SOME STUDIES OF FRICTIONAL PROPERTIES OF FABRICS

by

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This work is dedicated to my dear wife,
Mary Ola, for her unflinching support and
encouragement throughout the course of this project

LAYOUT OF THE THESIS

In view of the wide range of techniques and case studies employed in this research the Thesis has been divided into a series of Chapters. The first two of these deal with the Introduction and Literature Survey, and with Experimental Methods. The Chapters containing experimental work each start with an Abstract and Introduction followed by the results and discussion. A brief Conclusion section ends the Chapter.

The Appendices contain details of analyses involving fabric geometry, linkages in the Instron roller technique and handle trials.

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LIST OF SYMBOLS

F = Frictional resistance (gf)

F_S = Static frictional resistance (gf)

F_K = Kinetic frictional resistance (gf)

F_A = Amplitude of frictional resistance (gf)

F_N = Number of peaks/5cm in the "stick-slip" friction traces

$F_S - F_K$ = Difference between static and kinetic frictional resistances (gf)

μ = Coefficient of friction

μ_S = Static coefficient of friction

μ_K = Kinetic coefficient of friction

K = Friction constant (g/cm^2)

n = Friction index

N = Normal load (g) or pressure (g/cm^2)

C = Yarn crimp (%)

P = Yarn spacing = 1/threads/cm (cm)

T' = Yarn linear density (Tex)

$\beta\lambda$ = Fabric balance

H_C = Crimp height (mm)

R_N = Number of peaks/5cm in roller trace

R_A = Amplitude of roller pulse (gf)

R_δ = Mean deviation of roller pulses

S_N = Number of peaks/5cm in stylus traces

S_A = Amplitude of roller pulses (gf)

S_δ = Mean deviation of stylus pulses

LAF = Lateral air flow (cm^3/s)

Co = Coercive couple ($Dyn.cm.cm^{-1}$)

Go = Elastic flexural rigidity ($Dyn.cm^{2}.cm^{-1}$)

Co/Go = Subjective liveliness (cm^{-1})

G = Flexural rigidity (mg.mm)

c' = Bending length (cm)

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ABSTRACT

The frictional (fricative) properties of some 23 fabrics are reported. These properties include frictional resistance, amplitude of resistance, number of peaks, difference between static and kinetic frictional resistance in addition to coefficients of friction, all determined by trace analysis. Some assessments of properties of subjective handle likely to be related to objective measurements are also reported, for example fabric smoothness or roughness. The work is reported in series of case studies.

Firstly a general survey is made in order to demonstrate the likely range of properties, and the effects of experimental variables such as pressure, velocity of sliding, nature of sled surface, number of traverses. Secondly, a series of plain weave fabrics is used whose density of consolidation is systematically increased by increasing the picks per unit distance. Thirdly, the fricative resistance of a group of woven pile (cord) fabrics is measured with the purpose of demonstrating the sensitivity and selectivity of methods of measurement which include a roller, stylus, lateral air flow as well as the conventional fabric covered sled.

Fourthly, a series of knitted fabrics is used whose fibre content and construction differs systematically. For example they include cotton, wool and acrylic fibres, and are constructed as plain knit or rib knit.

Fifthly, the effects of various physical and chemical modifications of knitted and woven fabrics are illustrated. These treatements include those designed to increase frictional resistance such as starch and silica, or reduce friction such as polyethylene glycol.

By these case studies the relative influence of fibre content, fabric structure and also finishing treatments on fabric friction and handle are demonstrated.

CHAPTER 1

INTRODUCTION AND REVIEW OF LITERATURE

1.1 INTRODUCTION

Smoothness, softness and stiffness are three properties which determine the physical and mechanical behaviour of a fabric and the subjective assessment of quality when handled. A fabric which compresses easily is likely to be deemed soft, and to be found to possess a low modulus of compression and high compression. A fabric which bends easily is likely to be described as flexible, i.e. "not stiff", and such fabric will possess a low modulus of bending and high flexion. Any fabric which offers little fricative resistance to motion across its surface and possesses a low coefficient of friction is likely to be described as a smooth fabric.

Both softness and stiffness have been the subject of investigation recently and the statement above concerning softness and stiffness has been found to be generally valid(14-18). The aim of this work was to investigate the validity of the third statement.

Friction has been defined(2,5-7) as the resistance which any body meets with in sliding, rolling or flowing over another body. The ratio of the frictional resistance to the normal load pressing the two surfaces together is generally referred to as the coefficient of friction. The latter definition was based on the Amonton's laws of friction.

1.2 LAWS OF FRICTION

Historically, the laws of friction were first enunciated by Leonardo da Vinci in 1519(67), and were later rediscovered by Amonton in 1699, and were verified experimentally by Coulomb in 1785. These laws may be summarised as follows:

1. The frictional force or resistance (F) is proportional to the normal reaction (mass of the material)(N), i.e.

   $$F = \mu N \qquad (1.1)$$

   where μ = coefficient of friction.
   It follows from equation 1.1 that for bodies with similar values of μ, a heavier body will offer more resistance to motion than a lighter body. Similarly, for bodies with equal mass, the body with a higher coefficient of friction will offer more resistance to motion.
2. The coefficient of friction (μ) is independent of the geometric area of contact between the two surfaces (provided that force and mass remain in proportion).
3. Static friction is usually higher than kinetic friction (that is more force is required to initiate motion than to sustain it).
4. Kinetic friction is independent of the velocity of sliding (that means once in motion, the frictional resistance remains constant irrespective of any

change in velocity).

