYPE
T	TOP DYE	R	COUNT REGULARITY
C	TOP CHLORINATION	S	TWIST LEVEL
A	AUTOCLAVE SET	M	MOISTURE REGAIN
P	PACKAGE DYE	X	TWIST METHOD
H	HERCOSETT TREATMENT		

Figure 75 Source of Variation for U% Twofold Count

In Designs 5 and 6 we see that, as expected, the nominal level of yarn count regularity is by far the most important influence on the actual count regularity. It is then followed by fibre type, autoclave setting and twist level, in that order. Fibre type is likely to influence count regularity, and it is seen from the sign of the estimate (-) that acrylic fibres spin to a more regular yarn than wool of the same fibre diameter. The significance of autoclave setting is at odds with the results from the previous four experiments. The reason for its apparent significance is not immediately obvious although it is possible that its alias RF is operative in Design 5:

MEAN U% TWOFOLD COUNT (SAMPLES FROM DESIGN 5)

	Wool	Acrylic	All Fibres
Unset	10.64(REG)	17.80(IRREG)	14.22
Autoclave set	18.21(IRREG)	8.29(REG)	13.25

Although we have just seen that acrylic spins to a more regular yarn than an equivalent wool, the figures above show that in this experiment the difference was much more marked for yarns spun at the "regular" level and hence it is likely that an interaction is operative. Nevertheless, the effect represents only 1.4% of the total variance and for practical purposes can probably be ignored. In Design 6 "autoclaving" or possibly its interaction alias RX accounts for about 2.2% of the total variance. Again, a tabular presentation helps to clarify the true source of the variance:

MEAN U% TWOFOLD COUNT (SAMPLES FROM DESIGN 6)

	Ring-twisted	2-for-1 twisted	both twist methods
Unset	10.3(REG)	19.8(IRREG)	15.1
Autoclave set	17.9(IRREG)	9.5(REG)	13.7

It can be seen that the 2-for-1 twisting process produced a considerably more irregular "irregular" yarn than ring twisting but that at "low" irregularity the method gave a slightly more regular yarn. In other words, the rate of increase of twofold irregularity with increasing singles (spinning) irregularity is higher for 2-for-1 twisted yarns. It seems probable that again the interaction, rather than the main effect of "autoclaving", is the source of count regularity variance.

The final effect significant at the 1% level is "twist level" in Design 5. We have already suggested that the "RF" interaction, although real, is of minor practical importance. The same may also apply to the level of twist which accounted for an even lower proportion of the total variance, just 0.6%.

6.7.4. Flexural Rigidity

Referring to Figure 76, mean squares significant at the 5% level exceed 4.01×10^{-20} and those significant at the 1% level exceed 9.18×10^{-20}. In the first four experiments only fibre diameter is significant at the 1% level. This result is not surprising; to a first order of accuracy the flexural rigidity of a yarn is the sum of the flexural rigidities of its constituent fibres. Coarser fibres are stiffer than finer fibres and, although there are fewer of them in the cross-section for a given count of yarn, the yarn flexural rigidity can be shown to increase in proportion to the square of the fibre diameter[104]. Designs 3 and 4 each include an interaction significant at the 5% level. The effects observed are most likely due to the interactions DAH, rather than their aliasses TA (Design 3)

DESIGN 1			DESIGN 2			DESIGN 3		
Effect	Est.*	Mn. Sq@	Effect	Est.*	Mn. Sq@	Effect	Est.*	Mn. Sq@
D(TC)	39.2	192.1	D(PC)	40.7	207.1	D(TH)	31.5	124.0
TA(DAC)	4.0	2.0	P(DC)	-7.1	6.3	TA(DAH)	6.7	5.6
A(DATC)	-3.6	1.6	PA(DAC)	5.3	3.5	T(DH)	5.3	3.5
C(TD)	2.8	1.0	A(DAPC)	-2.3	0.7	A(DATH)	-5.1	3.3
T(DC)	-2.4	0.7	DA(APC)	1.5	0.3	H(TD)	-4.5	2.5
DA(ATC)	1.6	0.3	C(PD)	1.3	0.2	HA(DAT)	-1.9	0.5
CA(DAT)	-0.4	0	CA(DAP)	-0.3	0	DA(ATH)	-1.1	0.2
	TOTAL	197.7		TOTAL	218.1		TOTAL	139.6

DESIGN 4			DESIGN 5			DESIGN 6		
Effect	Est.*	Mn. Sq@	Effect	Est.*	Mn. Sq@	Effect	Est.*	Mn. Sq@
D(PH)	32.5	132.0	F(RA)	47.3	139.8	R(AX)	7.1	6.3
PA(DAH)	6.5	5.3	R(AF)	21.5	28.9	A(RX)	-6.6	5.4
H(PD)	-5.5	3.8	M(RAFM)	-20.0	25.0	RS(AXS)	2.8	1.0
A(DAPH)	-5.3	3.5	A(RF)	-16.8	17.6	XS(RAS)	2.8	1.0
HA(PDA)	-3.3	1.4	FM(RAM)	15.7	15.4	S(RAXS)	-2.3	0.7
P(DH)	1.1	0.2	FS(RAS)	9.5	5.6	AS(RXS)	-2.2	0.6
DA(PHA)	0.3	0	SA(RFS)	-1.6	0.2	X(RA)	1.5	0.3
	TOTAL	146.2	RS(SAF)	1.6	0.2		TOTAL	15.3
			S(RAFS)	1.1	0.1			
			RM	-1.8	0.2	} 0.67		
			SM	-2.8	0.5	} 0.67		
			AM	5.5	1.9	} 0.67		
			RSM	-1.2	0.1	} 0.67		
			FSM	-4.5	1.3	} 0.67		
			SAM	-0.2	0	} 0.67		
				TOTAL	236.8			

* x10^-10 ($\times 10^{-10}$)

@ x10^-20 ($\times 10^{-20}$)

KEY

D	FIBRE DIAMETER	F	FIBRE TYPE
T	TOP DYE	R	COUNT REGULARITY
C	TOP CHLORINATION	S	TWIST LEVEL
A	AUTOCLAVE SET	M	MOISTURE REGAIN
P	PACKAGE DYE	X	TWIST METHOD
H	HERCOSETT TREATMENT		

Figure 76 Source of Variation for Flexural Rigidity

and PA (Design 4); TA and PA were insignificant in Designs 1 and 2. The two alias pairs have already been discussed in Section 6.5.2 in relation to their influence on loop distortion. Package dyeing also features in Design 2 at the 5% level although it, and its alias DC, is not significant in other designs. Similarly, although Hercosett treatment almost reaches 5% significance in Design 4, it is of no significance in Design 3

Design 5 produced five estimates apparently significant at the 1% level or better:

Fibre type

Count regularity

Moisture regain

Autoclave setting

Fibre type/moisture regain interaction;

and one interaction significant at the 5% level: fibre type/twist level interaction.

The result for fibre type confirms the effect illustrated in Figure 43, that the flexural rigidity of acrylic yarns is, on average, higher than that of wool yarns for the same mean fibre diameter. Although the mean diameters of the "fine" wool and acrylic fibres were very similar (Figure 20), the distributions of the fibre diameters were not. The coefficient of variation of the wool fibre diameter was 25.0% but that of the acrylic was near zero, all fibres being produced to a nominal fineness of 5 denier. Because the flexural rigidity of a fibre varies with the square of its diameter, the coarser fibres in the range have an important bearing on the yarn flexural rigidity. A theoretical correction factor (C_1) to take account of the fibre diameter distribtuion can be applied to the rigidity calculated from the mean fibre diameter alone[105]:

$$C_1 = \frac{1+6V^2+4g_1V^3+g_2V^4}{1+V^2} ,$$

where V, g_1, and g_2 are the coefficient of variation, skewness and kurtosis of the fibre diameter distribution. Values for skewness and kurtosis were not available, but even assuming that distribution was symmetrical about the mean (in fact there was known to be a slight positive skew towards coarser fibres) the distribution would theoretically increase the flexural rigidity by a factor of 1.35 above the value for an equivalent yarn with fibres of identical diameter. Despite this, it is clear from the analysis of variance and from Figure 43 that acrylic yarns are significantly stiffer than wool yarns of the same mean fibre diameter. Presumably the difference would be even greater if the fibre diameter distributions in the two types of yarn were the same. The greater stiffness of the acrylic yarns was due to the greater stiffness of the constituent fibres in relation to wool.

The [regularity]+[autoclave/fibre type] aliases have already been discussed in Section 6.5.3. The apparent effect of regularity on flexural rigidity is more likely to be due to the interaction between autoclaving and fibre type. This may be illustrated by taking values for all samples in Design 5 and dividing them into groups according to fibre type:

	MEAN FLEXURAL RIGIDITY ($N.m^2 \times 10^{-10}$)		
	Acrylic	Wool	All Fibres
Regular	14.13 (SET)	10.32(UNSET)	12.23
Irregular	18.93 (UNSET)	10.92(SET)	14.93

Because wool and acrylic behave differently, the wool being marginally stiffer but the acrylic considerably less stiff after setting, the false impression could be gained, by taking all fibres together, that it is actually regularity which influences flexural rigidity. In fact, as far as wool is concerned, neither regularity nor set have much effect on rigidity (unless the two effects cancel each other out, which is unlikely). In the case of acrylic we can see a significant effect: either setting reduces stiffness or irregularity increases it. If stiffness were being increased as a result of changes in a purely physical effect such as count regularity, then we would expect to see the same effect apply to the wool yarns as well. Since this is not the case it is far more likely that the change in stiffness is a result of an effect of steam setting on the acrylic fibre which does not occur with wool. In other words the effective alias of the [R]+[AF] pair is AF.

The effect of moisture on the stiffness of wool yarns is well known and the effect estimate would have been even larger if only wool yarns had been included. Again, we can divide the sixteen yarn samples into groups according to fibre type:

	MEAN FLEXURAL RIGIDITY ($N.m^2 x 10^{-10}$)		
	Acrylic	Wool	All Fibres
Low relative humidity	16.80	12.86	14.83
High relative humidity	16.25	8.39	12.32

We can see that the stiffness of both fibres is reduced as the conditioning relative humidity increases and this is represented by the highly significant level of the effect M. However, because the flexural rigidity of wool is reduced by a far greater proportion than that of acrylic, we are not justified, in this instance, in assuming that the effect due to interaction FM is insignificant. In fact the interaction is significant at a level better than 1%. Therefore only six of the moisture level interactions were used for the estimation of the variance due to error in this analysis and in subsequent analyses of stiffness-related characteristics. Finally, at the 1% level, there is autoclave setting which, although highly significant, is still subordinate to its interaction with fibre type, AF.

The twist level interaction FS is significant at the 5% level. Figure 72 showed how twist level influences the stiffness of acrylic yarns. The same is not true to a significant extent for wool yarns. This is demonstrated in Figure 77 which shows a random scatter of points with no apparent relationship between actual twist level and flexural rigidity for either nominally high or low levels of twist.

Design 6 produced no effects significant at the 1% level, but two (regularity and autoclave setting) significant at the 5% level. As in the previous design, it is not clear why short term variations in count should influence the mean value of stiffness. Nevertheless, we already have six highly significant effects from the full set of experiments and therefore a more detailed investigation of effects of lesser importance is probably not of great value.

6.7.5. Torsional Rigidity

Figure 78 is a summary of the analysis of the estimates for torsional rigidity. For significance at the 5% level, mean squares should exceed 0.07×10^{-16} and at the 1% should exceed 0.16×10^{-16}. It is notable that the error mean square in this case is very low and that

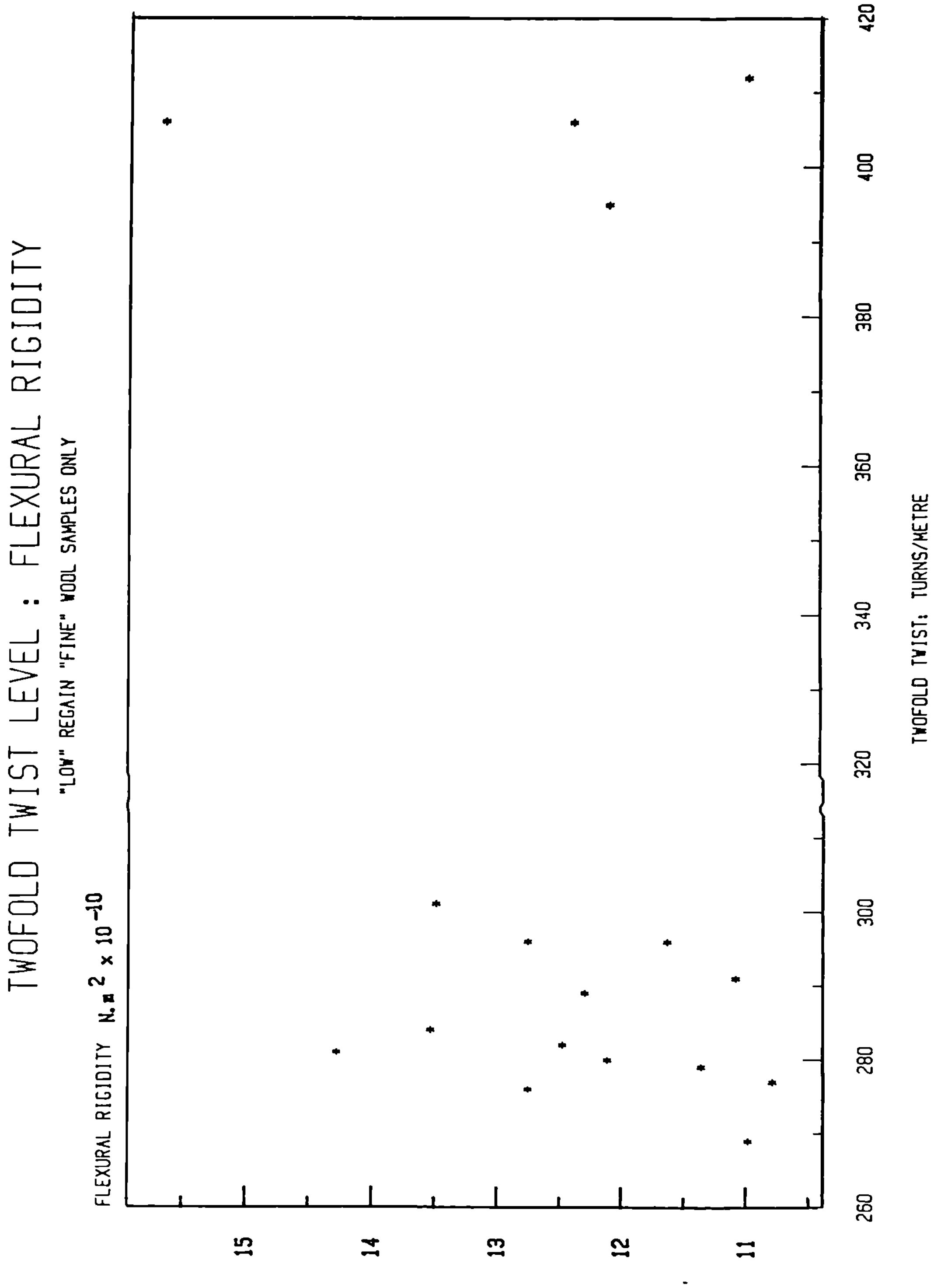


Figure 77 Twofold Twist Level : Flexural Rigidity
Low Regain Fine Wool Samples Only

DESIGN 1			DESIGN 2			DESIGN 3			DESIGN 4			DESIGN 5			DESIGN 6		
Effect	Est.*	Mn. Sq@	Effect	Est.*	Mn. Sq@	Effect	Est.*	Mn. Sq@	Effect	Est.*	Mn. Sq@	Effect	Est.*	Mn. Sq@	Effect	Est.*	Mn. Sq@
D(TC)	0.891	9.92	D(PC)	0.962	11.56	D(TH)	0.903	10.19	D(PH)	0.885	9.79	F(RA)	2.170	29.43	S(RAXS)	0.168	0.35
CA(DAT)	-0.114	0.16	A(DAPC)	-0.106	0.14	DA(ATH)	0.110	0.15	HA(PAD)	0.084	0.09	S(ARFS)	0.977	5.97	A(RX)	-0.120	0.18
T(DC)	0.090	0.10	DA(APC)	-0.094	0.11	TA(DAH)	-0.082	0.08	PA(AHD)	-0.056	0.03	M(RAFM)	-0.617	2.38	R(AX)	-0.108	0.15
A(DATC)	-0.086	0.09	CA(DAP)	-0.074	0.07	T(DH)	0.070	0.06	A(APHD)	0.052	0.03	FM(RAM)	0.540	1.82	XS(ARS)	-0.044	0.02
TA(DAC)	0.082	0.08	PA(DAC)	0.062	0.05	A(DATH)	0.026	0.01	H(PD)	0.040	0.02	FS(RAS)	0.500	1.56	AS(RXS)	-0.032	0.01
C(TD)	0.062	0.05	P(DC)	-0.042	0.02	H(DT)	0.022	0	P(HD)	0.036	0.02	R(AF)	-0.242	0.36	RS(AXS)	0.020	0.01
DA(ATC)	-0.054	0.04	C(PD)	-0.010	0	HA(DTA)	-0.002	0	DA(PHA)	0.024	0.01	A(RF)	-0.124	0.09	X(RA)	0.012	0
	TOTAL	10.44		TOTAL	11.95		TOTAL	10.49		TOTAL	9.99	RS(AFS)	-0.060	0.02		TOTAL	0.73
												SA(RFS)	-0.048	0.01			
												RM	0.020	0.002			
												SM	0.020	0.002			
												AM	0.064	0.026			
												RSM	-0.072	0.032	}0.012		
												FSM	-0.032	0.006			
												SAM	-0.012	0.001			
													TOTAL	41.7			

* $x10^{-7}$

@ $x10^{-16}$

KEY

D	FIBRE DIAMETER	F	FIBRE TYPE
T	TOP DYE	R	COUNT REGULARITY
C	TOP CHLORINATION	S	TWIST LEVEL
A	AUTOCLAVE SET	M	MOISTURE REGAIN
P	PACKAGE DYE	X	TWIST METHOD
H	HERCOSETT TREATMENT		

Figure 78 Source of Variation for Torsional Rigidity

consequently one should be a little cautious in the interpretation of significances. In the first four experimental designs only fibre diameter is of significance at a level better than 1% and this is clearly the single major influencing parameter. The graphical presentation in Figure 70 confirms this finding. The low estimate of error has produced a number of other treatment combinations significant at the 5% level. Reference to Figure 70 suggests that these other parameters, most of them interactions, can probably be ignored from a practical point of view. Furthermore, where they appear as significant at the 5% level in one experiment, virtually all do not reach this level in another, and this must cast doubts upon the practical reality of the statistical significance.