1.3 MECHANISM OF FRICTION IN SOLIDS

Over the centuries, many explanations of friction have been proposed. Amonton suggested that it was due to the force needed to lift one surface over the irregularities of the other. Other workers(8,66) believed that it was due to some attractive forces between the atoms of two surfaces or to electrostatic forces. While some of these explanations are still valid, the universally accepted theory of friction in solids (metals, polymers and textile assemblies) was based on the adhesion mechanism. This was originally sugggested by Holm(37) and later developed by Bowden and Tabor(5,6). They demonstrated that the frictional resistance developed between surfaces in contact is a result of two basically different actions. The first is the mechanical interference between surfaces. The surface asperities engage upon sliding, and force is required to deform or fracture them. When both surfaces are deformable, their mechanical properties, for example, shear strength and compressibility will determine how much each surface will deform(66). If one surface is harder than the other, then the former may act as an abradant and cut away softer asperities from the latter(1,8,20). The second action is the tendency for adhesion between the mating asperities. This is governed by a large variety of factors, of which the surface condition i.e. roughness and temperature are the most important(121).

It follows from Bowden and Tabor's theory(5,6) that, when two surfaces are in contact, the load would be borne by a few asperities projecting above the plane of the surface as illustrated in Figure 1.1. Consequently, the true area of contact will be much less than the geometric area of contact. Thus the real stress at the tip of each asperity would be high. These asperities may then deform either elastically or plastically depending upon the stress concentration, until sufficient area is available for even distribution of the load.

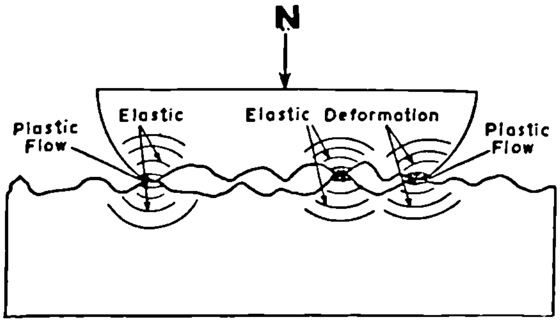


Figure 1.1

The mode of deformation at points of real contact showing welded junctions(5,6)

(N = Normal load)

At equilibrium, i.e. when the rates of increase in normal load, and area of contact are equal, the relation is given by:

$$N = pA \qquad (1.2)$$

where N = normal load

A = real area of contact

p = yield pressure.

At higher stress concentration, intimate contact (adhesion) of the junction may occur. Therefore, for relative motion, the adhesion or "cold welds" must be sheared. The frictional force (F) needed to shear these welds is given by:

$$F = sA \tag{1.3}$$

where s = specific shear strength of the weaker material.

From equations 1.2 and 1.3

$$F = \frac{s}{p}.N \tag{1.4}$$

In accordance with Amonton's law (equation 1.1) then:

$$\mu = s/p \tag{1.5}$$

From equation 1.5, the coefficient of friction is directly proportional to the shear strength and inversely proportional to the yield pressure (provided that force and mass remain in proportion). Accordingly, for materials with similar shear strength, the harder material (i.e. one with a higher yield pressure) will give a lower value of coefficient of friction. Similarly, for materials with similar yield pressure, (i.e. compressibility), the one with a higher value of shear strength will also give a higher value of coefficient of friction. These assertions have been found to be generally valid for metals(5,6,66). For fibrous materials (fibres, yarns, fabrics), several empirical relations have been proposed to explain the adhesion theory.

1.4 APPLICATION OF THE ADHESION THEORY OF FRICTION TO TEXTILE MATERIALS

It is well documented that textile materials such as fibres, yarns, and fabrics do not obey the simple linear relation $F = \mu N$(7,8,21-24,28,29,33,34,38-44,48-54, 88,91-94,110-115,131). The coefficient of friction(μ) may increase, or decrease to a constant value as the normal pressure (load) increased. A typical result is shown in Figure 1.2(*).

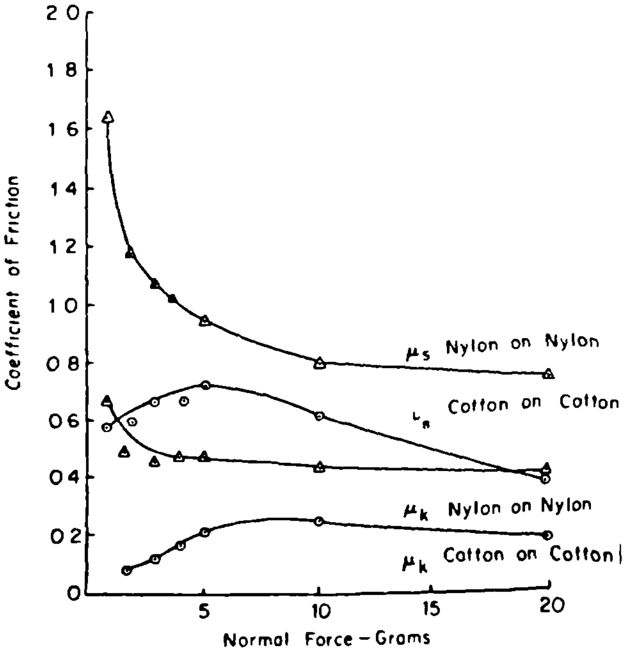


Figure 1.2

The influence of normal load on the coefficient of friction of fibres*

*Ducket, "Surface Characteristics of Fibres and Textiles", M.J.Schick(Ed.) Marcel Dekker Inc., New York, 1975.

Reference to Figure 1.2 shows that the coefficient of friction of nylon on nylon diminished rapidly at lower pressure, to a constant value at higher pressure. In the case of cotton on cotton, the coefficient of friction increased initially, followed by a decrease to a constant value at higher pressure.

Several attempts(7,8,26,38,44,75,87,98,131) have been made to explain the non-linearity of the relation between the coefficient of friction and normal pressure.

Morrow(87) fitted his experimental data to an empirical equation of the form:

$$F = K.P + bA \tag{1.6}$$

or its equivalent

$$\mu = K + b.A/P \tag{1.7}$$

where F = Frictional resistance

P = Pressure (equivalent to N/A)

A = Area of contact

N = Normal load

μ = Coefficient of friction

K and b = Constants.

Morrow(87) accepted the validity of the adhesion theory (Section 1.3) in which the resistance to motion arose from the cohesion of, and micro-irregularities in, surfaces. He then explained that the parameter K in equations 1.6 and 1.7 was a measure of such cohesion in cotton fibres.

In order to account for the plastic and elastic terms of the adhesion theory, Gralen(26) proposed an equation of the form:

$$F = aN + KN^n \qquad (1.8)$$

where a, K and n are constants, and n lies between 0 and 1.

Howell(38) and Makinson(75) both proposed a similar relation for viscose rayon and wool fibres respectively, as given below:

$$F = a + KN^n \qquad (1.9)$$

The power function (KN^n) in equation 1.9 was ascribed to the load (pressure) dependent frictional effect, and the constant (a) was attributed to the adhesion between the mating surfaces. This relation (equation 1.9) suggested a finite frictional resistance at zero load. Since Pascoe(98) could not detect any normal adhesion in a vacuum, he reduced Howell's and Makinson's relation(38,75) (i.e. equation 1.9) to the form:

$$F = KN^n \qquad (1.10)$$

where K = friction constant equivalent to μ when n = 1

n = friction index.

This power relation between the frictional resistance (F) and normal load (N) was found to be valid for textile materials.

The friction constant K had the dimension of $(\text{load})^{1-n}$, so that its value would depend on the units of load (pressure)(88). For textile materials, the value of n has been found to lie between 0.67 and 1.0(8,44,80,118,131,137). This was attributed to the limits of elastic and plastic deformations respectively (7,8,44,80,93,94,118,131,137). Some typical values of n obtained by Mazur(80) for similar and dissimilar fibres crossed at right angles are shown in Table 1.1. These ranged between 0.81-0.94, and was attributed to the visco-elastic behaviour of textile materials.

A negative correlation between the values of n and K have also been reported(93,127-129,131). That is, lower (higher) values of K were associated with higher (lower) values of n. This was explained by Wilson(131), and more recently by Carr et al(7) to be due to the manner in which the asperity contacts (i.e. real area of contact) varied with the normal load. If the asperity contacts increased with, but less rapidly than, the increase in load, the value of n lies between 0.67 and 1, and the coefficient of friction decreased with an increase in the normal load, i.e. nylon on nylon in Figure 1.2.

If the asperity contacts is directly proportional to the normal load, the value of n = 1, and Amonton's law is obeyed.

If the asperity contacts increased more rapidly than the load, the value of n, would be greater than 1, in this case the coefficient of friction increased with an increase in load, i.e. cotton on cotton in Figure 1.2.

Table 1.1

Results of Mazur(80) for single fibres crossed at right angles (fibres in vertical column sliding on fibres in horizontal column)

	Acetate	Nylon	Viscose Rayon	Polyester	Wool
Acetate	0.94	0.89	0.90	0.86	0.92
Nylon	0.86	0.81	-	-	-
Viscose Rayon	0.89	0.88	0.91	0.88	0.87
Polyester	0.88	-	-	-	-
Wool+	0.88	0.86	0.92	0.86	0.90

+ Mean value of "with and against scale"

These explanations were based on the load and area dependent effects of friction, i.e. first and second laws, as enumerated in Section 1.2. Although the static frictional resistance is generally greater than the kinetic (3rd law), the difference between them, and the influence of speed (4th law) on them are primarily the cause of intermittent (stick-slip) motion.

1.5 THE STICK-SLIP PROCESS

The sliding of one body over another under a steady force is frequently accompanied by an intermittent motion. It was therefore thought that a review of this aspect of friction would be useful.

Generally, the intermittent motion has been classified into two forms, namely regular stick-slip (Figure 1.3(a)) and irregular (Figure 1.3(b)) traces(5,6,94,105,106).

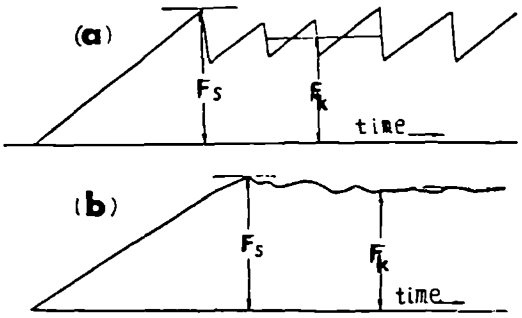


Figure 1.3

Examples of frictional movements(94)

(a

(a) regular stick-slip motion

(b) irregular trace

Both forms have been illustrated for various surfaces including metals(5,6,105,106) and fabrics(94).

Theoretical analyses by Bowden and Tabor(5,6), Morgan et al(86) and Rabinowicz(105,106) have shown that the main cause of the intermittent motion is the difference between static and kinetic frictional forces. A larger (smaller) difference gave a regular stick-slip (smooth) sliding. This difference was also time and deformation controlled. Scientifically, a longer time of contact frequently results in a larger deformation(44,88), particularly for visco-elastic materials(99). This caused a steady junction growth (adhesion) and consequently an increase in the stick-slip amplitude(5,6,105,106).

Hearle and Husain(34) reported a regular stick-slip motion for rayon fibres treated with water, polyethylene glycol and Syton (silica particles). Six different parameters were used to characterise the friction traces, namely:

1. frictional force corresponding to the first peak,
2. frictional force at the beginning of peak line,
3. frictional force at the end of peak line,
4. frictional force at the beginning of trough line,
5. frictional force at the end of trough line,
6. number of peaks/cm of cross-head movement.