Six treatment combinations reach a significance better than 1% in Design 5. Fibre type is the most important; as seen in Figure 43, when comparing fibres of the same diameter, acrylic has a significantly higher torsional stiffness than wool. Figure 43 also shows the great importance of twist in terms of torsional stiffness for acrylic - hence the position of twist as the second most important factor in Figure 78, Design 5. It is seen that twist is mainly of importance for acrylic , and for wool to a lesser extent, hence we find the interaction FS of relatively high significance. Conversely, moisture is a factor influencing mainly wool, and not acrylic, so M and FM are observed in third and fourth places among the treatments significant at a level above 1%. The final treatment significant at this level is apparently regularity. In the previous subsection it was shown by a tabular presentation that the alias of regularity, AF, was the effective parameter in Design 5. Again a tabular presentation may be helpful:

MEAN TORSIONAL RIGIDITY ($N.m^2 \times 10^{-7}$)

	Acrylic	Wool	All Fibres
Regular yarn	0.621 (SET)	0.364 (UNSET)	0.493
Irregular yarn	0.605 (UNSET)	0.319(SET)	0.462

The behaviour of both fibre types is similar in that irregular yarns have a lower mean torsional rigidity. In this case we cannot assume that the effect is due to the interaction between autoclave setting and fibre type (which would require the relationship between torsional stiffness and regularity to differ between wool and acrylic). It may be of interest to examine an idealised example to test whether an irregular yarn is theoretically likely to have a lower mean torsional rigidity than a regular yarn of the same mean count. Consider two idealised yarns of uniform density and circular cross-section. The first is perfectly regular, being cylindrical and having a unit cross-sectional radius. The second is irregular and composed of identical segments of unit length each having the form of a truncated cone (see Figure 79a). The mean count of both yarns is the same, and therefore the volumes of one segment of the irregular yarn and a unit length of the regular yarn are equal. Let us assume that the radius of the cross-section at the "thick" end of a segment is 4/3 (in comparison to 1 for the regular yarn). The radius at the "thin" end can then be calculated as follows (refer to Figure 79a):

For an axial section through a segment

$$t/q = (4/3)/(1+q)$$

$$\text{therefore } q = 3t/(4-3t)$$

The volume of the segment is given by

$$V = \pi/3.(16/9).(1+q) - \pi/3.t^2.q$$

which is equal to the volume of a unit length of the regular yarn:

$$V = 1.\pi.1^2 = \pi$$

Hence

a)

b)

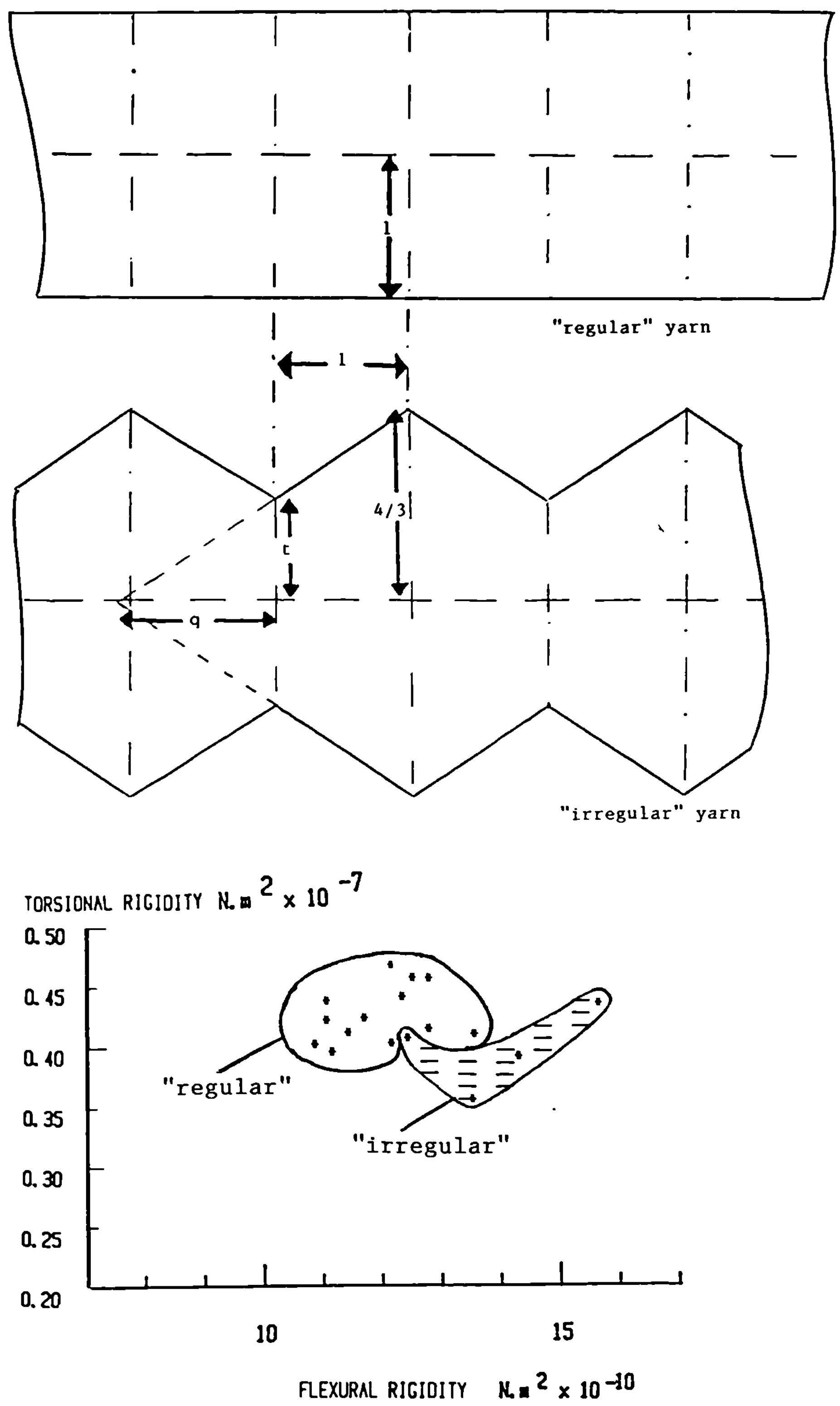


Figure 79 Influence of Count Regularity on Yarn Rigidity
a) Idealised "regular and "irregular" yarns
b) Subdivision of "low regain fine wool" group of Figure 43 into "regular and "irregular" levels

Hence

$$\pi/3.((16/9).(1+3t/(4-3t) - t^2.3t/(4-3t)) = \pi$$

which reduces to $27t^3 - 81t + 44 = 0$

where $t = 0.624$

In Section 5.5.1 we have seen that torsional rigidity (T) is defined as the couple induced when unit length of a material is twisted through 360^o, where $T = G.s^2$ for a material circular in cross-section. G is the shear modulus and s is the cross-sectional area. If we assume that, in the example being discussed, the yarns are composed of a material of unit shear modulus, then the regular yarn has a torsional rigidity of T_r where

$$T_r = 1.(\pi.1)^2 = \pi^2$$

If we assume that the couple induced in one segment of the irregular yarn is given by T_i and that the torsional rigidity of a thin segment, thickness δx, is T_s then

$$T_i = \sum_0^1 T_s.\delta x$$
$$= \sum_0^1 (\pi y^2)^2.\delta x$$

if the radius of the segment is y. As δx tends to zero

$$T_i = \pi^2 \int_0^1 y^4.dx$$

For an axial section through the truncated conical segment

$$y = (4/3 - t).x + t$$

at a distance x along the axis. Hence

$$T_i = \pi^2 \int_0^1 ((4/3 - t).x + t)^4.dx$$
$$= \pi^2 \int_0^1 ((4/3 - 0.624).x + 0.624)^4.dx$$
$$= \pi^2 \int_0^1 (0.253.x^4+0.890.x^3+0.391.x^2+0.689.x+0.152).dx^1$$
$$= \pi^2 [0.051.x^5+0.223.x^4+0.130.x^3+0.345.x^2+0.152.x+c]_0^1$$
$$= 0.90\,\pi^2$$

Hence, in this idealised case, the irregular yarn has a torsional rigidity only 90% that of the regular yarn. The real yarns used in the trials were obviously far more complex, being twofold structures composed of relatively loose fibre bundles, but there seems to be a theoretical basis for the apparent relationship between count regularity and mean torsional rigidity. Figure 79b looks in more detail at the "low regain fine wool" group of Figure 43 and subdivides into nominally "regular" and "irregular" yarns. It is seen that the average "irregular" torsional rigidity is a little less than that of the "regular" yarns, but in terms of the full range of torsional rigidities shown in Figure 43 the effect of regularity is not great. The apparent influence of regularity on flexural rigidity is also evident; aliases of "regularity" in Designs 5 and 6 were assigned to this effect in the previous subsection.

Design 6 confirms that the torsional rigidity of wool yarns is influenced by twist level, although to nothing like the extent that acrylic yarns were in the Design 5. Although autoclaving appears to be just significant at the 1% level in Design 6 (and at the 5% level in Design 5), the graphical presentation of the values shown in Figure 70 suggests that, in relation to other parameters, the influence of autoclaving on torsional rigidity is likely to be of low importance.

6.7.6. Flexural/Torsional Rigidity

Figure 80 summarises the analysis of variance for the ratio of flexural/torsional rigidity. Mean square values must exceed 0.18 x 10^{-4} and 0.41 x 10^{-4} for 5% and 1% significance respectively. Only fibre diameter exceeds the 1% significance level in the group of Designs 1-4 and this is in the two designs including chlorinated samples (1 and 2). The implication is that, for these samples,

DESIGN 1		
Effect	Est.*	Mn. Sq.@
D(TC)	2.03	0.52
T(DC)	-0.97	0.12
DA(ATC)	0.77	0.07
CA(DAT)	0.71	0.06
TA(DAC)	0.31	0.01
A(DATC)	-0.29	0.01
C(TD)	-0.03	0
	TOTAL	0.79

DESIGN 2		
Effect	Est.*	Mn. Sq.@
D(PC)	2.02	0.51
P(DC)	-1.14	0.16
DA(APC)	0.88	0.10
PA(DAC)	0.68	0.06
CA(DAP)	0.60	0.05
A(DAPC)	0.08	0
C(PD)	0.02	0
	TOTAL	0.88

DESIGN 3		
Effect	Est.*	Mn. Sq.@
TA(DAH)	1.69	0.36
A(DATH)	-1.01	0.13
H(DT)	-0.85	0.09
D(TH)	0.75	0.07
DA(ATH)	-0.63	0.05
T(DH)	0.31	0.01
HA(DAT)	0.01	0
	TOTAL	0.71

DESIGN 4		
Effect	Est.*	Mn. Sq.@
PA(DAH)	1.38	0.24
A(PHDA)	-1.32	0.22
H(PD)	-1.28	0.20
D(PH)	1.18	0.17
HA(PDA)	-0.80	0.08
P(HD)	-0.30	0.01
DA(PHA)	0.18	0
	TOTAL	0.92

DESIGN 5		
Effect	Est.*	Mn. Sq.@
S(RAFS)	-6.04	2.28
R(AF)	5.80	2.10
F(AR)	-3.38	0.71
FS(RAS)	1.14	0.08
A(RF)	-1.06	0.07
AS(RFS)	0.34	0.01
FM(RAM)	-0.24	0
RS(AFS)	-0.24	0
M(RAFM)	0.10	0
RM	0.02	0
SM	-1.30	0.11
AM	1.04	0.07
RSM	0.22	0
FSM	0.20	0
SAM	0.04	0
	TOTAL	5.43

(RM to SAM bracketed: 0.030)

DESIGN 6		
Effect	Est.*	Mn. Sq.@
R(AX)	2.49	0.78
S(RAXS)	-1.87	0.44
XS(RAS)	0.97	0.12
A(RX)	-0.65	0.05
AS(RXS)	-0.35	0.02
RS(AXS)	0.31	0.01
X(RA)	0.11	0
	TOTAL	1.42

* $\times 10^{-2}$

@ $\times 10^{-4}$

KEY

D	FIBRE DIAMETER	F	FIBRE TYPE
T	TOP DYE	R	COUNT REGULARITY
C	TOP CHLORINATION	S	TWIST LEVEL
A	AUTOCLAVE SET	M	MOISTURE REGAIN
P	PACKAGE DYE	X	TWIST METHOD
H	HERCOSETT TREATMENT		

Figure 80 Source of Variation for Flexural/Torsional Rigidity

coarser fibres caused flexural rigidity to rise proportionally more than torsional rigidity. At the 5% level of significance in Designs 3 and 4 are, in the first position, TA and PA both with the alias DAH (see subsection 6.5.2). This second order alias is one which has been suspected to influence loop distortion. It is worth noting that the effect of fibre diameter did not reach a level of significance above 5% in either of these two designs. The only difference between the design pair 1 and 2 and pair 3 and 4 is that chlorinated samples were replaced by Hercosett treated samples in the latter pair. These are surface treatments and unlikely to affect the fibre diameters to a significant extent; however the fibre:fibre friction levels are likely to vary, and consequently one might expect different contributions of interfibre friction to the coercive couples. In the first two designs, chlorination had no effect on the ratio of flexural to torsional rigidity. In Designs 3 and 4, Hercosett treatment (H) and the two main effects D and A take places 2-4 in the estimate rankings and the interaction between the three, DAH, the first place.

Design 5 features three parameters of significance at the 1% level: twist level, fibre type and count regularity. Since we have seen in the previous two subsections that twist level has little effect on flexural rigidity but increases torsional rigidity significantly, the importance of twist level on the ratio is to be expected. Twist level is a factor of particular significance for acrylic, but even in wool-only Design 6 it reaches a 1% level of significance.

Figure 47 shows the relationship between "fine" wool and "fine" acrylic groups at two levels of count regularity. The generally higher level of the ratio for wool is confirmed by the analysis of variance result. The third significant effect is count regularity (alias AF); regularity is also of significance at the 1% level in Design 6 (the alias in this case is AX). It has been shown in the two previous subsections that AF is likely to influence flexural rigidity, but that variations in mean torsional rigidity can be accounted for by different levels of count regularity:

-R → +R produces a significant decrease in torsional rigidity

-AF → +AF produces a significant decrease in flexural rigidity

Consequently, in Design 5, the alias pair [R]+[AF] have a cumulative effect on the ratio of flexural/torsional rigidity. A change in level from -R to +R is equivalent to a change from +AF to -AF; the effect is for the numerator in the ratio to increase and the denominator to decrease. Hence we see a highly significant effect for the alias pair on the estimate for the ratio. In Design 6 a similar effect is seen, but here the significance of the estimate is likely to be due to the effect of only one of the aliases: the reduction of torsional rigidity at high irregularity.

6.7.7. Bending Hysteresis

Figure 81 summarises the Analysis of Variance for the six experiments in terms of bending hysteresis. Mean square values exceeding 6.44 x 10^{-16} are significant at the 5% level and those exceeding 14.73 x 10^{-16} are significant at the 1% level. In the five wool-only experiments the significant factors are autoclave setting, package dyeing, fibre diameter (Design 1 and 2) and the interaction PA (Design 2 only, although the two separate main effects are of higher significance). Figure 73 gives a useful illustration confirming the differentiation of these yarn groups in terms of bending hysteresis.

DESIGN 1			DESIGN 2			DESIGN 3			DESIGN 4			DESIGN 5			DESIGN 6		
Effect	Est.*	Mn. Sq.@	Effect	Est.*	Mn. Sq.@	Effect	Est.*	Mn. Sq.@	Effect	Est.*	Mn. Sq.@	Effect	Est.*	Mn. Sq.@	Effect	Est.*	Mn. Sq.@
A(DATC)	-15.55	30.22	P(DC)	-15.89	31.56	A(DATH)	-12.81	20.51	A(APHD)	-8.55	9.14	F(RA)	51.65	166.74	A(RX)	15.09	28.45
D(TC)	11.97	17.91	D(PC)	11.27	15.88	H(DT)	-4.53	2.57	P(HD)	-8.33	8.67	A(RF)	39.94	99.71	AS(RXS)	4.54	2.58
T(DC)	-6.73	5.66	A(APDC)	-10.47	13.70	D(TH)	4.17	2.17	PA(AHD)	5.21	3.39	R(AF)	20.70	26.79	X(RA)	1.80	0.40
DA(ATC)	-5.31	3.52	PA(ADC)	9.19	10.56	DA(ATH)	-2.15	0.58	H(PD)	-4.07	2.07	SA(RFS)	9.36	5.47	S(RAXS)	1.41	0.25
TA(DAC)	4.11	2.11	DA(PAC)	-5.73	4.10	T(DH)	1.07	0.14	D(PH)	3.71	1.72	FM(RAM)	6.34	2.51	RS(AXS)	0.85	0.09
CA(DAT	2.23	0.62	C(PD)	2.19	0.60	TA(DAH)	0.95	0.11	DA(PHA)	-1.75	0.38	M(RAFM)	5.87	2.15	XS(RAS)	0.78	0.08
C(TD)	1.49	0.28	CA(PDA)	-1.81	0.41	HA(DAT)	0.51	0.03	HA(PAD)	0.11	0	RS(AFS)	4.46	1.24	R(AX)	0.61	0.05
	TOTAL	60.32		TOTAL	76.81		TOTAL	26.11		TOTAL	25.37	S(RAFS)	3.49	0.76		TOTAL	31.90
												FS(RAS)	2.02	0.26			
												RM	0.19	0			
												SM	1.91	0.23			
												AM	9.52	5.67			
												RSM	2.43	0.37	}1.075		
												FSM	1.72	0.18			
												SAM	0.03	0			
													TOTAL	312.08			

* $\times 10^{-8}$

@ $\times 10^{-16}$

KEY

D	FIBRE DIAMETER	F	FIBRE TYPE
T	TOP DYE	R	COUNT REGULARITY
C	TOP CHLORINATION	S	TWIST LEVEL
A	AUTOCLAVE SET	M	MOISTURE REGAIN
P	PACKAGE DYE	X	TWIST METHOD
H	HERCOSETT TREATMENT		

Figure 81 Source of Variation for Bending Hysteresis

Package dyed wool yarns tend to have the lowest values, then autoclaved wools and finally unset wools. The difference between coarse and fine wools is not great, but the coarser wools have a slightly higher average bending hysteresis. Experimental Design 5 yielded three parameters of significance: fibre type, autoclave setting and regularity. Figure 46 has illustrated clearly the high bending hysteresis of acrylic yarns compared with wool yarns. For both wool and acrylic, the value is reduced if the yarns are autoclave set. Although count regularity is apparently a significant effect in Design 5, it is of no significance in wool-only Design 6. We saw in subsection 6.7.4. that it was actually the alias of regularity, AF, which influenced the bending rigidity. Perhaps the same interaction also influences bending hysteresis. A tabular presentation of the results for Design 5 shows that this is the case:

MEAN BENDING HYSTERESIS ((N.m. x 10^{-8}

	Acrylic	Wool	All Fibres
Regular	8.93 (SET)	7.46 (UNSET)	8.20
Irregular	16.51 (UNSET)	5.07 (SET)	10.80

Taking all yarns together, there is an apparent increase in mean bending hysteresis for irregular yarns. However, when the two fibre types are separated, it is seen that the irregular (set) wool yarns have a lower bending hysteresis than regular (unset) wool yarns. The effect seen is the fibre type/autoclave setting interaction; both fibre types have a lower bending hysteresis after setting but the magnitude of the change is much greater for acrylic. But although the AF interaction is significant at the 1% level, the two individual main effects produce yet larger estimates.

CHAPTER SEVEN

DISCUSSION

7.1. INTRODUCTION

From a commercial point of view, the actual mechanism by which loop distortion takes place may not be of primary interest. The first priority is likely to be to find the most economic way of changing a processing route to achieve an acceptable level of loop distortion. In section 6.5 we have directly linked yarn production and processing variables to loop distortion and it is possible to identify the major sources of the problem and to suggest how the problem might be alleviated. The textile technologist would argue that this does not answer the fundamental question of how loop distortion actually comes about. If we can answer this, then we might be in a position to devise other means to reduce loop distortion, for example a new chemical treatment, than by simply choosing the optimum conditions within a range of existing production and processing parameters.

As was envisaged in the review of past work on this subject (section 2.3) the mechanism controlling the development of loop distortion is quite complex. A number of physical characteristics of a yarn can be related to loop distortion and each of these characteristics is, in many cases, influenced by a few different production and processing conditions.

7.2 IMPLICATIONS FOR THE MANUFACTURER

We will firstly summarise the findings of this work from a commercial viewpoint by directly relating loop distortion to the yarn production route. Figure 60 should be referred to, this ranking the variables which have been shown to influence loop distortion at the 1% significance level.

Although the variables are listed in order of influence, this only applies to the particular levels chosen for the variables. We can say, for instance, that package dyeing will cause more loop distortion than dyeing the same shade by a top dye route. Similarly, we can say that substituting a 60's quality wool with a 52's quality wool will cause more loop distortion than if we had package dyed the yarn spun from the 60's quality wool. But what if we used a 56's quality wool instead of the 52's, or dyed to deeper shade which requires a longer boiling time? In fact, all of the eleven independent variables, with the exception of the twisting method, could be considered continuously variable (e.g. wool/acrylic blends, different autoclave setting temperatures, etc.). A two level factorial design cannot be expected to paint more than a broad picture and indicate areas where more detailed research might be fruitful. Nevertheless, we are in a position to make some positive statements of direct application to industry:

1. Loop distortion increases with increasing wool mean fibre diameter.

2. Autoclave steamed wool yarns distort more than unset wool yarns.

3. Package dyed wool yarns distort more than yarns which have been top dyed to the same shade.

4. Top dyed wool yarns distort more than undyed wool yarns

5. Acrylic yarns distort less than equivalent wool yarns.

6. Loop distortion tends to increase with the level of yarn count irregularity.

7. Chlorinated and chlorine/Hercosett treated unset wool yarns do not produce significant loop distortion.

8. Loop distortion tends to increase with increasing level of twist.

In addition, there are other statements which could be made, but they would have to be qualified by referring to steaming temperatures, boiling times, etc.

For the variable levels chosen, fibre diameter was one of the most important parameters. Detailed work on the effect of mean fibre diameter and also fibre diameter distribution would be very worthwhile. The latter parameter is one which has been mentioned only briefly in this work, but a recent report[106] has given evidence that a small proportion of coarse fibres in an otherwise fine blend could lead to distortion problems. Such work should investigate the effect of fibre diameter not only on loop distortion and irregularity (which is well known to increase with fibre diameter) but also on other characteristics of the yarn discussed in the next subsection. Furthermore, such work would also be of greater commercial value if changes in distortion were related to that produced by other processing stages so that a spinner could choose the optimum economic route by which to obtain an acceptable product. To produce a suitable yarn it might, for instance, be cheaper for a spinner to keep to his normal blend and use a hank dyeing route rather than continue to package dye a more expensive blend of finer quality wool. The choice will vary with fluctuations in the price of raw materials and labour, the required delivery time for the yarn, etc. but the basic information should be available so that the choice can be made.

Perhaps one of the most disturbing findings has been the extent to which the package dyeing of wool yarns permits loop distortion to develop. Setting processes applied to a yarn have the effect of making loop distortion worse. The series UNSET-TOP DYED-AUTOCLAVE STEAMED-PACKAGE DYED is one of increasing severity of setting, the last involving, typically, an hour of boiling. Package dyeing has become increasingly popular as a yarn dyeing route in recent years for economic reasons and for the advantages of late-stage colouration (permitting faster response to orders, since undyed yarn can be held in stock). Industry may be reluctant to revert to top or hank dyeing and it must be accepted that package dyeing is likely to become yet more wide spread. Nevertheless, complaints of loop distortion from knitters seem to be on the increase and package dyeing may often be the culprit. There would seem to be an urgent need for work in this area, to reduce the setting severity of the package dyeing process. Reducing the dyeing temperature, for instance, could be one possible method.

The influence of wool shrink-resist treatments on loop distortion is also worthy of further study. Although it has been shown that chlorination and Hercosett treatments by themselves do not produce loop distortion, there have been unpublished reports from industry that loop distortion does seem to be related to the use of Hercosett yarns. These yarns will normally have been steamed and there could be a relationship here with the findings in the present work of the importance of the interaction DAH (fibre diameter - autoclave setting -Hercosett treatment), which appeared to be more important than autoclave setting alone (Figure 60). The interaction has also been correlated with flexural rigidity at the 5% level, a characteristic closely related to loop distortion and discussed further in the next subsection.

Loop distortion is essentially a short-term manifestation and, as shown in Figure 14, many workers relate it to the short-term variations in count in a yarn, the count regularity. The average regularity of commercial yarns has tended to deteriorate in recent years as spinners have responded to economic constraints partly by using shorter processing routes but especially by using slightly coarser (and cheaper) wools. The I.W.T.O. values given in Figure 82 show that an increase of two microns in fibre diameter will lead to a significant increase in U% for a singles yarn, typically 0.8-1.2%. These two commercial trends, the move towards package dyeing and the increase in yarn irregularity, are likely to be fundamental to the noticeable increase in loop distortion in knitwear, particularly that produced from wool botany yarns.

Acrylic yarns are nowhere near as susceptible to distortion as wool. There are apparently a number of reasons for this, related to the physical properties of the yarn; these have already been discussed to some extent in the previous section and they are now summarised below.

7.3 IMPLICATIONS FOR THE TEXTILE TECHNOLOGIST

We may begin summarising the physical causes of loop distortion with the example of the difference between acrylic and wool. The physical differences between wool and acrylic yarns may be listed as follows:

1. The torsional rigidity of acrylic yarns tends to be higher than that of equivalent wool yarns (Figure 43).

2. The bending hysteresis of acrylic yarns tends to be higher than that of equivalent wool yarns (Figure 46).

3. Acrylic yarns tend to have a lower value of flexural/torsional

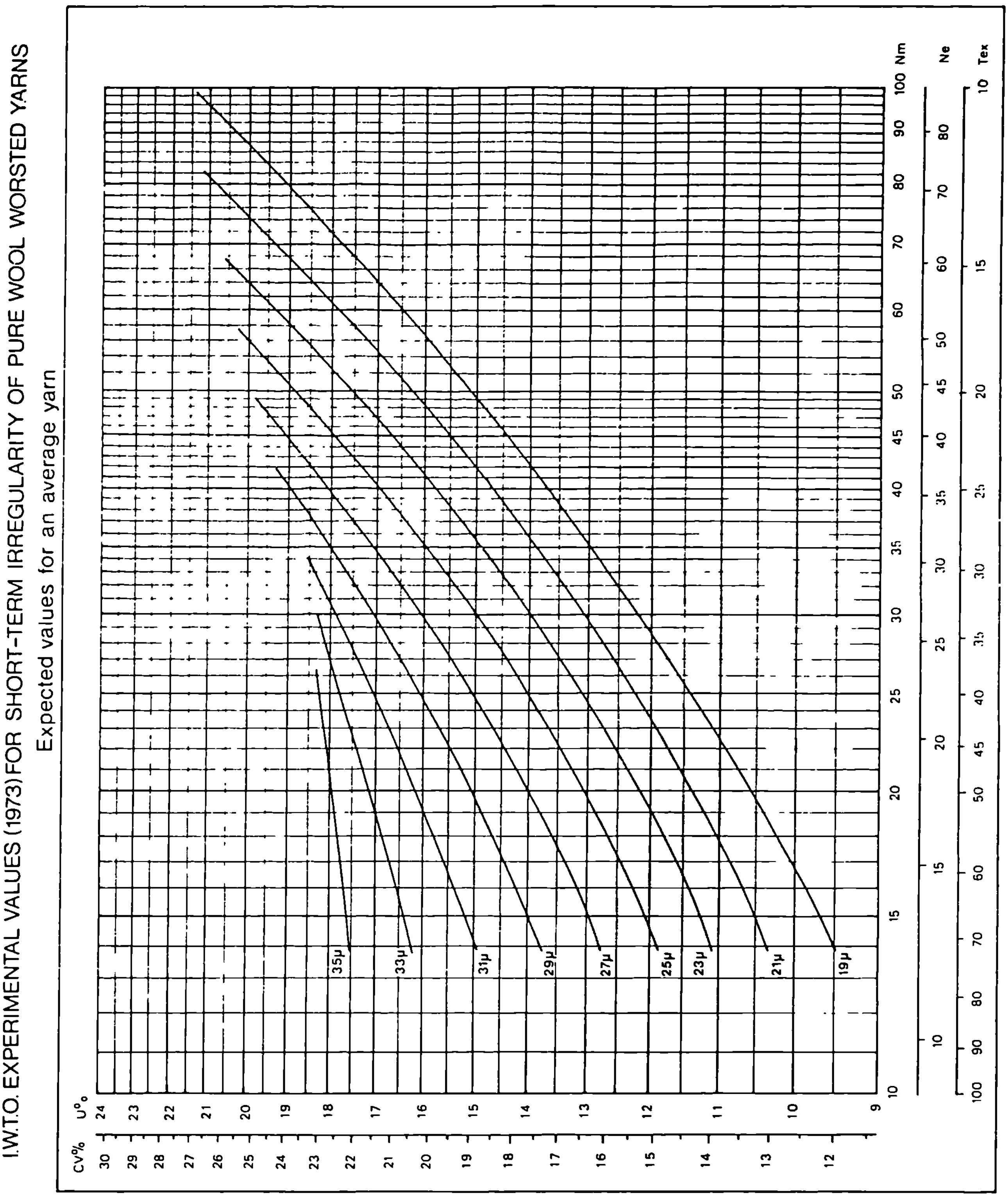


Figure 82 The Influence of Fibre Diameter on Count Regularity

rigidity than equivalent wool yarns (Figure 47).

4. Acrylic yarns tend to be more regular than wool yarns of the same mean fibre diameter (Figure 47).

But we have already seen that loop distortion increases with increasing irregularity (Figure 68), increasing value of flexural/torsional rigidity (Figure 71) and decreasing bending hysteresis (Figure 73), so wool is clearly disadvantaged. Another aspect is the different responses of the two fibres to moisture and steam, and the repeated occurence of the interaction AF in the analyses of section 6.7 is a reflection of this.

In order to clarify the importance of the many physical properties and even larger number of production and processing characteristics which appear to influence loop distortion we have tabulated the parameters which are correlated at the 1% significance level, and these are shown in Figure 83. This table was compiled by first referring to Figure 67 and extracting the four yarn physical properties correlating with loop distortion within the full set of thirty seven samples. Referring then to Figure 60, a list was made of the sixteen independent production and processing variables and interactions correlated with loop distortion at the 1% level. Of these, nine had been correlated with the four physical properties at the 1% significance level in section 6.7.

The experiments were designed such that, within each, every production and processing parameter was independently variable. However, the physical properties were not necessarily so, as was shown for certain properties in section 6.3. Correlation coefficients for the four dependent physical properties in Figure 83 were calculated as follows:

	Count Regularity	Twist Regularity	Flexural/torsional Rigidity	Bending Hysteresis
Count regularity	1.000			
Twist regularity	0.914	1.000		
Flex/tors. rig'y	0.694	0.552	1.000	
Bending hyst.	0.416	0.323	0.139	1.000

Coefficients exceeding 0.32 represent significance at the 5% level, those exceeding 0.42 are significant at the 1% level. The high correlation between count and twist regularity has been illustrated in Figure 41 and the relationship between the flexural/torsional rigidity raio and count regularity plotted in Figure 47. As discussed in section 6.3, the latter correlation defines the relationship only crudely. When the yarns are divided into the five fibre groups isolated in Figure 47, we see within each group a relatively wide range of values for the ratio for a narrow range of U% values. In other words, when the groups are taken individually the correlation between the two variables is not so clear. Nevertheless, we have been able to account for the influence of regularity on the ratio of flexural/torsional rigidity (sections 6.7.5, 6.7.6 and Figure 79b) but the ratio is also seen, from Figure 47, to be independently influenced by the fibre characteristics. Following the high correlation between count and twist regularity, the relatively high correlation coefficient between flexural/torsional rigidity and twist regularity (0.552) is not unexpected.

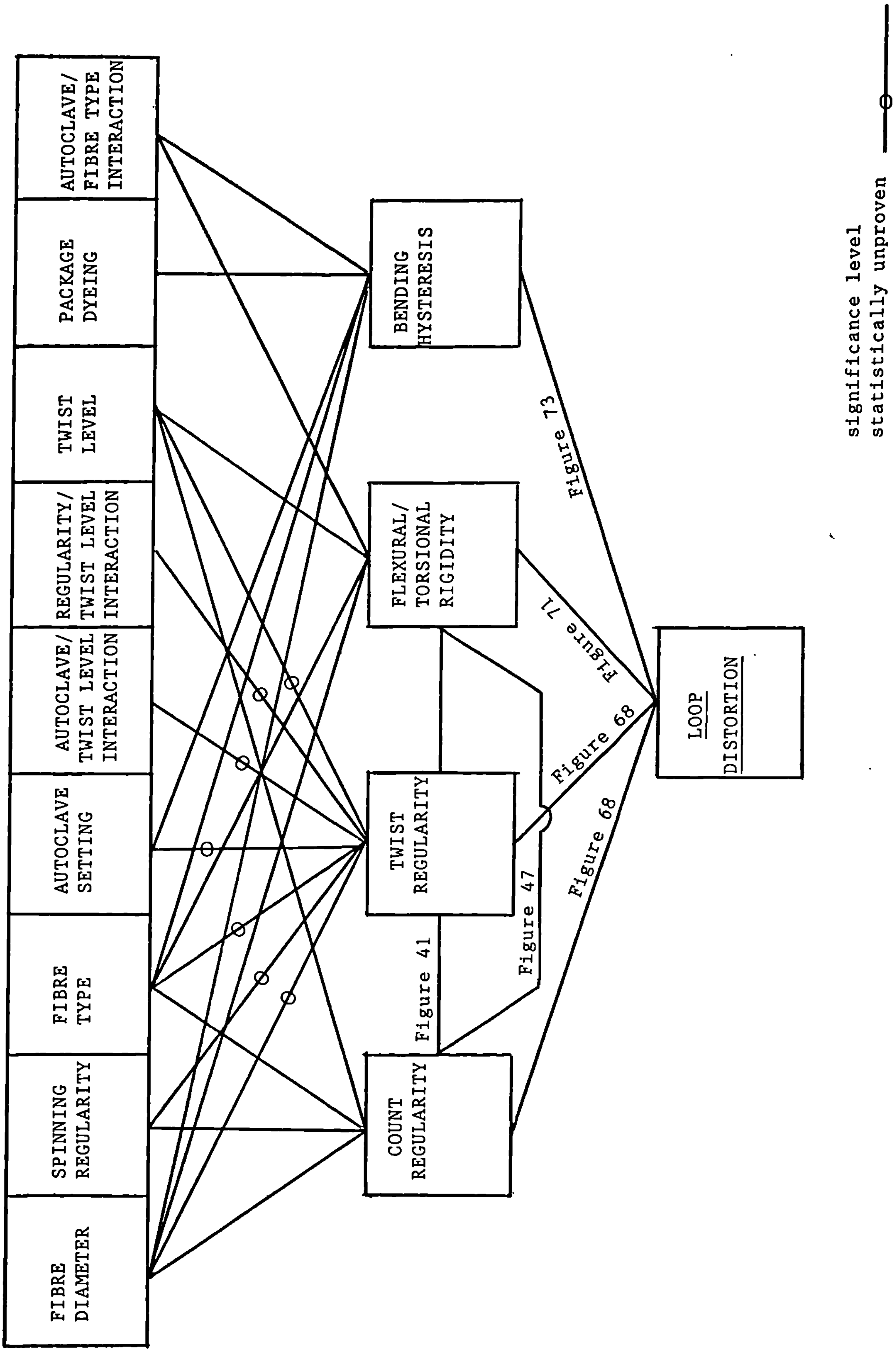


Figure 83 Correlations with a Significance at the 1% Level (all samples)

Loop distortion, we may postulate, is produced by at least two types of yarn characteristic, one short-term (which is reflected in the short-term nature of the defect) and one long-term, in order to account for the range of loop distortion known to occur within yarns having the same short-term characteristics (i.e. count and twist regularity).

The four characteristics listed in Figure 83 comprise two from each group. The two short-term characteristics are closely related, although twist regularity is also influenced by setting processes (Figure 41). If we were looking for a short-term variable through which we could attempt to predict loop distortion, we might prefer, of the two, twist regularity because it is influenced by the yarn setting processes which, we have seen, affect loop distortion. Conversely, from a practical point of view, we might prefer to use the count regularity as the "short-term" factor because it can be more easily measured, and ensure that the "long-term" factor was influenced by the setting processes. The ratio flexural/torsional rigidity is a long-term variable which has been shown to theoretically influence three-dimensional loop shape, but has the disadvatage of being influenced by the regularity of the yarn. Furthermore, it is not significantly influenced by autoclave setting or package dyeing which are important in the development of loop distortion. So, for example, an attempt to define loop distortion purely in terms of U% regularity and flexural/torsional rigidity would be unsatisfactory because it would not include factors influenced by yarn setting. In fact, only bending hysteresis is influenced by package dyeing (which certainly influences loop distortion) and therefore this factor, which is sensitive to yarn setting processes in general, must be regarded as the more important long-term factor for loop distortion prediction.

Let us plot values of a short-term parameter against those for a long-term parameter for all yarns and superimpose upon this the levels of loop distortion. We may choose in the first instance U% count regularity and bending hysteresis. This scattergram is shown in Figure 84; the actual sample code numbers are given with each point for further reference. For simplicity we have reduced the fourteen significantly different levels of loop distortion listed in Figure 51 to only four, arbitrarily designated "very poor" (ranked 1.5-9.5), "poor" (ranked 13.5-20.5), "acceptable" (ranked 24.5-33) and "good" (ranked 34.5-36.5). Figure 84 appears to demonstrate the disadvantage of wool's low bending hysteresis regarding the formation of loop distortion. If we imagine, for instance, a wool yarn and an acrylic yarn of the same irregularity, say with a U% value of 9.0, the bending hysteresis of the wool yarn is likely to be in the 3-6 x 10^{-8} $N.m^2$ range and the acrylic above 8 x 10^{-8} $N.m^2$ (Figure 46 illustrates the typical spread of values). For these fixed values of bending hysteresis, if the irregularity increases, the wool shifts from the "acceptable" zone to the "very poor" zone on reaching a U% value of 12. The irregularity of the acrylic yarn can deteriorate to a value of 18 or higher and still not reach this high level of loop distortion.

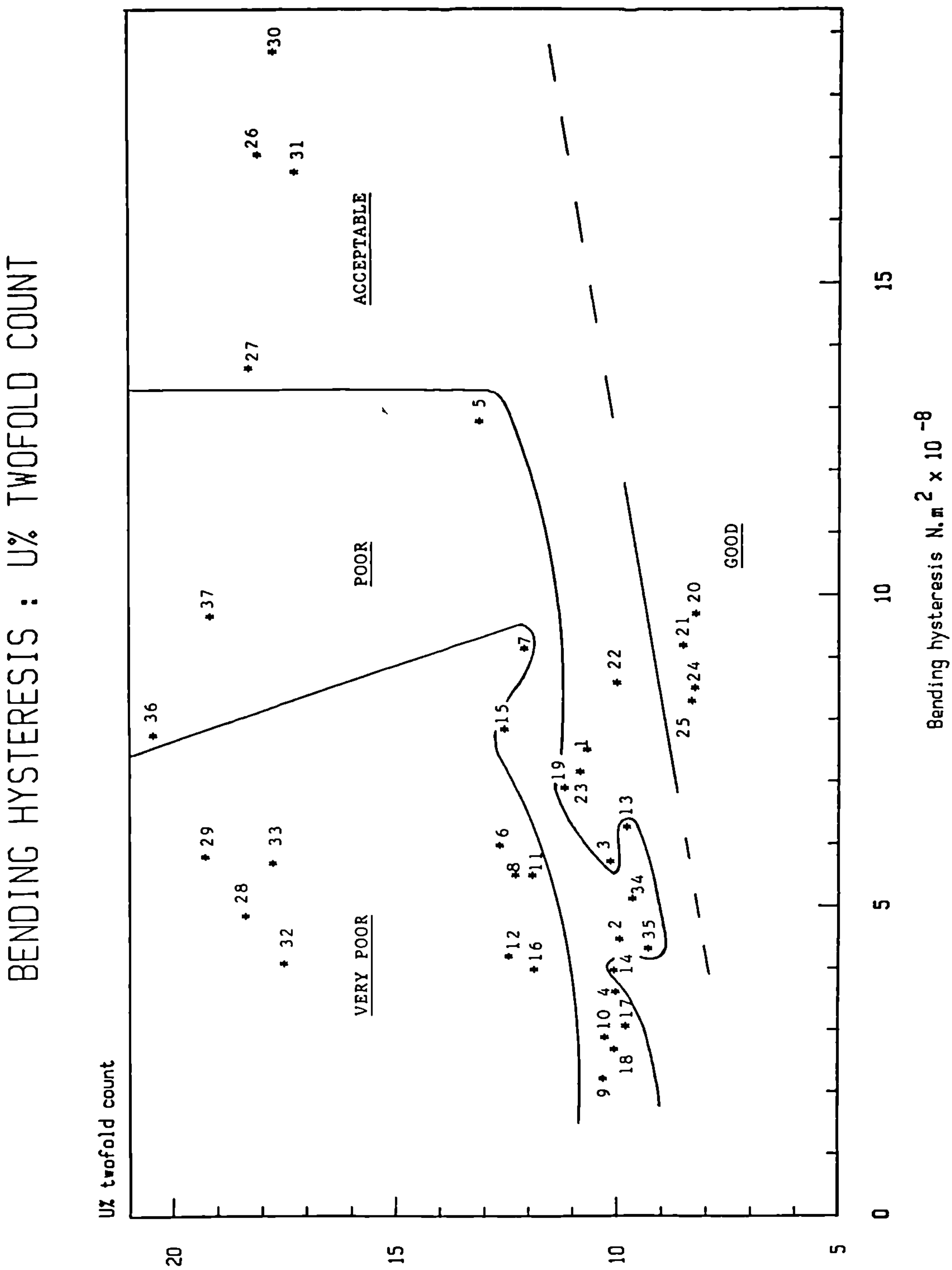


Figure 84 The Influence of Count Regularity and Bending Hysteresis on Loop Distortion

Figure 85 illustrates the relationship between bending hysteresis and twist regularity. Overall the pattern is very similar to that of Figure 84, although the divisions between the zones are a little confused by one or two values. Sample 14, for instance (autoclave set,top dyed Hercosett wool), is shifted from the "unset" (Sample 13, top dyed Hercosett wool) position in relation to both axes by its setting treatment; in Figure 84 it was shifted only in relation to the x-axis (count regularity being unaffected by setting processes). Similarly, sample 16 is "very poor" and yet has a lower CV% twist regularity than sample 14, which is "acceptable". But if we refer to Figure 84, sample 16 is seen to have a higher count irregularity than sample 14 and here the positions of the two samples within their respective zones is as we might expect them. In other words, the yarn setting processes are primarily important in terms of loop distortion in so far as they affect the bending hysteresis. We know that these processes also influence twist regularity (Figure 41) but the importance of twist regularity regarding loop distortion is primarily in its close correlation with count regularity and the secondary influence of setting may complicate the use of the parameter for loop distortion prediction. Disregarding twist regularity, however, does mean that the two twist level interactions listed in Figure 83 are not taken into account, since these parameters are not significantly correlated with any other characteristics. Ultimately, it might be preferable to use twist, rather than count, regularity but it may be desirable to apply a correction factor to the values to allow for the effect of the setting processes in order to simplify the relationships.