These parameters gave complete topographical information on the frictional trace. They may also be referred to as static friction, kinetic friction, amplitude of resistance, number of peaks per unit distance and difference between static and kinetic frictional forces. The latter parameters have been reported to correlate with the tactile sensations of scroopiness, slipperiness and softness of textile materials(25,26,34,44, 88,96,105,109). These are examined in greater detail in subsequent sections.

1.6 FIBRE FRICTION

Since most fabrics contain fibres (natural and synthetic) and many contain yarns (in form of staple and filament fibres), the frictional properties of fabrics may be expected to depend on the component fibres and yarns. It seemed appropriate to review the relevant literature on fibre and yarn friction before considering fabric friction.

The frictional properties of fibres play an important role in mechanical processes such as carding, drafting, spinning and winding. They determine how easily fibres slide over each other and other surfaces.

Gralén and Olofsson(95), in their studies of the frictional and drafting behaviour of fibres found that the magnitude of kinetic friction must be low in order to facilitate fibre movement. However, for optimum yarn strength, and inter-fibre cohesion, a higher value of static friction was desirable. These authors also found that the greater the difference between the static and kinetic coefficients of friction, the greater the irregularities in, and the poorer the quality of, the resultant yarn.

Some typical values of coefficient of friction of fibres are given in Table 1.2. The static coefficient of friction is consistently greater than the kinetic. The difference affected the feel and processability of the material(25,26,34,44,88,96,108,109).

Table 1.2

Coefficient of friction of fibres(25)

Fibres	Coefficient of friction	
	Static	Kinetic
Wool on wool 1	0.13	0.11
2	0.61	0.38
3	0.21	0.15
Wool on rayon 1	0.11	0.09
2	0.39	0.35
Wool on nylon 1	0.26	0.21
2	0.43	0.35
Rayon on rayon	0.35	0.26
Nylon on nylon	0.47	0.40

1 = with scale direction
2 = against scale direction
3 = same direction

Röder(107-109) measured the coefficient of friction of fibres (viscose rayon) at two different speeds namely 3cm/min (static) and 90cm/min (kinetic), and found that the difference was related to handle. A greater difference gave a crunchy and scroopy handle. Such fibres gave a fabric that rustled like silk owing to the marked "stick-slip" motion(88). When the difference was moderate, a softer handle resulted. A negative difference matched a very soft and slippery handle. A typical result given by Röder(109) is shown in Table 1.3.

Table 1.3

Relations between differences in the magnitude of static and kinetic coefficients of friction and the handle of the material(109)

Difference $\mu_s - \mu_k$	Handle
<0	Extremely slippery
0 - 0.015	Normal soft
>0.015	Scroopy

Röder's line of investigation was enterprising, and was expected to stimulate further works. Unfortunately, his results and conclusions were based upon values small enough to be within experimental variations (Table **1.3**). However, later works by Hearle and Husain(34) supported Röder's findings.

Hearle and Husain(34) studied the frictional properties of rayon staple fibres before processing as card web, and after needling (non-woven). Treatments designed to increase (Syton) or decrease (polyethylene glycol) friction were applied. The ultimate objective was to increase or decrease inter-fibre cohesion in non-woven fabrics. These authors found no significant difference between the static friction of the control (scoured) and the original (untreated) samples, but the kinetic friction of the former was reduced. This might be due to the lubricating effect of any residual moisture. Owing to this greater difference in the static - and kinetic - frictional forces, the scoured sample felt harsher than the untreated materials.

Treatments with polyethylene glycol reduced both static and kinetic friction. Accordingly, these samples had the softest and smoothest handle. These agreed with Röder's findings(107-109)

Hearle and Husain(34) also explained other frictional parameters, such as number of peaks per displacement of fringes. The scoured samples were found to show fewer peaks (or troughs) than the polyethylene glycol-treated samples. This was also attributed to the difference between the static and kinetic coefficient of friction. When the difference between the two coefficients was small (large), the number of peaks was large (small).

In view of the fact that a direct relation existed between these parameters and the handle of materials, and that they are not frequently used in the objective specification of fabric handle, they are among the items to be studied in this work.

1.7 YARN FRICTION

Basically, fibres and yarns do not always obey the simple linear relation $\mu = F/N$. Therefore the coefficients of friction reported in the literature are only typical values. An example is given in Table 1.4, and this is discussed in relation to the present work in Chapter 4.

Reference to Table 1.4 shows that the rayon yarn gave the highest coefficient of friction, and Teflon (polytetrafluoro ethylene) monofilament the lowest. The difference, in accordance with the adhesion theory, has been ascribed to the lower shear strength of the Teflon(9,44).

Forth and Olsen(21) found a significant reduction in the coefficient of friciton of these yarns, i.e. 0.45-0.50 to 0.07-0.09 respectively, by the application of lubricants. A similar order of reduction was found by Wilson and Hammersley(132,133) who attributed the effect to wax redistribution. In this case, discrete particles of wax were transferred to the rubbing surface which performed the lubrication.

A comparison of yarn and fabric friction may be useful. Ferguson(20) found that the coefficients of friction of fabrics were significantly higher than those of their component yarns. Among other reasons, this

Table 1.4

Kinetic coefficient of friction of yarns against different surfaces(21)

Yarn Details			Coefficient of Kinetic Friction			
Fibre Content	Count (Tex)	Twist (Turns/m)	Yarn to Yarn	Chrome	AlSiMag[1]	Sapphire[2]
Nylon	70	50	0.63	0.56	0.60	0.55
Rayon	150	250	0.72	0.80	0.81	0.70
Acetate	300	-	0.68	0.70	0.75	0.11
Acrylic	75	30	0.48	0.47	0.50	0.42
Teflon	400	-	0.10	0.10	0.10	0.10
Polyester	250	-	0.70	0.73	0.71	0.73

1 and 2 Types of guides used commercially

was attributed to the dissimilar geometry of the test surfaces which was flat in the case of fabrics and cylindrical in the case of yarns. Ferguson(20) concluded that the two might not be comparable. A recent study(11) has confirmed Ferguson's findings. The coefficient of friction obtained on the Wira (linear) and Shirley (capstan) friction meters show that the former was lower than the latter.