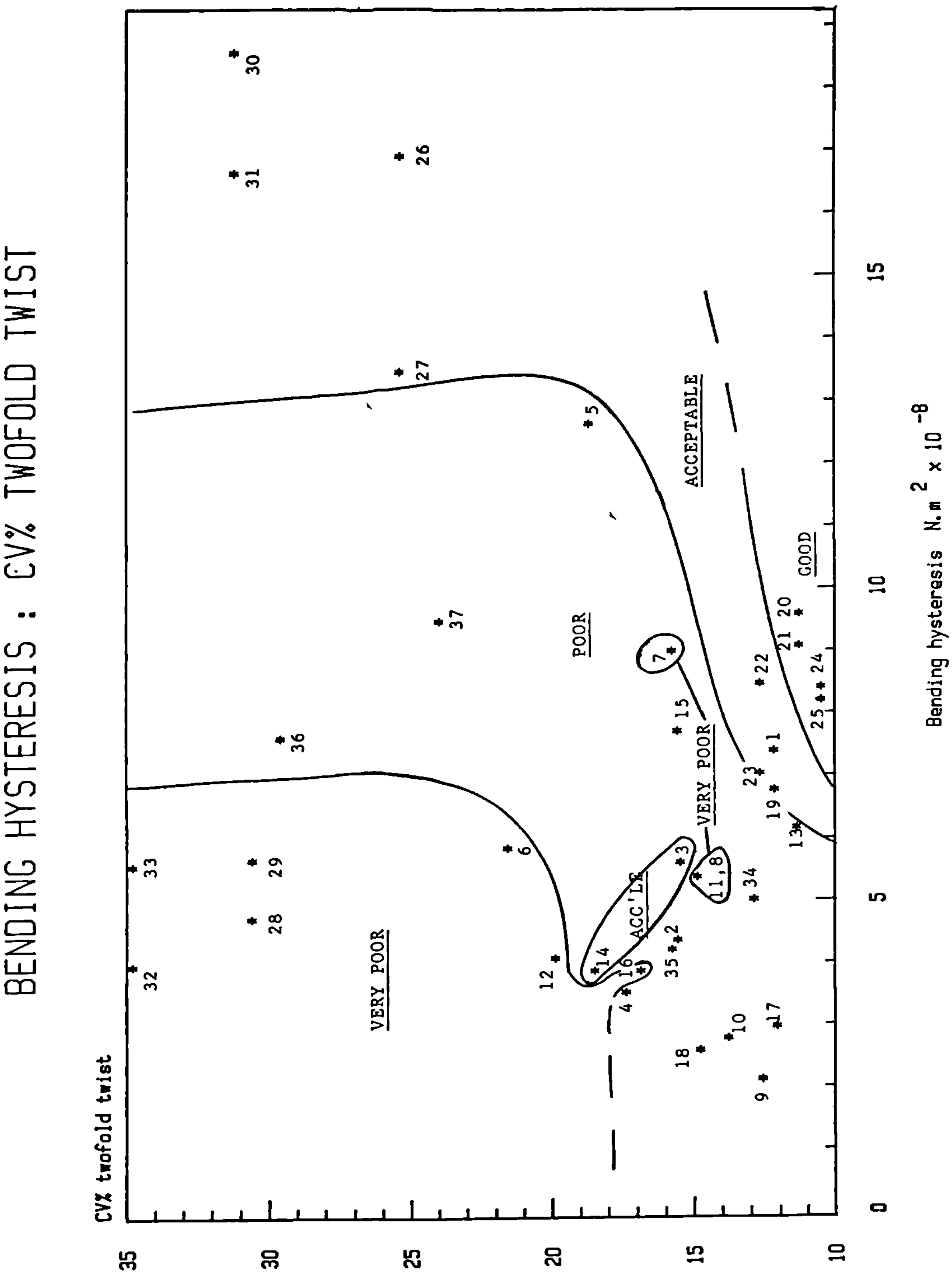


Figure 85 The Influence of CV% Twofold Twist and Bending Hysteresis on Loop Distortion

Finally, we should examine the possibility of predicting loop distortion using three yarn-related characteristics: count regularity, flexural/torsional rigidity and bending hysteresis. These variables may be plotted on a graph using three orthogonal axes, x (bending hysteresis), y (flexural/torsional rigidity) and z (U% count regularity). The x-y and y-z projections are shown in Figures 86 and 87 respectively. These projections appear to be less useful than the x-z projection (Figure 84) in terms of loop distortion zoning; the zones tend to contain inliers and anomalies due to the influence of the third variable. For instance, in Figure 87, the group of "acceptable"/"poor" samples with high irregularity had high values of bending hysteresis, which is not revealed on the plot.

Consequently, it appears that the inclusion of a third parameter, flexural/torsional rigidity, does not permit a more accurate prediction of the level of loop distortion beyond that given by the two parameters of Figure 84 alone. If we refer to Figure 73 it is seen that there are effectively two bending hysteresis : loop distortion curves, "coarse fibres" and "fine fibres". Although there is a correlation between fibre diameter and count regularity (Figures 75 and 82) the two curves could be differentiated by the level of flexural rigidity, as shown in Figure 69. Flexural rigidity, therefore, could be an alternative second long-term parameter, preferable to flexural/torsional rigidity, although as the only long-term parameter it would prove too crude an indicator. Flexural rigidities should be measured at one fixed relative humidity. The

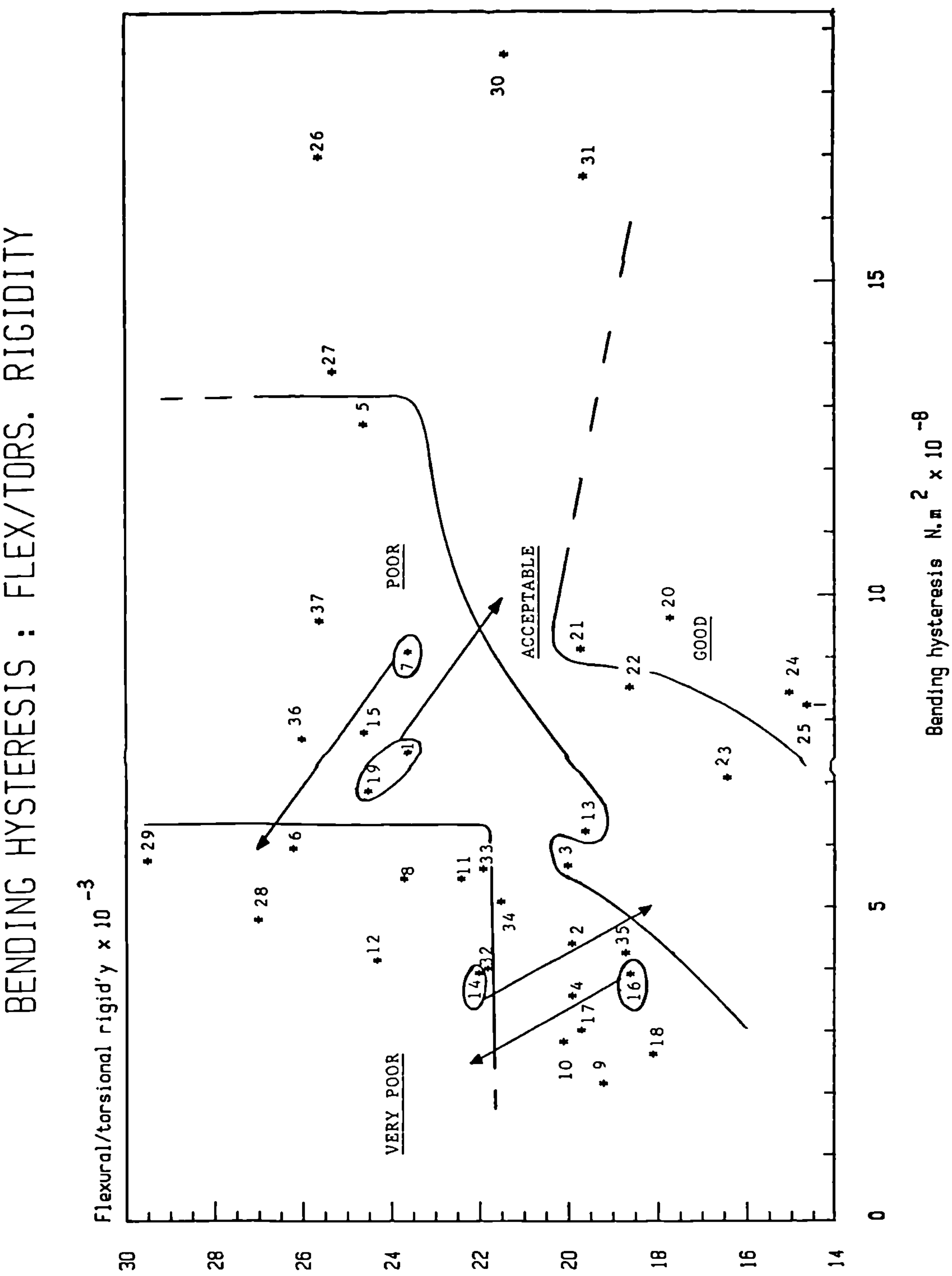


Figure 86 The Influence of Flexural/Torsional Rigidity and Bending Hysteresis on Loop Distortion

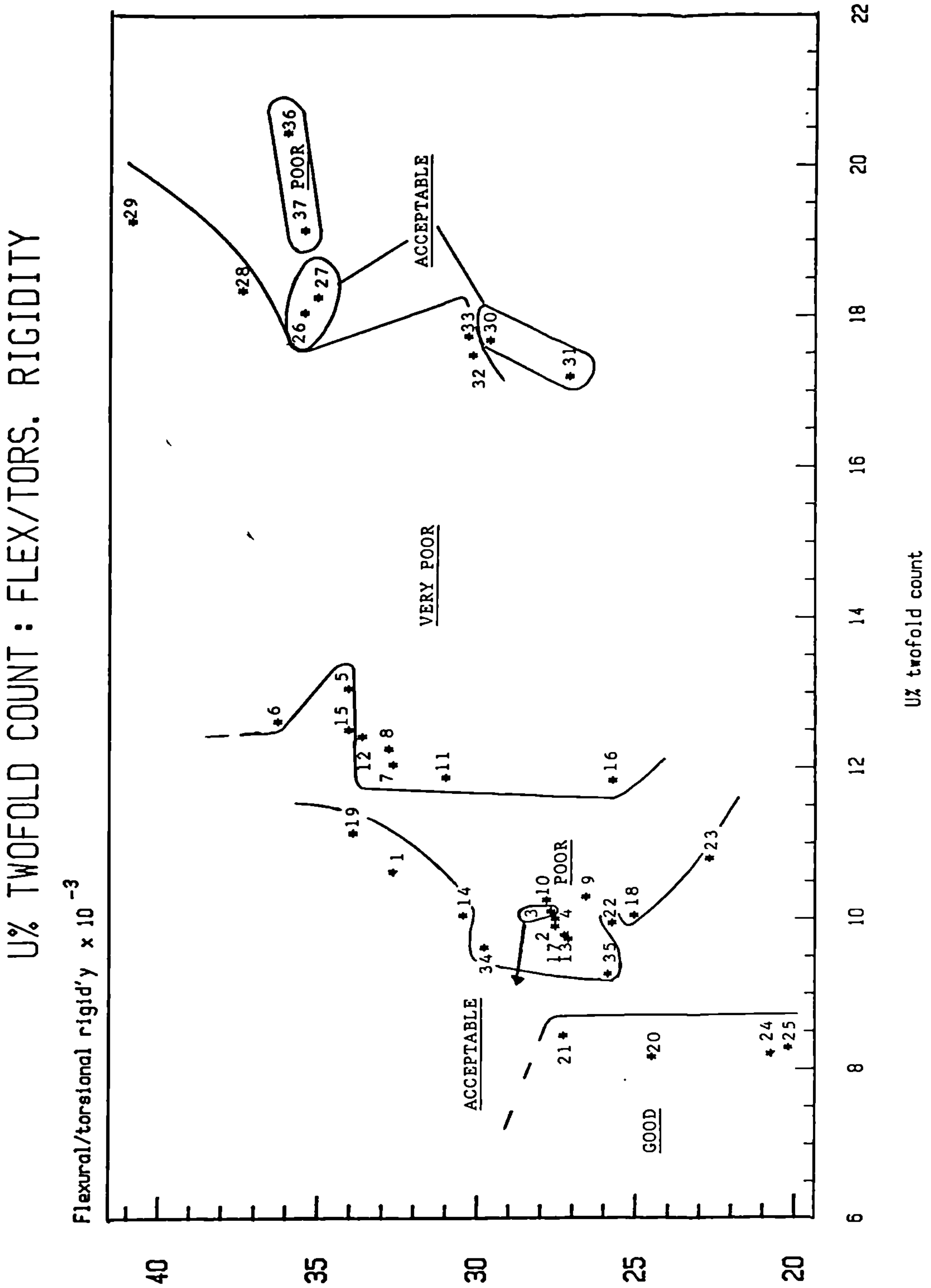


Figure 87 The Influence of Flexural/Torsional Rigidity and Count Regularity on Loop Distortion

inclusion of low and high regain samples in the first column of Figure 67 suggested no correlation between loop distortion and flexural rigidity, but when the high regain samples were eliminated the correlation was of significance at the 1% level.

The two worst samples were numbers 11 and 29 (Figure 51). Figure 24 shows that Sample 11 was very stiff, with a flexural rigidity of 20.2 x 10^{-10} N.m^2. The value for Sample 29 was only 9.4 x 10^{-10} N.m^2 at the time of knitting (it was conditioned to high regain) although subsequently, during relaxation and assessment, it followed exactly the same route as Sample 11. The stiffness of Sample 29 under "low" humidity conditions would have been 13.5 x 10^{-10} N.m^2 (the same as Sample 28) which, although over 40% stiffer, is still well below that of Sample 11. Referring to Figure 84, samples 29 and 11 are both within the "very poor" zone, but well separated within it. Sample 29 is particularly bad because it combines very high irregularity with relatively low bending hysteresis; Sample 11 is particularly bad because it combines very high stiffness with relatively low bending hysteresis and relatively high irregularity.

Figure 88 shows levels of flexural rigidity superimposed upon the regularity : bending hysteresis plot of Figure 84. For clarity, samples have been divided into groups of "low rigidity" (below 14.0 x 10^{-10} N.m^2), "medium rigidity" (14.0-17.0 x 10^{-10} N.m^2), and "high rigidity" (above 17.0 x 10^{-10} N.m^2). High humidity samples were assigned the values of their low humidity counterparts to avoid anomolous results. The "very poor" zone contains two major groups -

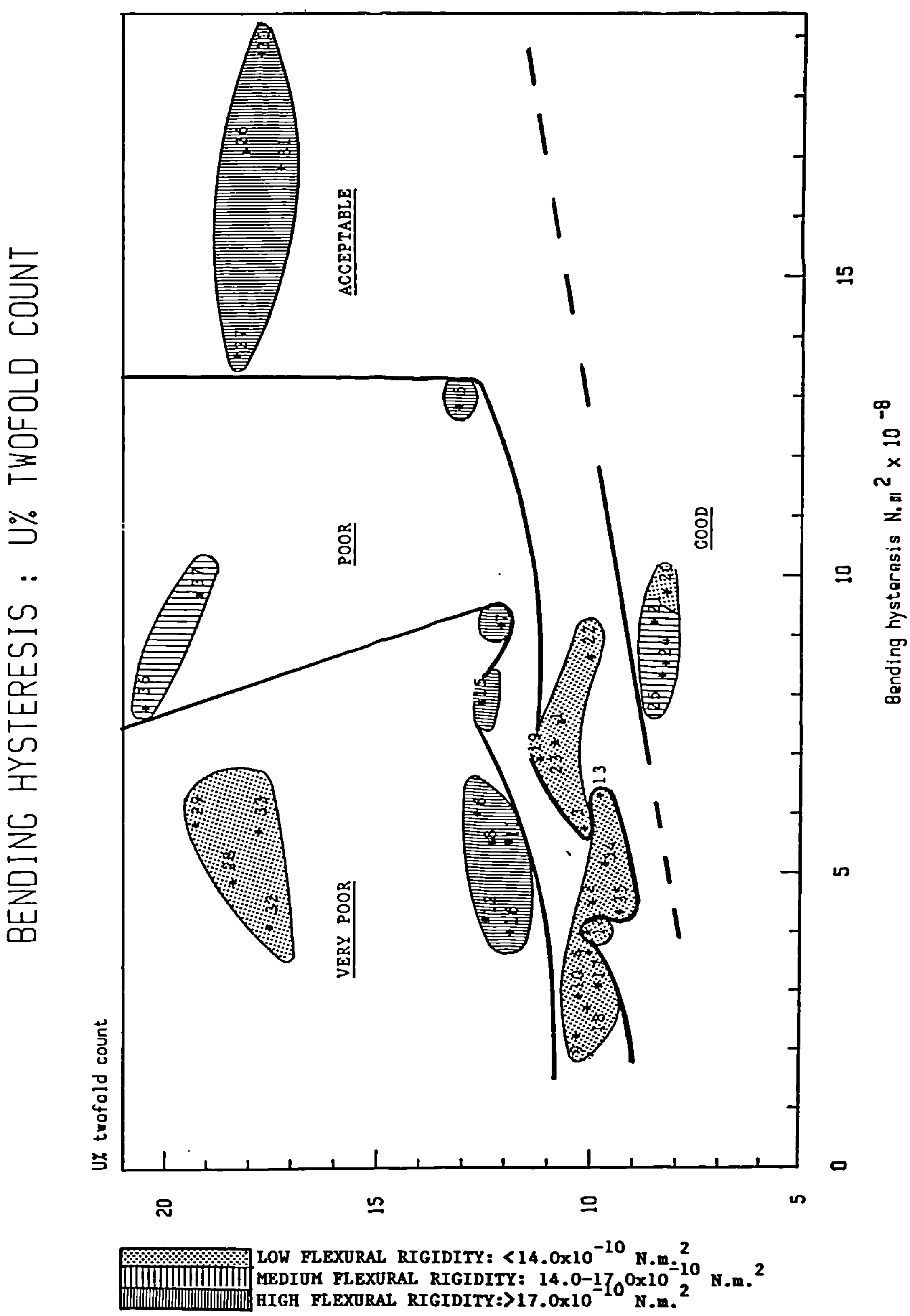


Figure 88 Loop Distortion as a Function of Count Regularity Bending Hysteresis and Flexural Rigidity

low rigidity/high irregularity and high rigidity/medium irregularity. Both groups have low bending hysteresis. The "poor" zone is roughly the form of a reversed "L"; starting at the left hand side, the samples have low irregularity and low rigidity, which is advantageous, but a low bending hysteresis which prevents them from being graded "acceptable". Moving to the right, the bending hysteresis increases, but this is counteracted by an increase in bending stiffness (Samples 15 and 5), so there is no net improvement. The zone then moves in the direction of the y-axis as the irregularity increases. This detrimental change is counteracted by a decrease in bending rigidity, so again there is no net change. Consequently, there are three main groups within the "poor" zone, and in each one there is a different detrimental factor preventing the group reaching a higher grading of loop distortion. Moving round the zone these factors are: too low a bending hysteresis, too high a bending stiffness and too high an irregularity.