1.8 FABRIC FRICTION

The resistance to motion which is detected when a fabric is rubbed mechanically against itself, or tactually between fingers and thumb, is commonly called fabric friction. This property determines quality features such as handle, i.e. smoothness or roughness, and performance features such as abrasion resistance, wear and shrinkage.

Changes in fibre content, yarn and fabric structures frequently interact with finishing treatments. Assessments of the acceptability of a given combination involves objective and subjective measurements of which friction and smoothness are of interest here. Other parameters such as compression and softness(14,15), and flexion and stiffness(16-18) have been covered.

The frictional properties of fabrics in relation to handle (smoothness and roughness) were investigated by Dreby(13). His parameters included the effects of repeated traversal of sled over the fabric, nature of sled surface and finishing treatments. Different fibre contents (cotton, rayon, wool and wool-rayon blends) were used. Fabric structures included plain, twill and sateen weaves, and warp and hosiery knits. Dreby(13) found a 100% and 20% reduction in static and kinetic friction forces respectively after five traverses. The large reduction, particularly in static friction, was ascribed to the directional alignment of the projecting hairs, and matting them into a smoother compact surface. Fabric-on-fabric friction was found to be the most sensitive test surface. The domestic finishing treatments produced only 15% reduction in friction. There was no clear cut effect of fibre content and fabric structure. Dreby(13) concluded that the coefficient of friction may contribute to the evaluation of smoothness, but in itself, is not always a measure of smoothness. For similar fabrics, in which other properties were approximately the same, the fabric wth a lower coefficient of friction was smoother.

Dreby's conclusions were later supported by Hoffman and Beste(35) who also expressed considerable doubt about the correlation between tactile assessment and coefficient of friction. In their experiments, a piece of soft cowhide was used to approximate the human skin. A linear friction method was employed, and the sled mass was 180g (18g/cm^2 pressure). A series of five twill fabrics were tested. Subjective rankings, i.e.

magnitude estimations were also carried out by a panel of ten judges, who ranked the fabrics from low to high smoothness by assigning 1 to 5 respectively. Because of the similarity in fabric structure (twill) these subjective ratings and objective measurements agreed fairly well.

In another experiment, two pieces were cut from a worsted fabric. A nap was raised on one piece by means of a hand card. The coefficient of friction was measured under a lighter pressure ($0.95 g/cm^2$). The napped piece gave a higher value (0.67) than the original unraised fabric (0.63). A velvet was also included as a control, with a coefficient of friction of 1.31, under the same condition. Tactually, the napped fabric was found to be softer than the original specimen, and the velvet felt very soft and smooth.

Thorndike and Varley(122) measured the coefficient of static friction between fabrics. The influence of fabric structure, yarn types, regain and acidity, i.e. pH, on this quantity were investigated. Clothes made in plain, twill, matt and warp cord weaves were tested, normal and high draft yarns were used. To test the effect of regain at constant temperature, (25.5±0.5°C), the relative humidity was varied between 45-85%. Tests were run with pH values ranging from about 3-7. The tests were limited to measurement of samples from the same fabric.

The coefficient of friction was approximately

10% greater when sliding along the weft direction, probably due to a higher warp yarn crimp. An increase in float length of yarns in fabrics was accompanied by a reduction in the coefficient of friction. High draft (fine) yarns also gave fabrics (worsted panama cloths) with a lower coefficient of friction than the cloth obtained from normal draft yarns. These results suggested that yarn properties may have some relation with fabric friction. Thorndike and Varley(122) also found a small reduction in the coefficient of friction with an increase in fabric regain, due probably to the lubricating effect of moisture. An alkaline cloth, with a "soapy" handle was found to give a higher coefficient of friction than a similar cloth with a lower pH. They concluded that the handle of cloth was related to the coefficient of friction. As the coefficient increased, the handle became harsher (rougher).

Wilson(131) measured the kinetic coefficient of friction of several fabrics. The fibre content included cotton, wool, silk, viscose rayon, acrylics, nylon, polyester and polypropylene. The structure included plain, twill and satin weaves. Finishing treatments consisted of those that were designed to smoothen fabric surfaces, i.e. mercerisation and hot calendering.

The main objective of the study was to examine the application of the adhesion theory of friction, as modified by Huffington(48-50,52,53), and Huffington and Stout(51), to fabrics.

Wilson(131) found that the frictional resistance per unit area (F) was related to the normal pressure (N) by an equation of the form $F = KN^n$, where K and n were constant for a given fabric. The values of n and K were found to be negatively correlated, a result that was attributed to the structural interlocking.

Ohsawa and Namiki(93) investigated the anisotropy of the static friction of plain weave filament fabrics (rayon and polyester). These authors confirmed earlier findings by Wilson(131). The frictional resistance per unit area was also found to be related to the normal pressure by a similar relation $F = KN^n$. A larger value of K was also associated with a smaller value of n. This was ascribed to the interlocking action of the contact points (i.e. yarn crowns, hairs, etc.).

These authors also found that the mean coefficient of friction diminished as the relative angles of orientation of the rubbing and rubbed fabrics was increased, but may increase again.