There are two main groups within the "acceptable" zone. For the lower group, the only average bending hysteresis is more than compensated for by the low rigidity and relatively low irregularity. The other group is graded "acceptable" despite the high irregularity and high rigidity of the yarns. This demonstrates clearly the dominant influence of a high bending hysteresis in preventing loop distortion. The final zone, "good", contains samples of particularly low irregularity combined with fairly high bending hysteresis and rigidities which are either low or medium.

It is therefore apparent that three yarn variables are required in order to predict loop distortion to a reasonable degree of accuracy: count regularity, bending hysteresis and flexural rigidity. Although the first two are indispensable, flexural rigidity cannot be ignored.

We may surmise why these three factors influence the development of loop distortion in a plain knit structure. The defect is of short-term random character requiring a similar short-term yarn parameter for it to occur. If, for instance, the yarn were perfectly regular like a wire, whatever the long-term values of bending hysteresis, bending rigidity, etc., every loop would behave identically and the appearance of the fabric would be of overall uniformity even if a defect was apparent. Spirality, for instance, is a fabric defect produced by distorting loops which does not require a short-term yarn parameter in order to occur. A spiralled plain knit structure can be completely free of loop distortion as understood in the context of the present work. Immediately after knitting, the loops in plain knit structure are perfectly symmetrical but not necessarily in a relaxed state. Each individual loop will tend to distort from the symmetrical configuration until it reaches a minimum internal energy condition. In a yarn of irregular count each loop would be expected to distort to a different extent because variables such as flexural rigidity and bending hysteresis are dependent upon count. The "long-term", or mean, values of these variables will indicate, knowing the count regularity of a yarn, the range of short-term values of the variables to be expected. For instance, in two yarns of the same regularity, the thick places in the yarn of higher mean stiffness will be stiffer than equivalent thick places in the yarn of lower mean stiffness. Similarly, for two identical count yarns of the same mean stiffness, the more irregular yarn will contain thicker, and hence stiffer, places than the less irregular yarn.

Bending hysteresis and flexural rigidity could be regarded respectively as measures of the internal friction of the yarn and of the energy gradient between the relaxed state and the initial symmetrical configuration. For example, we could imagine an irregular copper wire knitted into a plain knit structure. It would not distort despite its irregularity and high flexural rigidity because copper is relatively plastic (i.e. it has a high bending hysteresis) and once bent into a shape it will remain there. Hence we can see the advantage that acrylic has over wool; acrylic yarn is less elastic than wool and tends to remain in its original knitted configuration. The degree of distortion will also depend on how far the symmetrical configuration is, in energy terms, from the relaxed state. This depends upon the flexural rigidity. Thus, a lot of loop movement can be expected if the yarn is stiff and has a low bending hysteresis; a steeper energy gradient is created within each loop for a given flexural or torsional strain and the internal friction is low so that on relaxation a close approximation to the minimum energy state is easily achieved. In this case, a wide range of loop movements will be observed (i.e. the level of loop distortion will be high) if the yarn is of irregular count.

A method for quantifying loop distortion in absolute terms would greatly assist research into the development of distortion-free yarns. The physical characteristics of a yarn, possibly others in addition to the three which have just been discussed, could be related directly to loop distortion, for instance by regression analysis. There is, however, little point in carrying out regression analysis for predicting dependent ranked values when the rank steps are of random unknown size. The difficulty of measuring loop distortion absolutely should not be underestimated. In section 2.2 different methods of assessment were discussed, the majority relying upon subjective judgement which inevitably produces ranked data. Prior to commencing the present work, two possible methods of absolute determination of loop distortion were investigated. Both relied upon producing a photographic negative of a fabric using high contrast film. In the first method, the laser diffraction pattern of a reduced size negative was analysed and in the second the distribution of the areas of the loop "holes" was determined (the area becoming smaller as a loop twists). Neither method gave very satisfactory results and, in particular, were not able to take into account the surface distribution of the distorted loops - whether the loops were evenly distributed over the fabric or occurred as a small number of prominent rows. However, if some similar technique could be refined, and if the measurements correlated closely enough with subjective assessment, it could prove a very useful tool for further research.

7.4. CONCLUDING SUMMARY

This work was initiated to investigate yarn-related loop distortion, as opposed to loop distortion influenced by knitting machine or fabric structural parameters. Despite a number of recent studies into the problem, complaints from the knitting industry have not abated. Because of the large number of variables which have been claimed to influence loop distortion, advice has been diverse and sometimes contradictory.

The present work set out with two primary aims. The first was to examine the major yarn production and processing variables claimed to be associated with loop distortion in order to assess their order of importance and to ascertain whether any of them interact. Such a study would assist in the optimisation of yarn production to minimise distortion and also highlight the particular variables upon which more detailed research should be concentrated. The second aim was to determine the mechanism by which loop distortion occurs, in terms of the physical parameters of the yarn, such parameters being dependent upon the production variables. This would permit not only an understanding of the reason for the importance of cerain production and processing variables, but would also help in the development of distortion-free yarns through new treatments or techniques. The work was centred upon the problems of wool botany yarns, but coarse wools and acrylic yarns were also examined.

It has been shown that in order to satisfactorily predict the extent to which a yarn is likely produce a distorted knitted fabric, at least three yarn characteristics should be taken into account. Loop distortion can be explained in relation to short term variations in bending hysteresis and flexural rigidity in a yarn. It is most convenient to express distortion in terms of the mean values of these variables and also the count regularity of the yarn. Further study may permit the inclusion of other variables but, ideally, such variables would be related to absolute, rather than ranked, values of loop distortion. It is envisaged that the absolute measurement of loop distortion would be difficult to achieve because of the many subjective factors which contribute to the impression of a distorted fabric.

Within the framework of half factorial experimental designs it has been possible to isolate and rank the major independent production and processing variables which are linked to the manifestation of loop distortion. Altogether, sixteen main effects and interactions were related to the defect at the 1% level of significance. Most of these, in turn, were associated with physical characteristics also shown to be related to distortion. For instance, the three most important characteristics were dependent upon the following main effects:

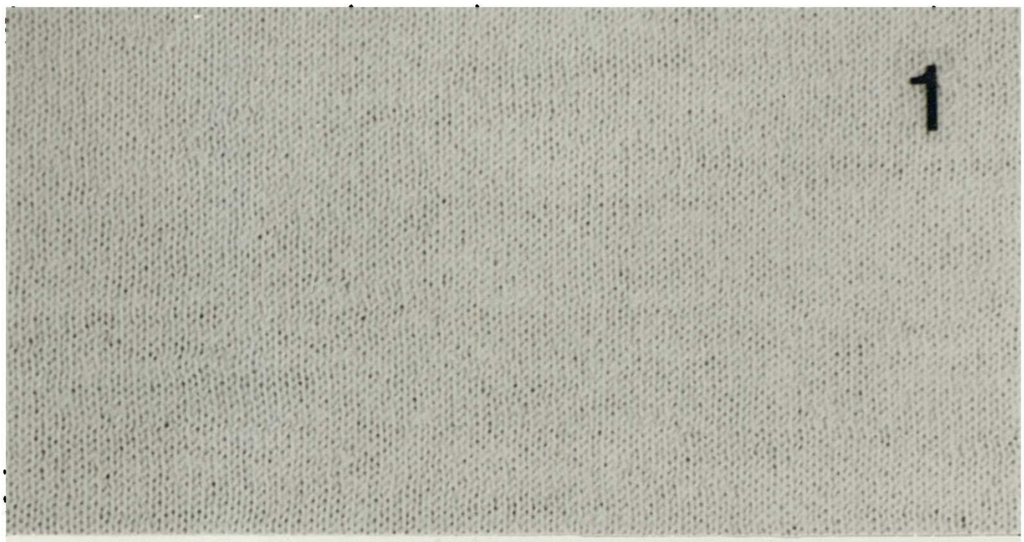
COUNT REGULARITY	BENDING HYSTERESIS	FLEXURAL RIGIDITY
mean fibre diameter	mean fibre diameter	mean fibre diameter
spinning regularity	fibre type	spinning regularity
fibre type	autoclave setting	fibre type
twist level	package dyeing	moisture regain

The conditions for minimum loop distortion are: low irregularity, high bending hysteresis and low flexural rigidity. The primary reason why wool is far more susceptible to loop distortion than acrylic is because of its much lower bending hysteresis. Bending hysteresis is reduced by yarn setting processes. Autoclave steaming and especially package dyeing significantly lower bending hysteresis and these processes can cause severe distortion problems. For a given fibre type, yarn flexural rigidity is primarily influenced by fibre diameter, although coarse, stiff fibres do not necessarily produce loop distortion if the bending hysteresis is high enough. Irregular yarn is a prerequisite for distortion; bending hysteresis and flexural rigidity are dependent upon yarn diameter and it is the short term variation of these parameters which causes the variations in loop configuration apparent in a fabric as distortion.

APPENDIX A

THE THIRTY SEVEN KNITTED FABRICS

ASSESSED FOR LOOP DISTORTION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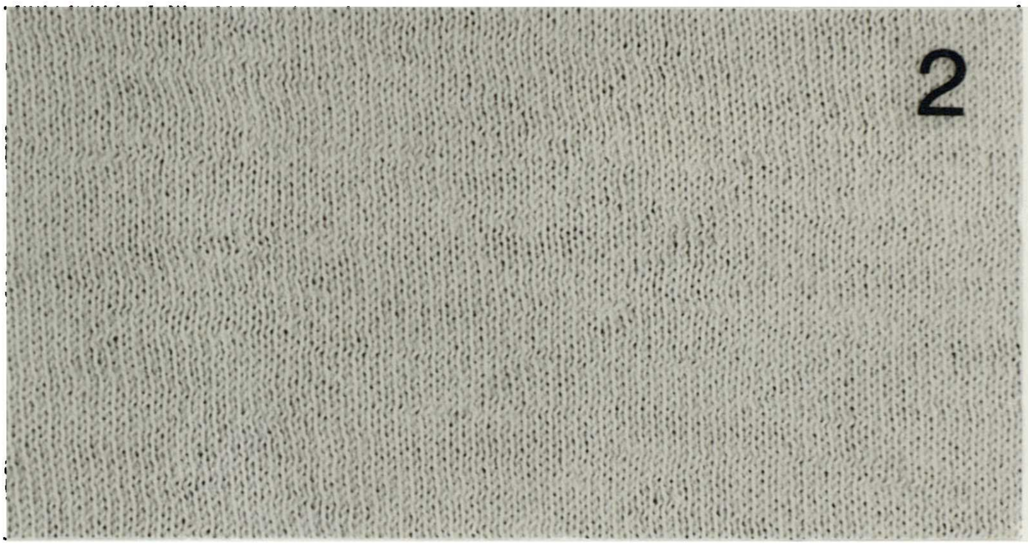
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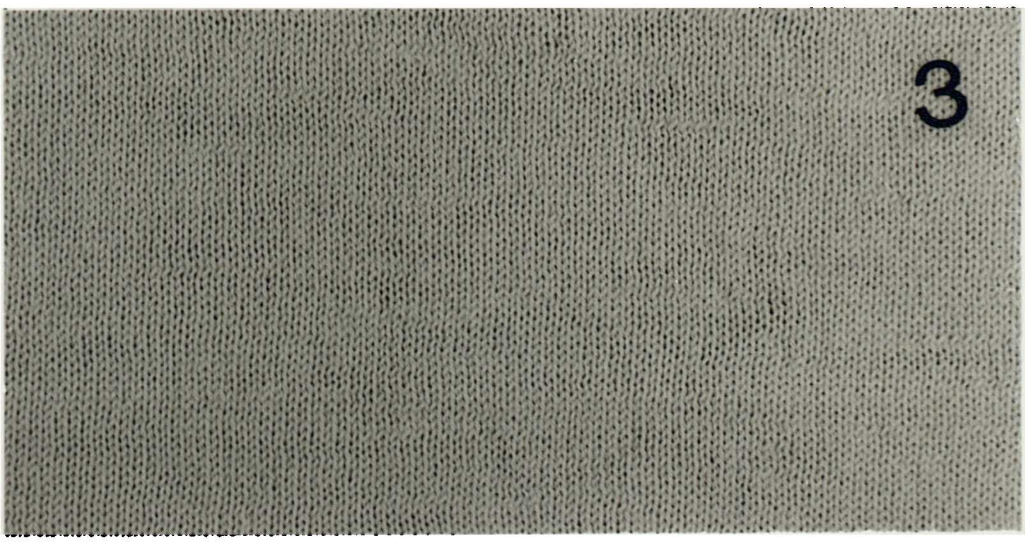
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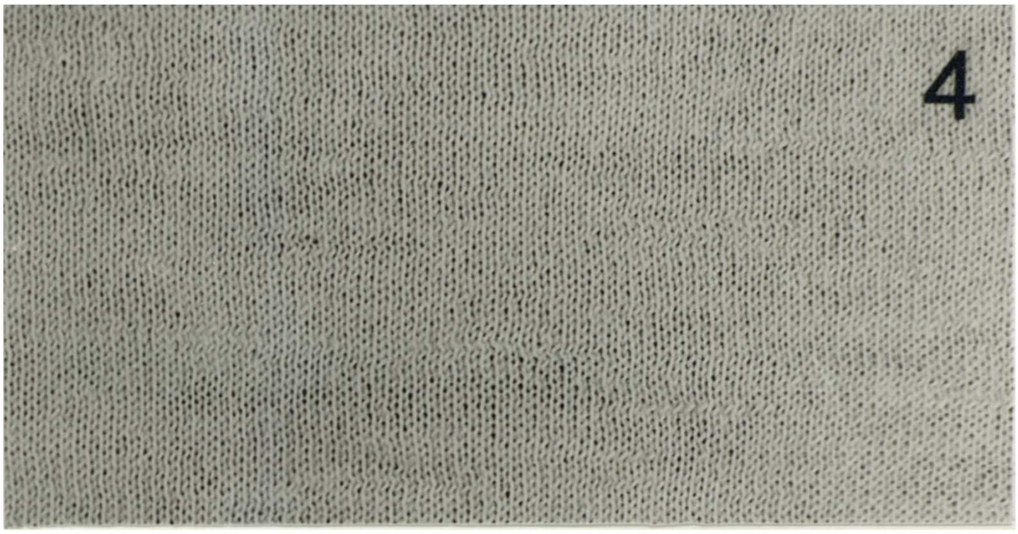
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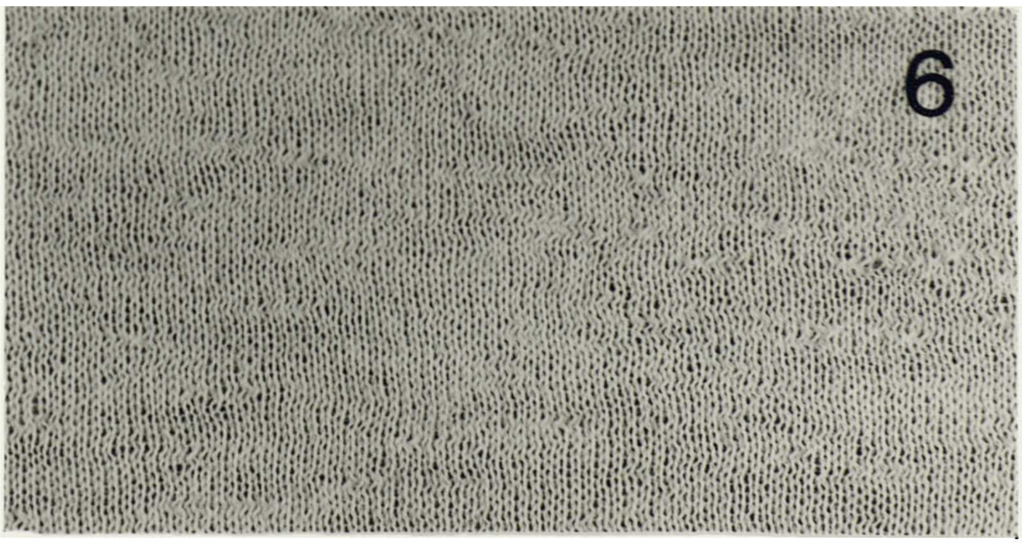
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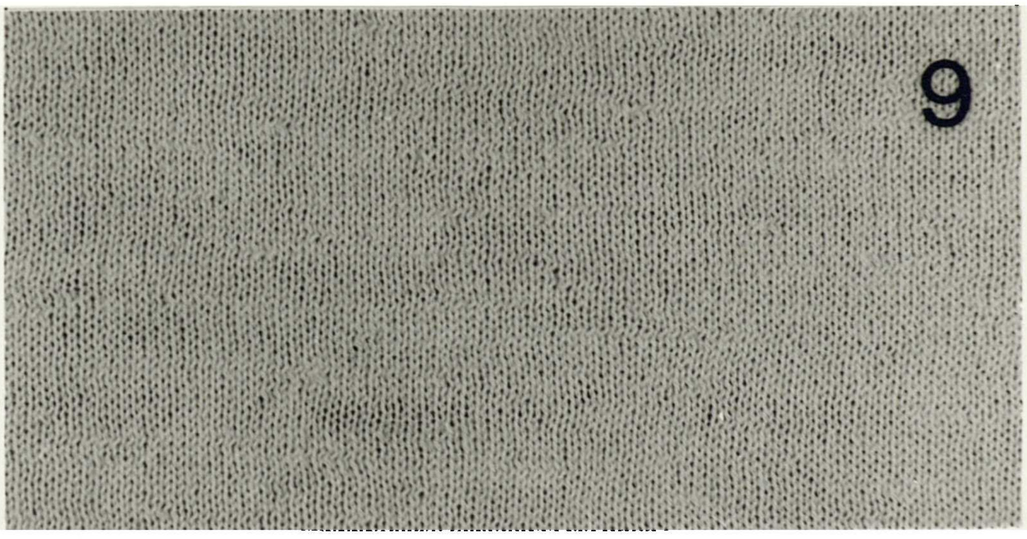
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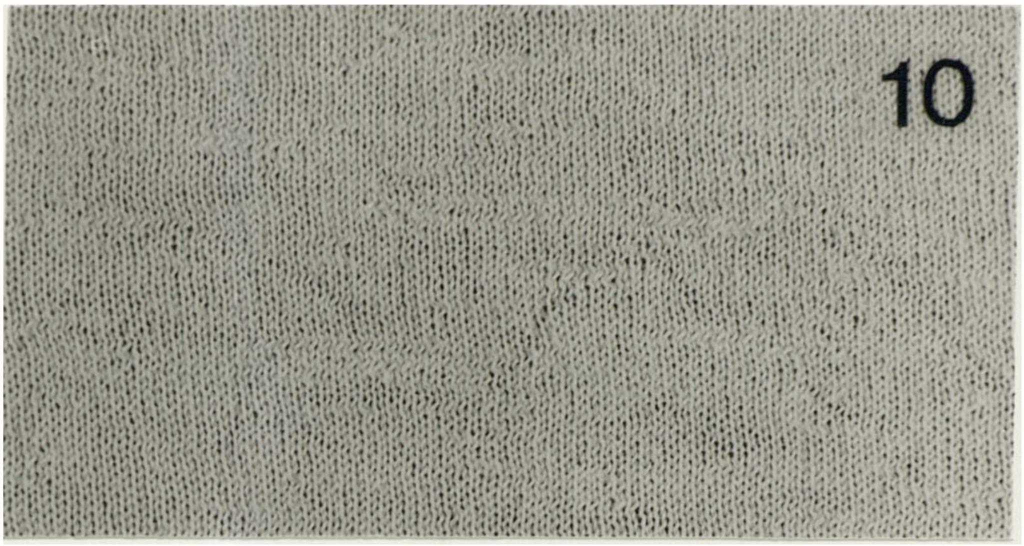
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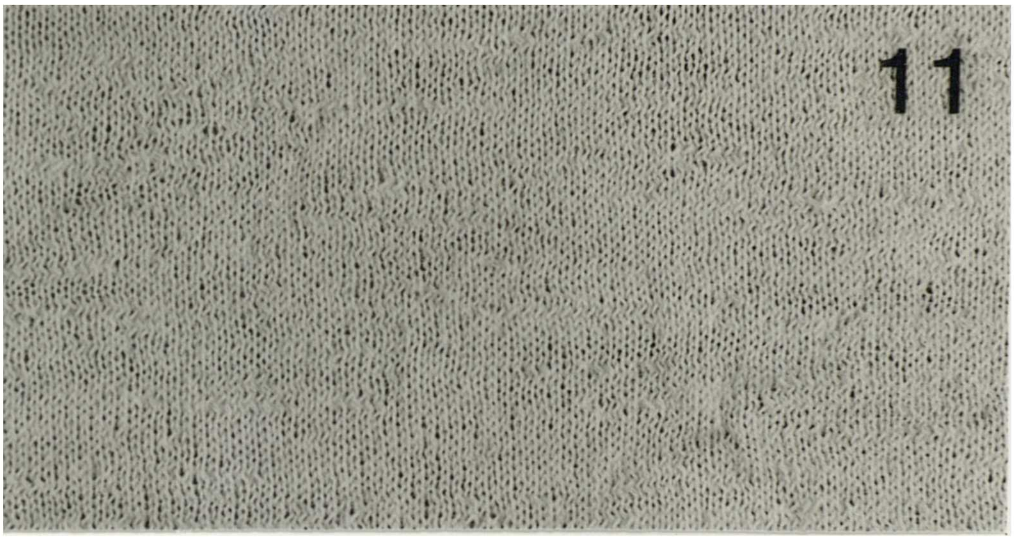
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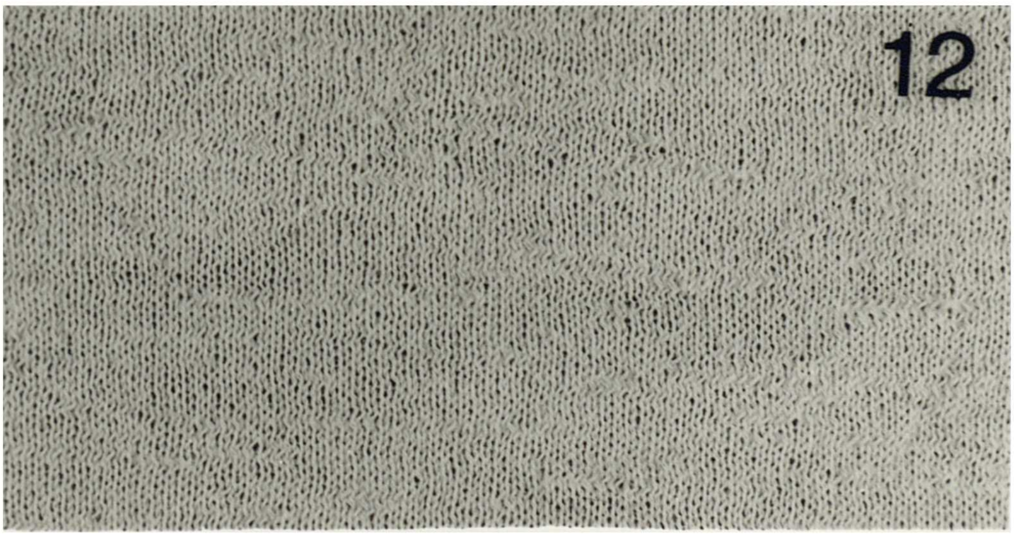
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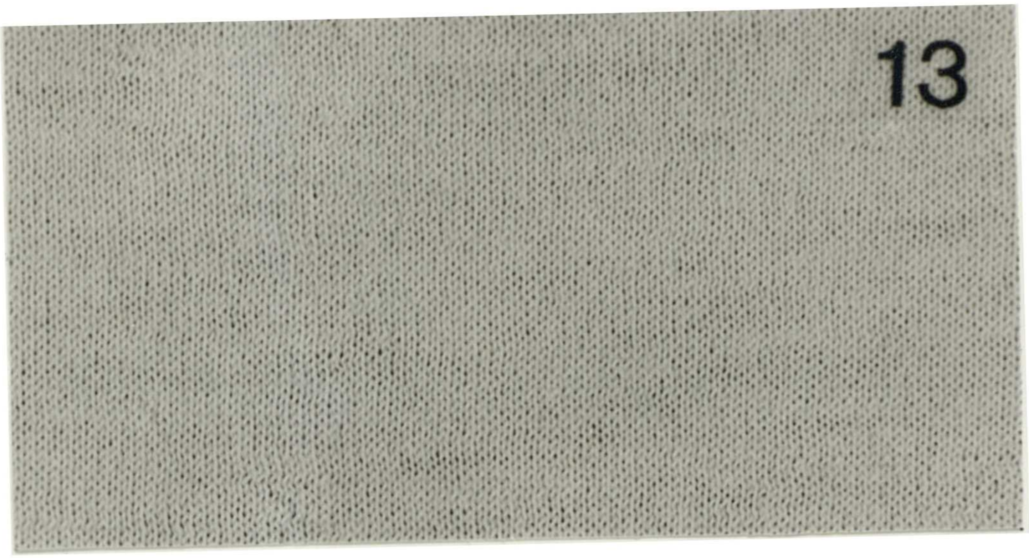
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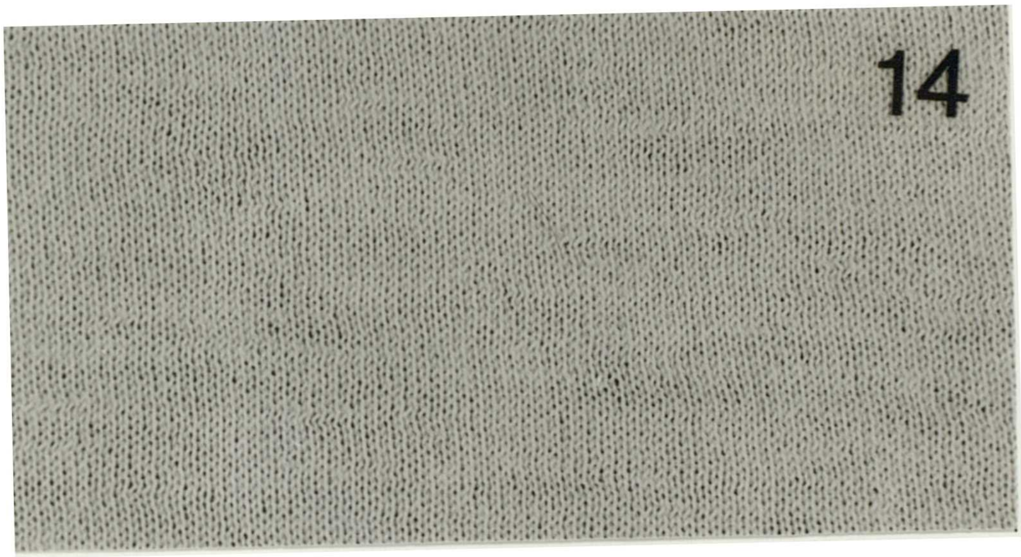
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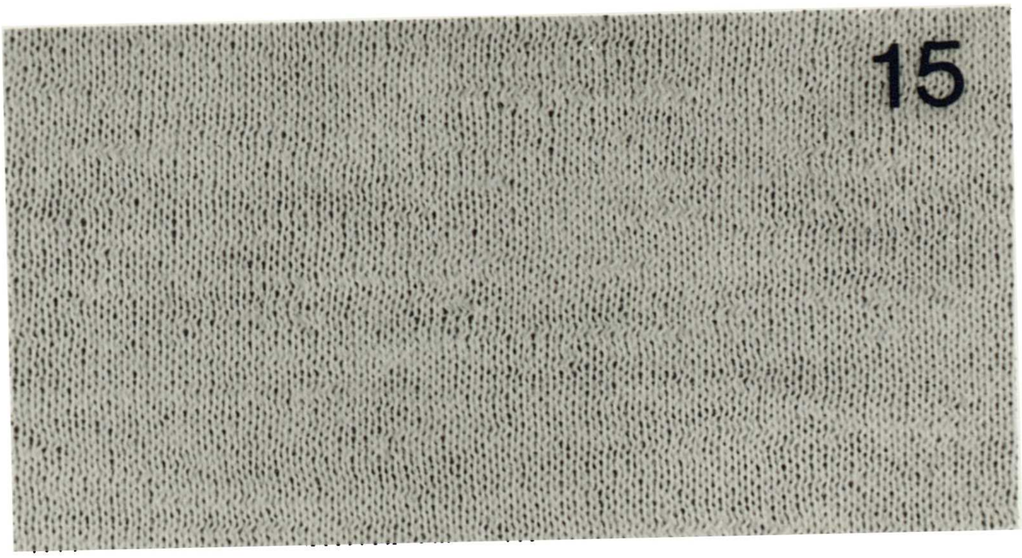
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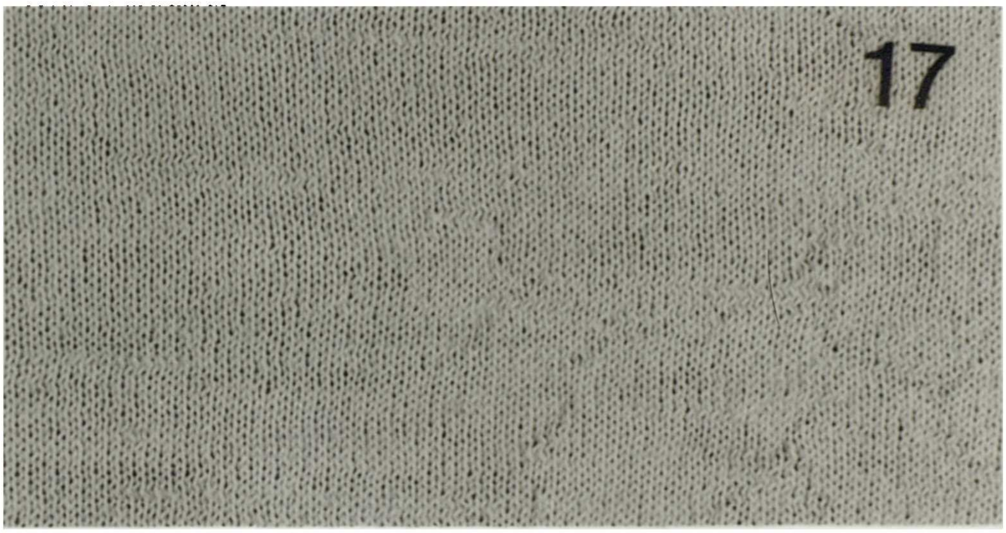
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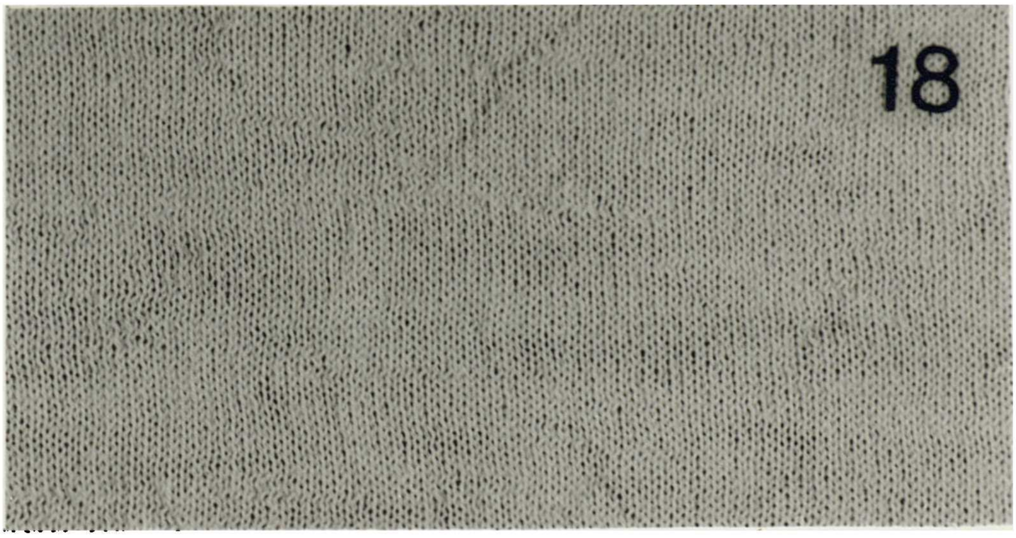
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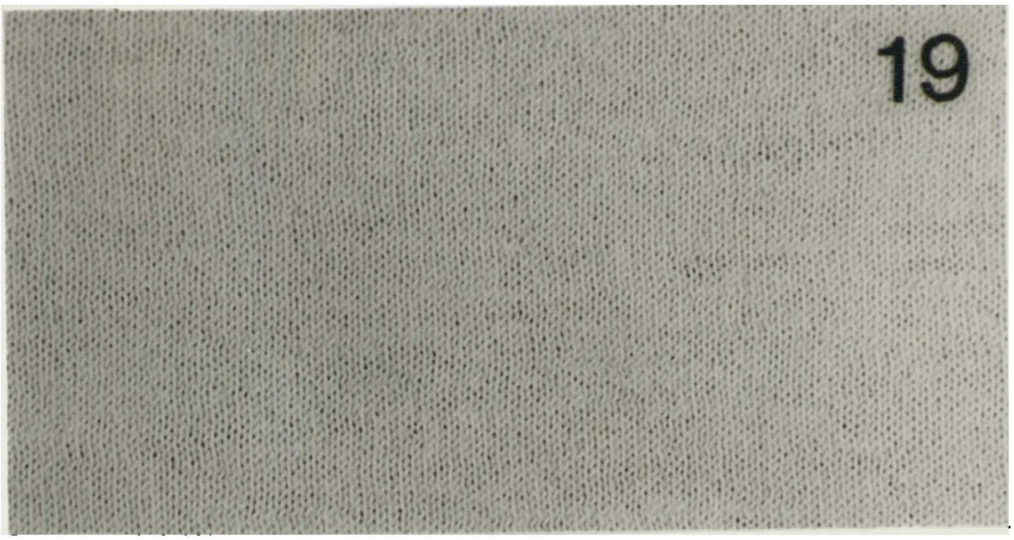
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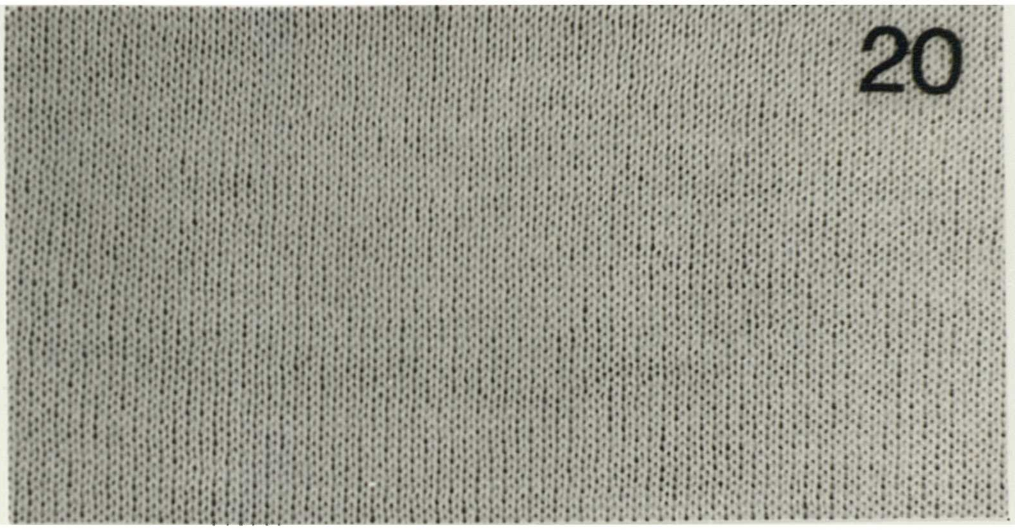