Ohsawa et al(94) studied the relation between fabric geometry (fabric balance) and surface friction in plain weave fabrics. Fabric balance has been defined as the ratio of the warp and weft cover factors(32). Filament fibre -(viscose rayon , cupra and polyester); spurn fibre - (cotton , flax, wool) and a blend of 65% polyester and 35% cotton fibre - fabrics were used. These authors found a negative correlation between fabric balance and static (-0.91) and kinetic (-0.93) friction in filament fabrics. In the case of fabrics composed of spurn yarns, a high degree of fabric balance which was not related to the frictional property was found. This was attributed to the effect of hairiness in the latter fabrics.

Ohsawa et al(94) also classified the stick-slip friction traces of fabrics. They concluded that the surface condition of the specimen (sett, crimp, hair), speed, load and spring constant (i.e. full scale deflection) all contributed.

Zurek et al(137) studied the effect of fabric structure on surface frictional resistance. Their line of investigation included the relationship between the frictional parameters (such as frictional index, n) of yarns and fabrics. The control fabrics included plain and sateen weaves. In order to eliminate any structural irregularity in yarns, only filament fabrics were considered. (Nylon, polyester, viscose rayon and acetate.) The method of fabric friction measurement was also based on the rectilinear motion of the sled over a horizontal platform. Yarn friction was measured on the capstan system. The frictional index n was evaluated from Howell's equation(38-44)

$$T_1^{(1-n)} = T_o^{(1-n)} + (1-n)(K\Theta R^{(1-n)})$$

where T_1 = output tension

T_o = input tension
θ = angle of lap
R = radius of capstan
n = friction index
K = friction constant

The results of these authors may be summarised as follows:

1. The coefficient of friction of fabrics consistently diminished as the normal load was increased.
2. The coefficient of fabric-fabric friction was significantly greater than yarn-yarn friction. A similar result obtained by Ferguson(20) was attributed to experimental variation. A lower pressure in fabric friction measurement ($1{\cdot}7$ g/cm^2) allowed snagging and catching of projecting fibres which resulted in excess frictional resistance.
3. The frictional resistance was greatest when the direction of motion was perpendicular to axes of orientation of yarns with higher crimps.
4. The frictional indices (n) of yarns and fabrics under a unit pressure had similar magnitudes.

Nishimatsu and Sawaki(90-92) investigated the frictional properties and handle of warp pile (terry towels) cotton fabrics. Their parameters included normal load, area of contact, and velocity of sliding. They found that the frictional resistance increased as the normal load, and area of contact increased. The frictional resistance diminished at first as the velocity of sliding increased (0.5-5mm/s) and then increased again. These observations were not explained by the authors.

Scientifically, an increase in the velocity of sliding implies a reduction in the time of contact between the rubbing surfaces. For viscoelastic materials in which deformation increases as the time of contact increases(8), an increase in velocity should result in a decrease in resistance(44).

Other changes occurred in the stick – slip motion. At low velocity of sliding (0.5-5mm/s) the frictional traces show a regular - stick-slip motion. The amplitude gradually diminished as the velocity of sliding increased. Nishimatsu and Sawaki(90-92) also demonstrated the influence of relative humidity on frictional resistance. An increase in relative humidity also produced an increase in the resistance to motion. This contradicted an earlier finding by Thorndike and Varley(122), and may be due to the tackiness of the pile fibres at higher humidity.

More recently Carr et al(7) and Yoon et al(136) have studied the influence of fibre blending on the frictional properties of woven and knitted fabrics. Similar methods of measurement (linear friction method) were used. Their results for similar fabrics (i.e. blend ratio) are given in Table 1.5. The coefficients of friction of knitted fabrics are significantly higher

Table 1.5

Effect of blend ratio on the coefficient of friction of knitted and woven fabrics(7,136)

Fibre Blend Ratio	Knitted Fabrics(136)		Woven Fabrics(7)			
			Warp on Warp		Weft on Weft	
	Static	Kinetic	Static	Kinetic	Static	Kinetic
100% Polyester	1.52	1.25	1.00	0.86	0.96	0.85
65% Polyester/35% Cotton	1.78	1.52	0.97	0.82	1.03	0.83
50% Polyester/50% Cotton	1.98	1.98	0.86	0.65	0.97	0.66
100% Cotton	2.40	1.98	0.91	0.70	1.05	0.77

than the plain weave fabric. Yoon et al(136) obtained an increase in coefficient of friction as the proportion of cotton in the blend (knitted fabrics) increased. The reason was ascribed to an increase in the number of projecting fibre ends. With the plain weave fabrics, no consistent change in the value of coefficient of friction was found(7). However the static friction was significantly greater than the kinetic friction. These results are discussed in relation to the present work in subsequent chapters.

1.9 OBJECTIVE AND SUBJECTIVE MEASUREMENTS AS GUIDES TO FABRIC HANDLE

Many authors(11-13,35,36,46,47,56,59,60,62-65,73,101,124-126) have sought to relate objective measurements and subjective assessments of fabric handle. What is obvious is the amount of interest. In an earlier paper(101), which is commonly regarded as the foundation, frictional, compressional and flexural properties of fabrics were considered. Tensile stiffness, and change in stiffness with increasing load were related to impression of limpness, harshness and compliancy(35). The properties of smoothness, weight, thickness, and changes in thickness (compression) were related to subjective assessments by multiple factor analysis, with some successful correlations(46,47).

Dreby(12) also reported three physical parameters, flexibility, compressibility, and surface friction to be the most important factors contributing to the handle of soft finished fabrics. To obtain overall effects of physical parameters on hand, rank of desirability of dress goods were compared with measured data. It was found that dress goods having planoflex value greater than 6.0, coefficient of friction greater than 0.48 and compression greater than 0.057mm, had a good handle.

Howorth and Oliver(45) employed factor analysis to study the relationship among subjective assessment of smoothness, softness, coarseness, thickness, weight, flexural rigidity, bending modulus and cover factor, for twenty seven worsted type suiting fabrics. A three factor solution was obtained which represented the relationships between objective tests and subjective rankings. It was concluded that stiffness, smoothness and thickness gave a complete description of the handling qualities of worsted fabrics.

Similar investigations were pursued by Kobayashi (62-65), in which an examination was made of the relation between the sensory and physical values. The range of fabrics included silk, wool, cotton, nylon and polyester. By the use of multiple factor analysis, good correlations were reported between subjective smoothness, and compressional properties. He also compared softness with compression modulus, fluffiness with compressional properties, and liveliness with crease resistance modulus, with good correlations.

In a more recent paper, Elder et al(15) have successfully correlated the results of subjective finger pressure and fabric softness. These authors also stated that the pressure applied on a fabric during subjective assessment was light (20g/cm²). The degrees of compression will vary just as the amount of pressure will vary. However, if two fabrics matched each other in these characteristics, then their handle might be regarded as similar in this respect at least.

A transmission of information caused by stimuli to human response(62-65), and the establishment of a numerical scale of fabric handle is useful. Using a translation equation, Elder et al(18) have established a scale for the inter-conversion between objective data, such as drape coefficient, and subjective ratings (stifs). A similar approach was suggested for fabric friction. In an evaluation of cotton calendering, a seven point scale (0.2 smooth - 0.8 not smooth) was used, on the basis of the coefficient of friction(14).

The conflicting reports in the literature as to whether or not this quantity (coefficient of friction) described the stimuli of smoothness or roughness appeared to hinder progress. This last item seems to point to the need for international co-operation in this field of study.

Other surface properties, such as lateral air flow, may be examined. The study of surface contour is another possibility, primarily because of its relationship with the study of texture and handle. Compared with fabric friction, references to this topic are few. Consequently this is one of the subjects to be investigated.

1.10 CONCLUSIONS

It would appear from the foregoing that the frictional properties of fabrics have been accepted for a long time in the subjective evaluation of smoothness or roughness, and perhaps taken for granted.

Fabrics do not obey the simple linear relation known as Amonton's law ($F = \mu N$). A relation of the form $F = KN^n$ has been found to be generally valid. Also, values of fabric friction can vary for a number of reasons. Care is necessary to define the nature of fabric, i.e. finish, geometry, structure, as well as the experimental conditions, i.e. pressure, velocity, number of traverses and temperature and relative humidity of the testing environment.

It may be necessary to measure several other parameters such as amplitude, number of peaks, and the difference between static and kinetic frictional forces in order to quantify the handle of fabrics (smoothness or roughness). These are among the items to be studied. The suitability of frictional resistance as an index will also be examined.

CHAPTER 2

MATERIALS AND METHODS

2.1 YARN DETAILS

Nine different types of yarns were used in this investigation. These encompassed natural (cotton and wool), regenerated (viscose rayon) and synthetic (acrylic) fibres. Some details of these yarns are given in Table 2.1.

2.2 FABRIC DETAILS

Four groups of fabrics were used in this investigation. The fabrics were grouped together according to the case studies in subsequent chapters. Some of these fabrics had been used by several other workers(15-18,33, 120,124-126) in the Fibre and Textile Research Unit. The same method of fabric coding was also adopted here to facilitate the comparison of results.

The first group (Case 1) consisted of five woven and one non-woven fabrics (Table 2.2).* These were selected to reflect differences in surface properties such as weave (plain, i.e. C_2 and twill, i.e. C_3), smoothness, i.e. W_1, roughness, i.e. fabric C_{11}, hairiness, i.e. fabric W_2. The mass of fabrics range between 83-584g/m^2 and thickness range between 0.11-2.56mm.

The second group (Case 2) consisted of five plain weave fabrics with systematic increase in the density

* and three knitted fabrics (Table 2.5)

of weft yarn sett, i.e. 10-21 threads/cm, but with a constant warp thread sett, i.e. 36 threads/cm. The yarns count was constant (warp 22 Tex, weft 55 Tex). Fabric mass range between 126-204g/m², and thickness was more or less constant (Table 2.3).

The third group (Case 3) consisted of weft pile cotton fabrics with systematic increase in the height and width of Cords. A plane face velveteen (fabric C_{12}) was used as a control. Fabric mass range between 228-382g/m² and thickness range between 0.85-1.42mm (Table 2.4).

The fourth group (Case 4) consisted of knitted fabrics. With the exception of fabric KC_2, all fabrics were knitted in the Fibre and Textile Research Unit. Details of knitting process and dry and wet relaxation are given in Sections 2.3 and 2.4.1. Fabric mass range between 163-580g/m² and thickness range between 0.92-3.80mm. Other details are given in Table 2.5.

2.3 KNITTING PROCEDURE

In order to minimise the variation in fabric thickness arising from the use of yarns of different linear densities, yarns were suitably combined to give a resultant linear density of about 71 Tex for plain, and 120 Tex for rib knitted fabrics in accordance with the B.S. Specification(40).