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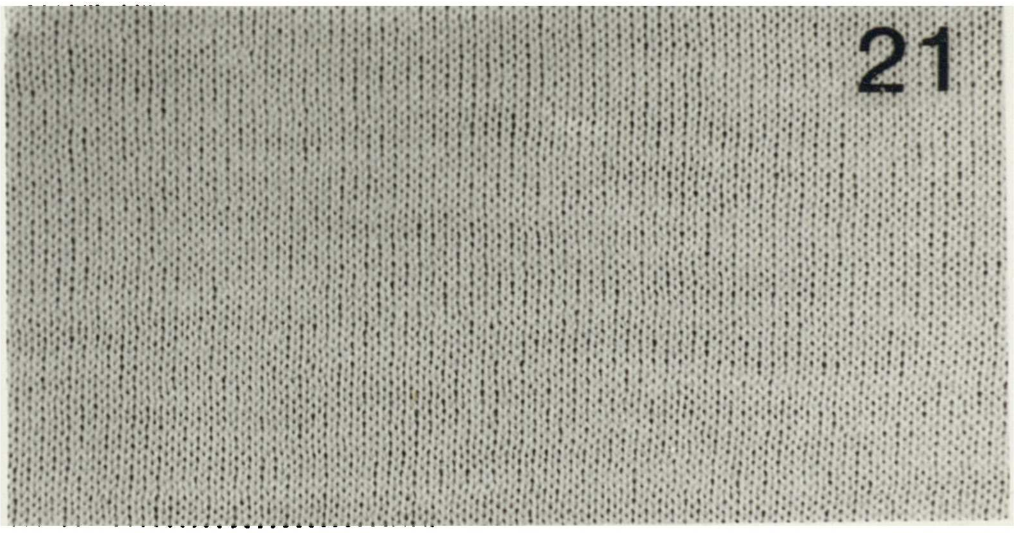
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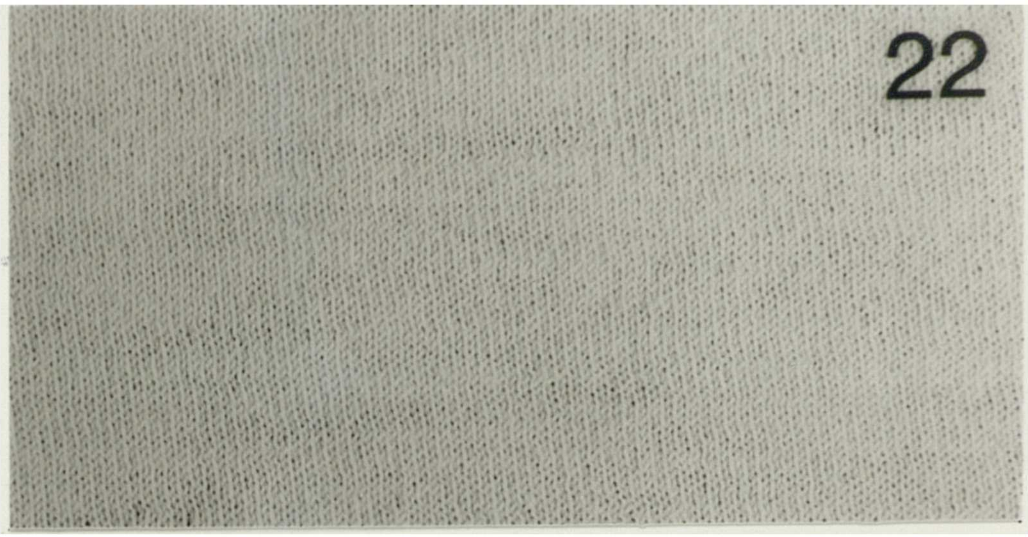
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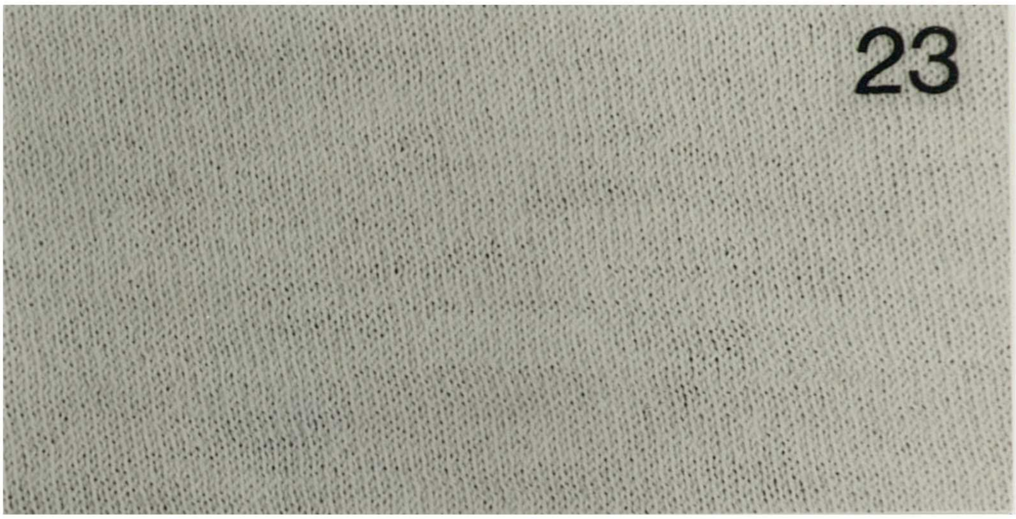
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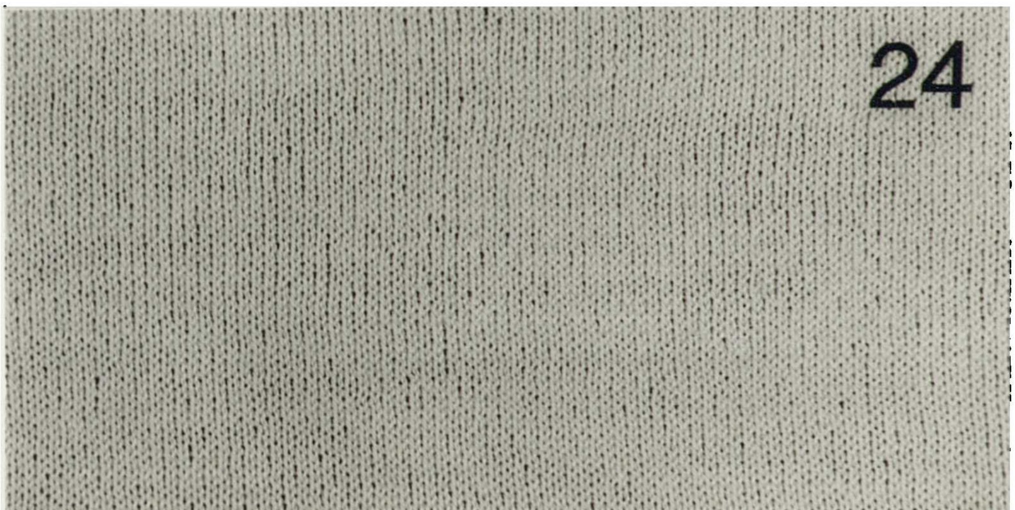
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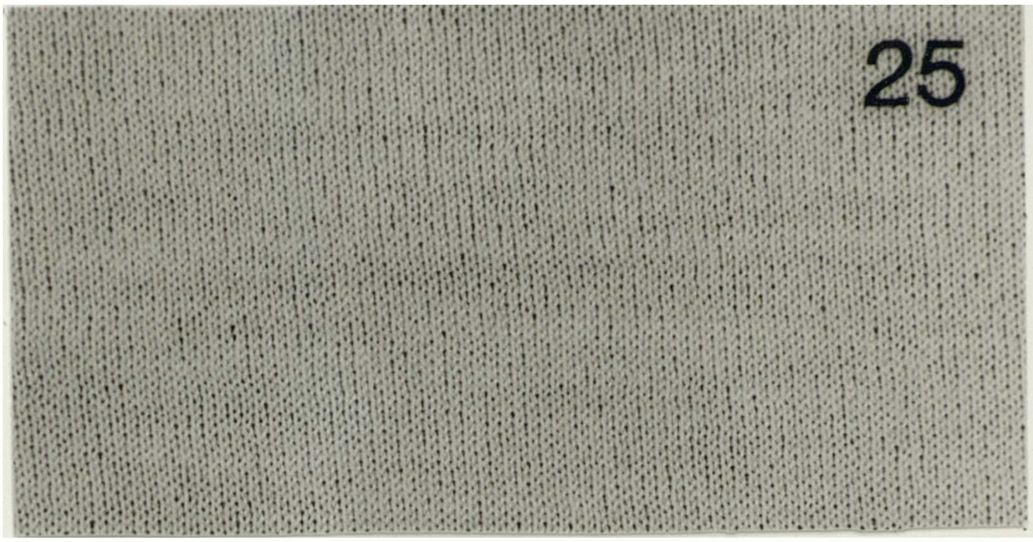
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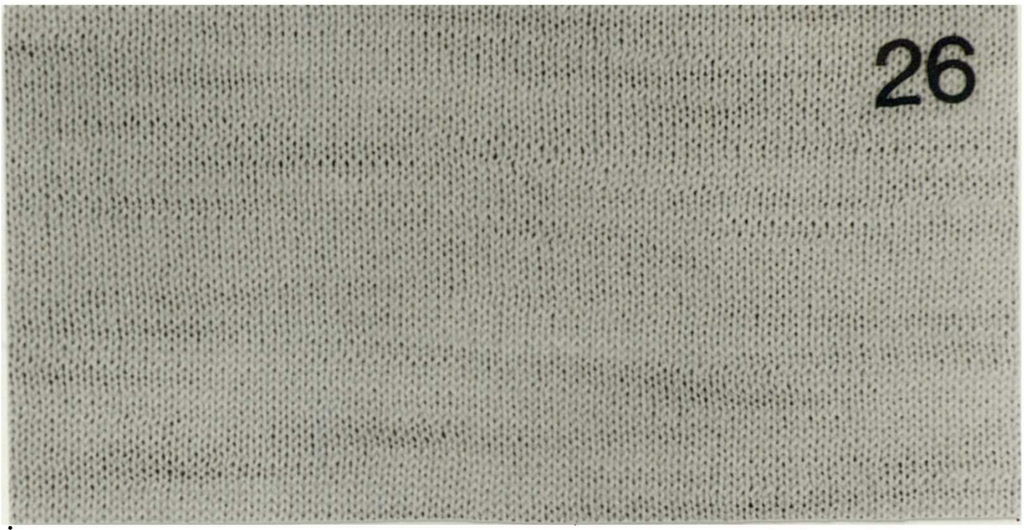
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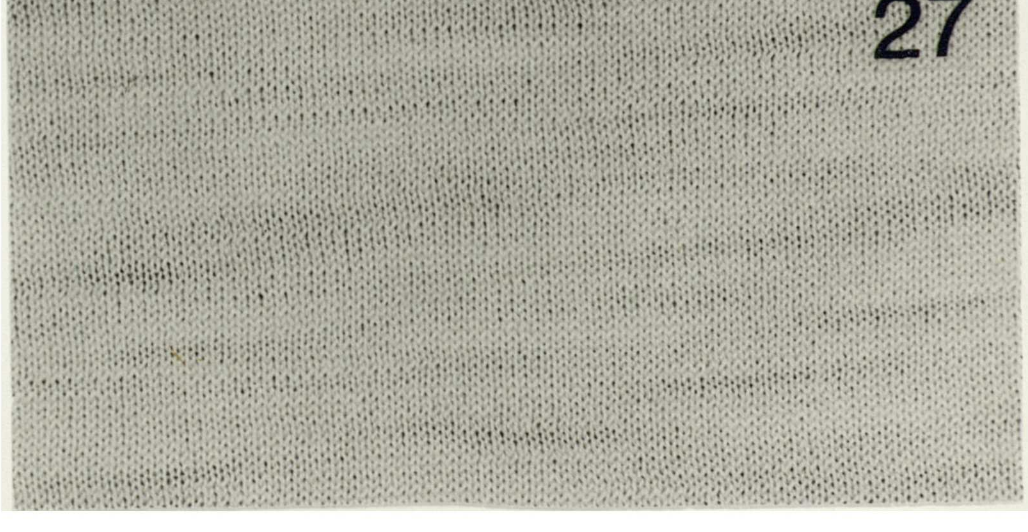
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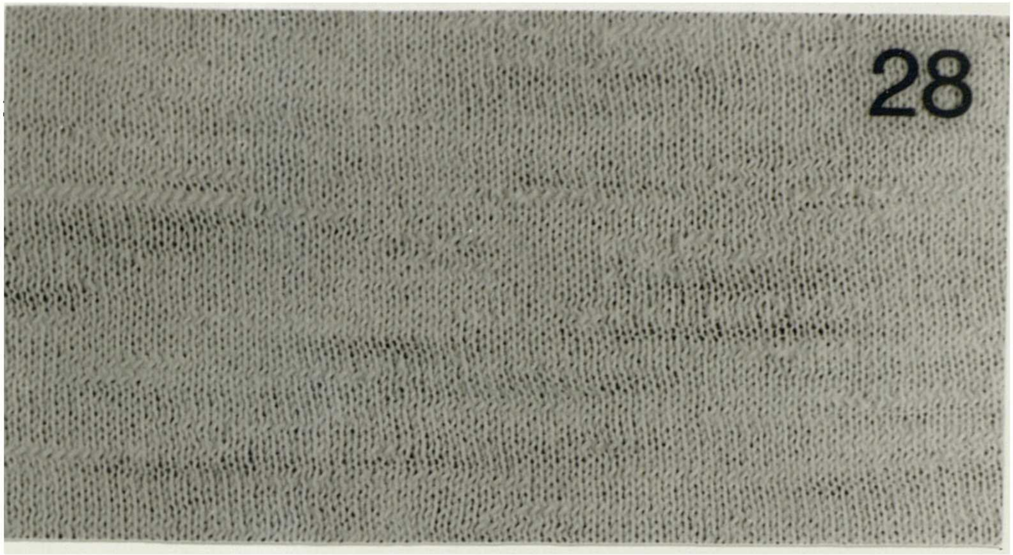
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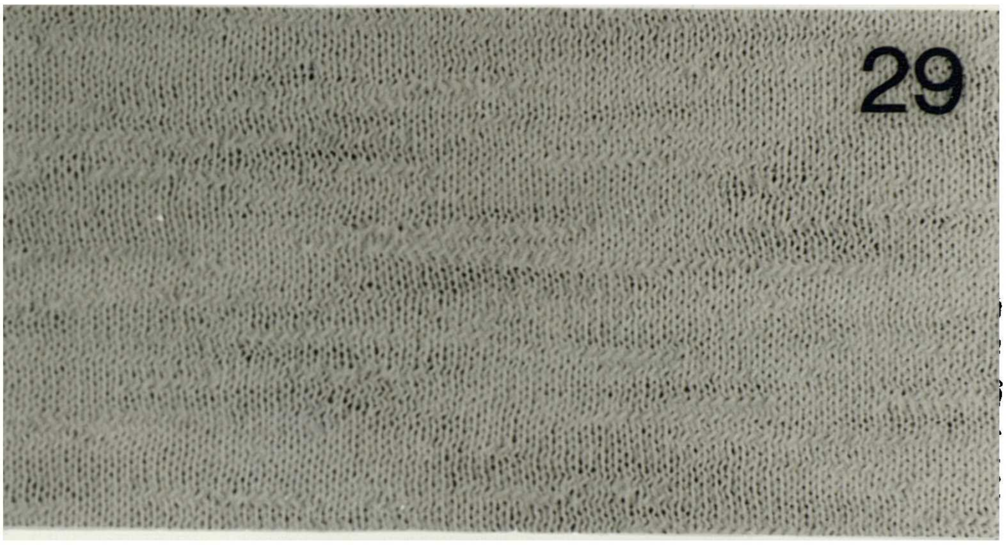
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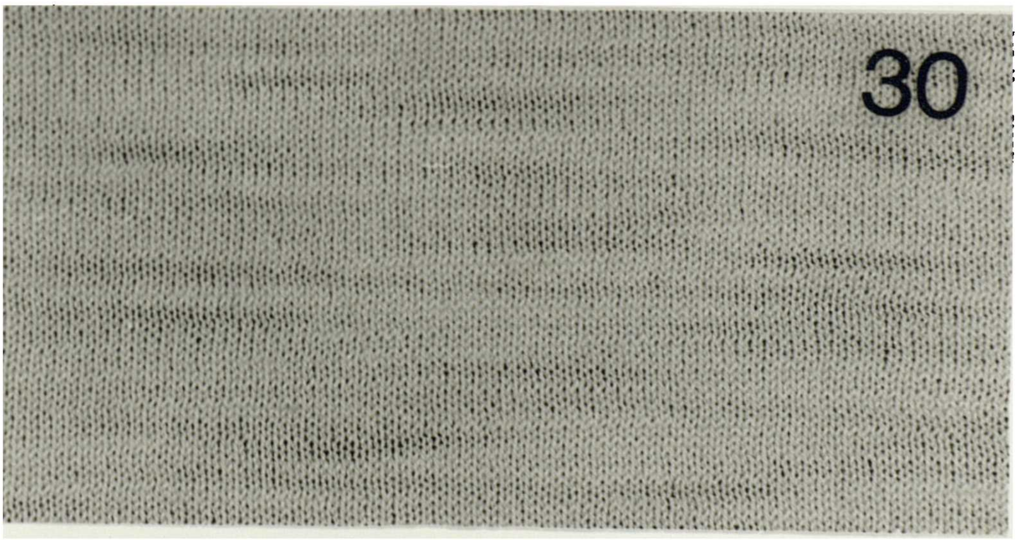
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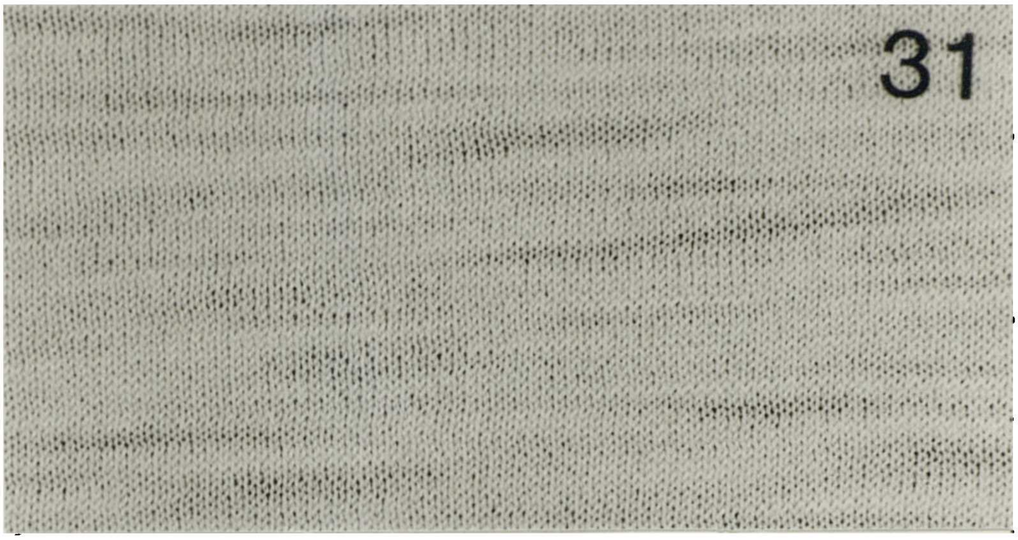
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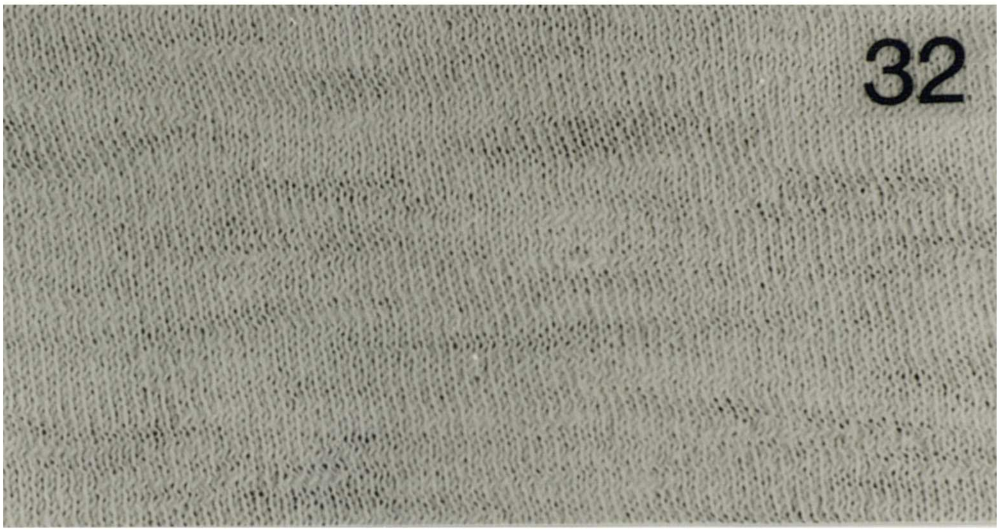
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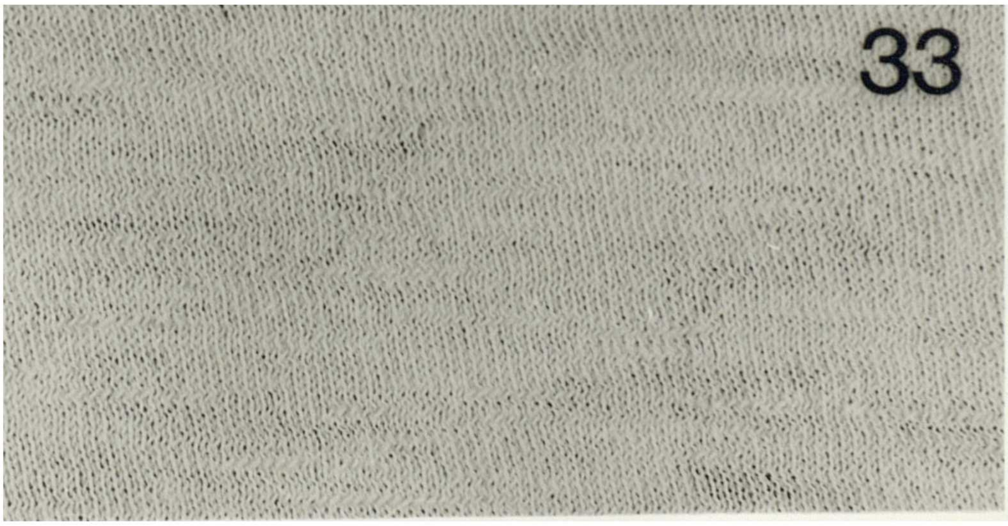
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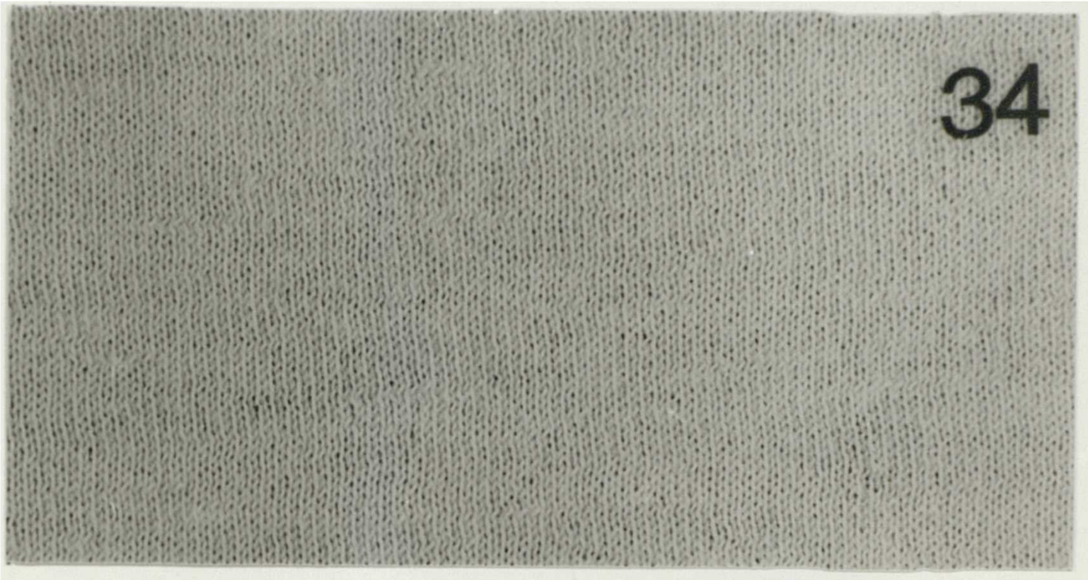
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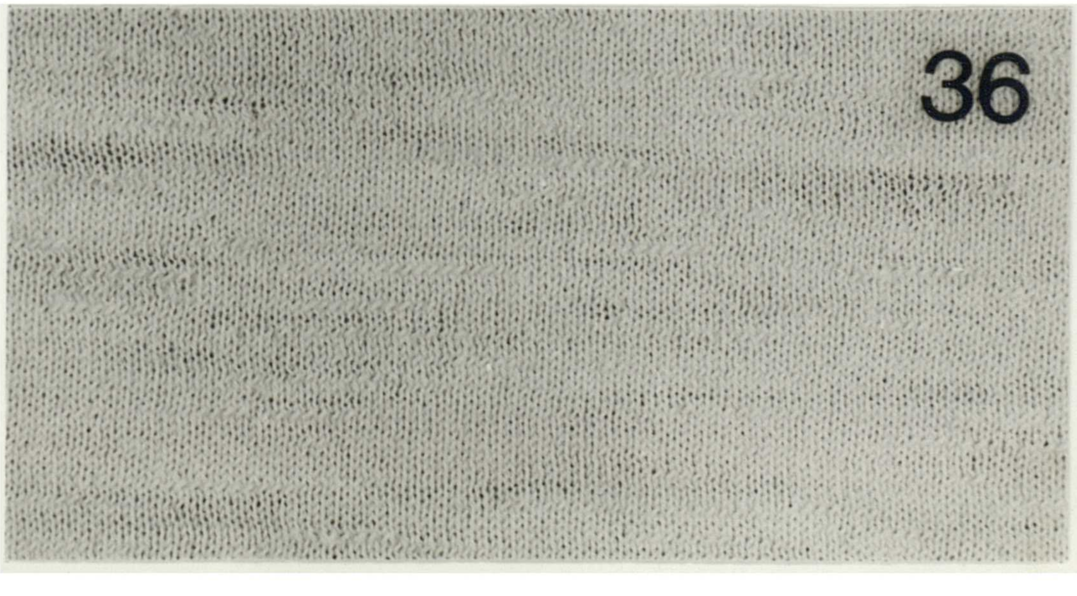
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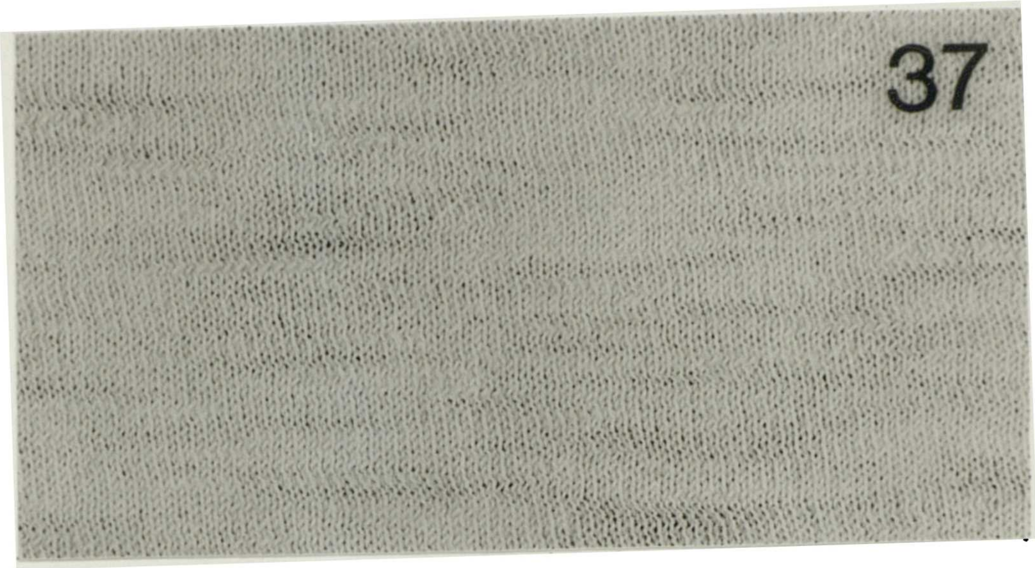
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REFERENCES

1. Davis, W., Edwards, C.H., Stanbury, G.R. "Spirality in Knitted Fabrics" J. Text. Inst. 1934, 25, T122

2. Nutting, T.S. "Spirality in Weft Knitted Fabrics" Hosiery Res. Bull. 1960, 4, 18

3. Textile Terms and Definitions, 7th Ed. p.38. The Textile Institute

4. Tompkins, E. "The Science of Knitting" John Wiley & Sons, New York, 1914.

5. Chamberlain, J. "Hosiery Yarns and Fabrics" City of Leicester, College of Technology,1949, 106-108.

6. Pierce, F.T. "Geometrical Principles Applied to the Design of Functional Fabrics" Text. Res. J. 1947, 17, 144

7. Shinn, W.E. "An Engineering Approach to Jersey Fabric Construction" Text. Res. J. 1955, 25, 270

8. Doyle, P.J. "Fundamental Aspects of the Design of Knitted Fabrics" J. Text. Inst. 1953, 44, P561

9. Leaf, G.A.V. and Glaskin, A.J. "The Geometry of a Plain Knitted Loop" J. Text. Inst.1955, 46, T587

10. Fletcher, H.M. and Roberts, S.H. "The Geometry of Plain and Rib Knit Cotton Fabrics and its Relation to Shrinkage in Laundry" Text. Res. J. 1952, 22, 84

11. Fletcher, H.M. and Roberts, S.H. "The Geometry of Knit Fabrics Made of Staple Rayon And Nylon and its Relationship to Shrinkage in Laundry" Text. Res. J. 1952, 22, 466

12. Fletcher, H.M. and Roberts, S.H. "The Relationship of the geometry of Plain Knit Cotton Fabric to its Dimensional Change and Elastic Properties" Text. Res. J. 1954, 24, 729

13. Leaf, G.A.V. "A Property of a Buckled Elastic Rod" Brit. J. Appl. Physics 1958, 9, No.2

14. Munden, D.L. "The Geometry and Dimensional Properties of Plain Knit Fabrics" J. Text. Inst. 1959, 50, T448

15 Leaf, G.A.V. "Models of the Plain Knitted Loop" J. Text. Inst. 1960, 51, T49

16. Munden, D.L. "Dimensional Stability of Plain Knit Fabrics" J. Text. Inst. 1960, 51, P200

17. Nutting, T.S. "Changes in the Dimensions of Plain Knitted Wool Fabrics with Variation of Moisture Regain" J. Text. Inst. 1961, 52, T407

18. Nutting, T.S. and Leaf, G.A.V. "A Generalized Geometry of Weft-Knitted Fabrics" J. Text. Inst. 1964, 55, T45

19. Centre de Recherches de la Bonneterie. Bull. Inst. Text. de France 1964, 18, 421

20. Postle, R. "Dimensional Stability of Plain Knitted Fabrics" J. Text. Inst. 1968, 59, 65

21. Knapton, J.J.F. et al. "The Dimensional Properties of Knitted Wool Fabrics. Part I: The Plain Knitted Structure" Text. Res. J. 1968, 38, 999

22. Knapton, J.J.F. and Fong, W. "The Dimensional Properties of Knitted Wool Fabrics -Part IV Some Observations of Completely Relaxed Fabric Geometry" Text. Res. J. 1971, 41, 894

23. Postle, R. and Munden, D.L. "Analysis of the Dry Relaxed Knitted Loop Configuration. Part I: Two Dimensional Analysis" J. Text. Inst. 1967, 58, T329

24. Postle, R. and Munden, D.L. "Analysis of the Dry Relaxed Knitted Loop Configuration. Part II: Three Dimensional Analysis" J. Text. Inst. 1967, 58, T352

25. Shanahan, W.J. and Postle, R. "A Theoretical Analysis of the Plain Knitted Structure" Text. Res. J. 1970, 40, 656

26. Hepworth, B. et al. "The Plain Knitted Structure" Text. Res. J. 1970, 40, 863

27. Shanahan, W.J. and Postle,R. "A Theoretical Analysis of the Tensile Properties of Plain Knitted Fabrics. Part II: The Initial Load-Extension Behaviour for Fabric Extension Parallel to the Wales" J. Text. Inst. 1974, 65, 254

28. Hepworth, B. and Leaf, G.A.V. "The Shape of the Loops of an Undeformed Plain Knit Structure" Text. Inst. Conf. May 1970, 181

29. Konopasek, M., Ph.D. Thesis, U.M.I.S.T., Manchester, 1970

30. Hepworth, R.B. and Hepworth, K. J. Text. Inst. 1974, 65, 561

31. Shanahan, W.J. and Postle, R. J. Text. Inst. 1974, 65, 562

32. Hepworth, R.B. and Hepworth, K. Text. Res. J. 1975, 45, 86

33. Shanahan, W.J. and Postle, R. Text. Res. J. 1975, 45, 87

34. de Jong, S. and Postle, R. "Energy Optimization Methods in Fabric Mechanics" Mechanics of Flexible Fibre Assemblies, Sijthoff & Noordhoff, 1980, 227

35. de Jong, S. and Postle, R. "An Energy Analysis of the Mechanics of Weft Knitted Fabrics by means of Optimal Control Theory. Part I: The Nature of Loop Interlocking in the Plain Knit Structure" J. Text. Inst. 1977, 68, 307

36. de Jong, S. and Postle, R. "An Energy Analysis of the Mechanics of Weft Knitted Fabrics by means of Optimal Control Theory. Part II: Relaxed Fabric Dimensions and Tensile Properties of the Plain Knitted Structure" J. Text. Inst. 1977, 68, 316

37. de Jong, S. Ph.D. Thesis, University of New South Wales, 1976

38. Hepworth, R.B. and Leaf, G.A.V. "The Mechanics of an Idealized Weft-Knitted Structure" J. Text. Inst. 1976, 67, 241

39. Hepworth, R.B. Ph.D. Thesis, University of Leeds, 1971

40. Hepworth, R.B. "The Biaxial Load-Extension Behaviour of a Model of Plain Weft Knitting. Part I" J. Text. Inst. 1978, 69, 101

41. Hepworth, R.B. "Some Aspects of the Mechanics of a Model of Plain Weft Knitting" Mechanics of Flexible Fibre Assemblies, Sijthoff & Noordhoff, 1980, 175

42. Hepworth, R.B. "The Dimensional and Mechanical Properties of Plain Weft Knits" Knitting International, Jan. 1982, 33

43. Brown, T.D., Mills, J.H. and Hamilton, R.J. "Rib/Plain Interactions of Knitwear" 6th Quinquennial International Wool Textile Research Conference (1980) Pretoria

44. Parker, R "Cockling in Fully Fashioned Garments" Knitting Industry Technical Review, 1981, 1, 25

45. Robinson, G.A., Green, M.V., and Hunter, L. "Cockling in Fully Fashioned Knitwear, Part I,: A Preliminary Report" S.A.W.T.R.I. Tech. Rep. 279 (Jan. 1976)

46. Robinson, G.A. and Green, M.V. "Cockling in Fully Fashioned Knitwear, Part III,: A Comparison of Two Similar Merino Wools of Different Origin" S.A.W.T.R.I. Tech. Rep. 345, (May 1977)

47. Robinson, G.A., Cawood, M.P. and Dobson, D.A. "Assessment of Cockling by Means of S.A.W.T.R.I. Standard Photographs" S.A.W.T.R.I. Bull. 12 (1), (Mar. 1978)

48. Robinson, G.A., Cawood, M.P. and Dobson, D.A. "The Cockling of All-Wool Plain Single Jersey Knitted on Different Machines" S.A.W.T.R.I. Bull. 12 (4), (Dec. 1978)

49. Robinson, G.A., Cawood, M.P. and Dobson, D.A. "Cockling in Fully Fashioned Knitwear, Part IV,: The Effect of Fibre Diameter, Crimp and Yarn Linear Density" S.A.W.T.R.I. Tech. Rep. 423, (Aug. 1978)

50. Robinson, G.A., Cawood, M.P. and Dobson, D.A. "Cockling in Fully Fashioned Knitwear Part V,: The Effect of Shrink-Resist and Anti-Cockle Treatments" S.A.W.T.R.I. Tech. Rep. 452, (Oct. 1979)

51. Robinson, G.A., Cawood, M.P. and Dobson, D.A. "Cockling in Fully Fashioned Knitwear" 6th Quinquennial International Wool Research Conference (1980) Pretoria

52. Benson, M.R. "Loop Distortion in Superwash Knitwear" I.W.S. Product Development Rep. 162 (Nov. 1974)

53. Kendall, M.G. "Rank Correlation Methods" 3rd Ed. 1962, pp.144-161, Griffin & Co. Ltd.

54. Haigh, J.S. "The Influence of Package Dyeing on Loop Distortion in

Plain Knits Produced from Chlorine/Hercosett Botany Yarns"I.W.S. Rep. FACT 403 (Jan. 1982)

55. Robinson, G.A. and Green, M.V. "Cockling in Fully Fashioned Knitwear, Part II,: An Investigation into the Effect of Various Fibre, Yarn and Fabric Properties on Cockling" S.A.W.T.R.I. Tech. Rep. 334 (Dec. 1976)

56. Robinson, G.A. and Green, M.V. "Some Aspects of the Use of Storage Feed Units on Fully Fashioned Machines" S.A.W.T.R.I. Bull. 10 (2), (1976)

57. Bodenschatz, S. "The Effect of Bending Resistance in Yarns on Loop Distortions in Single Jersey Wool Fabrics and Wool/Acrylic Fabrics" WST Knitting Technic 2 (4), (1980)

58. Buhler, G. Diehl, G "An Investigation into the Causes of Cockling in Knitted Fabrics Produced from Wool Yarns and Wool/Acrylic Mixture Yarns (Part I)" WST Knitting Technic 3 (3), (1981)

59. Buhler, G. Bodenschatz, S. and Schatz, A "Ermittlung der Ursache von Maschenverwerfungen in Maschenwaren aus Wollgarnen und Wolle/Acryl-Mischgarnen (II Teil)" Wirkerei- und Strickerei-Technik 31 (6), (1981)

60. Pittner, J.J. "Cockling in Fully Fashioned Garments" H.A.T.R.A. Report (May 1969)

61. Haigh, J.S. "The Influence of Yarn Regain on Cockling in Single Jersey Fabrics" I.W.S. Report No. F.A.C.T. 361 (May 1980)

62. Smith, D. and Benson, M.R. "Factors Affecting Loop Distortion in Knitwear - Post Knitting Treatments" I.W.S. Report No. F.A.C.T. 389 (Mar. 1981)

63. Haigh, J.S. "The Influence of Chlorine and Hercosett Dosage Levels on Loop Distortion in Plain Knit Botany Fabrics" I.W.S. Report No.F.A.C.T. 382 (Dec. 1980)

64. Kerley, L.A. "Some Factors Influencing Puckering and Cockling in Fully-Fashioned Garments" J. Text. Inst. 1968 59, 405

65. Le Centre de Recherches de la Bonneterie de Troyes "La Distortion des Mailles des Jerseys en Retors" L'Industrie Textile (Jan. 1972)

66. Henshaw, D.E. "Knitting of Self-Twist Yarn" Text. Inst. and Ind. 157, (May 1976)

67. Haigh, J.S. "The Effect of Ammonia Treatment and Hacoba Steaming on the Loop Distortion of Self-Twist Yarns" I.W.S. Report No. F.A.C.T. 244 (Feb. 1976)

68. Haigh, J.S. "The Effect of Winding Conditions and Autoclave Conditions on the Loop Distortion of Self-Twist Yarns" I.W.S. Report No. F.A.C.T. 234 (Nov. 1975)

69. Haigh, J.S. "Torsionally Insensitive Yarns - A Solution to Loop Distortion?" I.W.S. Report No. F.A.C.T. 348 (Nov. 1979)

70. Barella, A. "The Influence of Twist on the Regularity of the

Apparent Diameter of Worsted Yarns" Int. Wool Text. Org. Conf., Barcelona (May 1951), 734

71. Sustman, C. "A Study of Twist Distribution in Irregular Yarns" Int. Wool Text. Org. Conf., Brussels (June 1954), 106

72. Commonwealth Scientificand Industrial Research Organisation U.K. Patent GB 1015291

73. Davies O.L., "The Design and Analysis of Industrial Experiments", 2nd Edition, 440-83, Longman Group Ltd., 1979.

74. IWTO 8/66

75. IWTO 5/65

76. Lewis, J., "Continuous Shrinkproofing Processes" Wool Science Review, May 1978, 55, 23.

77. U.K. Patent GB 1495748.

78. Oxtaby, E., "The Twisting of worsted Yarns", Wool Review Nov 1964, 523, 14.

79. Meredith, R., "The Torsional Rigidity of Textile Fibres", J. Text. Inst. 1954 45,T489

80. Guthrie, J.C. et al. "An Investigation into Bending and Torsional Rigidities of Some Fibres", J. Text. Inst. 1954 45, T912

81. Berndt, H-J and Beier, M., "Bestimmung des Uberichtigen Dralls von Garnen und Zwirnen" Melliand Textilberichte 1984 65, 150

82. Karrholm, M. et al. "Penetration of Alkaline Solutions into Wool Fibres Determined by Changes in the Rigidity Modulus" Text. Res. J. 1955 25, 922

83. Goodings, A.C., "A Method for the Measurement of the Rigidity of Fibers Immersed in Liquids : The Torsion Double Pendulum" Text. Res. J. 1968 38, 123

84. Morton, W.E. and Permanyer, F. "The Measurement of Torsional Relaxation in Textile Fibres" J. Text. Inst. 1947 38, T54

85. Mertens, J.J. "The Torque in Highly Twisted Nylon 6 Monofilaments" J. Text. Inst. 1959 50, T70

86. Mitchell, T.W. and Feughelman, M. "The Torsional Properties of Single Wool Fibers" Text. Res. J. 1960 30, 662

87. Skelton, J. "The Measurement of the Torsional Elastic Recovery of Filaments" J. Text. Inst. 1965 56, T443

88. Dhingra, R.C. and Postle, R. "The Measurement of Torque in Continuous Filament Yarns" J. Text. Inst. 1974 65, 126

89. Kawabata, S. et al. "Torsional Testing Apparatus and its Application to Experimental Investigation on the Relationship Between Torsional Properties of Yarns and Fibers" J. Text. Mach. Soc. Japan 1976 29, 43

90. Okabayashi, M. et al. "Measurement of Torsional Rigidity of Fibers" Text. Res. J. 1976 46, 429

91. Carlene, P.W. "The Measurement of the Bending Modulus of Monofils" J. Text. Inst. 1947 38, T38

92. Pierce, F.T., J. Text. Inst. 1930 21, T377

93. Livesey, R.G. and Owen, J.D. "Cloth Stiffnes and Hysteresis in Bending" J. Text. Inst. 1964 55, T516

94. Abbott, G.M. and Grosberg, P. "Measurement of Fabric Hysteresis in Bending" Text. Res. J. 1966 36, 928

95. Chapman, B.M. "An Apparatus for Measuring Bending and Torsional Stress/Strain Time Relations in Single Fibres" Text. Res. J. 1971 41, 705

96. Grey, S.J. "The Role of Inter-Fibre Friction in Fabric Bending" Ph.D. Thesis, University of Leeds, 1978

97. Yates, F. "Design and Analysis of Factorial Experiments" Imperial Bureau of Soil Science, London (1937)

98. Duckworth, W.E. "Statistical Techniques in Technological Research" 1968 pp. 214-217 Methuen & Co. Ltd, London

99. Spearman, C. "A Footrule for Measuring Correlation" Brit. J. Psych. 1906 2, 89

100. Kendall, M.G. "Rank Correlation Methods" 3rd Ed. 1962 Griffin & Co. Ltd., London

101. Kramer, A. "A Rapid Method for Determining Significance of Differences from Rank Sums" Food Technol. 1960 14, 576

102. Kramer, A. "Revised Tables for Determining Significance of Differences" Food Technol. 1963 17, 1596

103. Kramer, A. et al. "A Non-Parameteric Method for the Statistical Evaluation of Sensory Data" Chem. Senses and Flavor 1974 1, 121

104. Ly, N.G. and Denby, E.F. "The Bending Rigidity and Hysteresis of Wool Worsted Yarn" Text. Res. J. 1984 54, 180-187

105. Ly, N.G. "The Contribution of Fibre Diameter Distribution to the Bending Rigidity of Yarns" J. Text. Inst. 1983 74, 228-230

106. Williams, V.A. "Loop Distortion or Stitch Distortion in Knitwear" C.S.I.R.O. Division of Textile Industry, Geelong, Australia. Internal Report, May 1986