All yarns were knitted into 1x1 plain and rib

Table 2.1

Yarns Details

Fibre Content	Yarn Count (Tex)	Yarn Twist (Turns/m)	Finish
Cotton	21	500z	Grey
Cotton	29	550z	Grey
Cotton	38	700s	Grey
Cotton	50	600z	Scoured
Cotton+	76/2	500z	Scoured
Wool++	120/3	200s	Dyed
Viscose Rayon	47	300s	Dyed
Acrylic+	72/2	250	Texturised
Acrylic+	97/2	240	Dyed

\+ Two fold yarn

++ Three fold yarn

Table 2.2

Some details of fabrics (Case 1)

Fabric Code	Fibre Content	Fabric Structure	Sett[1] (Thd/cm)		Yarn Count[2] (Tex)		Yarn Crimp[3] (%)		Cover Factor[4]		Mass[5] (g/m^2)	Thickness[6] (mm)
			P	T	P	T	P	T	P	T		
C_2	Cotton	Plain	28	39	10	15	0.8	8.1	0.9	1.5	83	0.22
C_3	Cotton	Twill	40	20	38	58	8.1	8.4	2.5	1.5	275	0.55
C_{11}	Cotton	Plain	18	12	160	180	23.0	4.2	2.3	1.6	500	1.01
W_1	Wool	Plain	21	19	30	33	2.8	9.2	1.2	1.1	121	0.34
W_2	Wool	Plain	10	11	85	100	3.3	9.1	0.9	1.1	179	1.09
W_6	Wool	Non-woven	-	-	-	-	-	-	-	-	584	2.56

1 Test method BS2862 1974

2 Test method BS2865 1974

3 Test method BS2863 1974

4 Cover Factor = $\frac{\text{Threads/cm} \times \sqrt{\text{Tex}}}{100}$

5 Test method BS2471 1974

6 Test method BS2544 1967 (Pressure $36g/cm^2$)

P = warp T = weft

Table 2.3

Some details of plain weave cotton fabrics (Case 2)

Fabric Code	Fibre Content	Fabric Structure	Sett (Thd/cm) P	Sett (Thd/cm) T	Yarn Count (Tex) P	Yarn Count (Tex) T	Yarn Crimp (%) P	Yarn Crimp (%) T	Cover Factor P	Cover Factor T	Mass (g/m²)	Thickness (mm)
C_6	Cotton	Plain	36	10	21	55	5	1.0	1.7	0.7	126	0.47
C_7	Cotton	Plain	36	13	22	55	8	1.5	1.7	1.0	144	0.47
C_8	Cotton	Plain	37	15	23	55	10	2.1	1,8	1.1	154	0.47
C_9	Cotton	Plain	36	18	23	56	12	2.5	1.7	1.4	171	0.45
C_{10}	Cotton	Plain	36	21	23	56	14	3.0	1.7	1.6	204	0.47

Table 2.4

Some details of weft pile cotton fabrics (Case 3)

Fabric Code	Fabric Structure	Sett* (Thd/cm)		Number[1] of cords (per 5cm)	Cord[2] Width (mm)	Cord[3] Height (mm)	Mass (g/m^2)	Thickness (mm)
		P	T					
C_{12}	Velveteen	35	39	-	-	-	319	1.23
C_{13}	Corduroy	18	17	32	1.0	0.67	228	0.85
C_{14}	Corduroy	25	21	20	2.0	0.95	257	1.14
C_{15}	Corduroy	35	39	16	2.5	1.06	316	1.30
C_{16}^{**}	Corduroy	18	23	8(8)	4.5 (2.1)	1.18 (0.84)	382	1.42

* Sett of base weave (plain)

1,2 Test method: Cooke's Micrometer (Essentially a microscope with a traversing eye piece)

3 Test method: Projection microscope (see Section 2.8.1)

** Two types of cords, values in parenthesis refer to the smaller cord

Table 2.5

Some details of knitted fabrics (Cases 1 and 4)

Fabric Code	Fibre Content	Fabric Structure	Courses/ cm	Wales/ cm	Yarn Count (Tex)	Fabric Mass (g/m^2)	Thickness (mm)
KC_2 (Case 1)	Cotton	Plain	14.1	15.2	14	195	0.92
KC_{71} (Case 1)	Cotton	Plain	8.5	5.0	90	215	1.21
KC_{120}	Cotton	Rib	8.1	4.2	104	580	2.80
KW_{71}	Wool	Plain	7.6	5.2	94	530	1.41
KW_{120}(Case 1)	Wool	Rib	7.8	3.8	125	480	3.40
KA_{71}	Acrylic	Plain	8.0	4.8	71	163	1.29
KA_{120}	Acrylic	Rib	6.5	3.9	97	400	3.80

structures on an 8-gauge power driven V-bed knitting machine (Model MC-1 Universal). The yarn tension was suitably adjusted to prevent slackness and snarling especially of the high twisted yarns. The check plate position, and stitch cam were set with the aid of a stitch knock-over gauge in accordance with the manufacturer's bulletin. This enabled good control to be exercised over the loop formation by the knitting needles.

All fabrics were preconditioned for four weeks at standard atmosphere (20°±2°C, 65±2%R.H.) before tests were made.

2.4 FINISHING TREATMENT

2.4.1 SCOURING (CONTROL)

All fabrics used in the wet treatments, as well as the knitted fabrics (Section 2.3), were scoured in a 0.2% solution of Teepol at 60°C for about 10 minutes in a domestic washing machine. The goods to liquor ratio was 1:20, i.e. 1 gram of fabric required 20ml of Teepol solution.

After the washing treatment, the fabrics were rinsed and hydro-extracted and tumble dried at 60°C for about 20-30 minutes followed by calendering on the Hoffman Press to remove creases.

All fabrics were subsequently conditioned in a standard atmosphere (20°±2°C, 65±2%R.H.) for two weeks before tests were made.

2.4.2 MERCERISATION

Mercerisation was carried out on the control fabric (i.e. scoured and hydro-extracted) by immersion in a tensionless state, into a 25% solution of sodium hydroxide (NaOH) at room temperature (20°C) for ten minutes(104,120,123).

This was followed by neutralisation in 5% solution of acetic acid at 20°C for five minutes. The fabric was rinsed, hydro-extracted and tumble dried.

2.4.3 SOFTENING

Two brands of commercial fabric softeners were used, namely Softlan and Comfort, believed to be made up of emulsions of fatty acid amide, although detail compositions were not known.

Application consisted of rinsing the fabric with a solution of 2% softener at room temperature (20°C) for five minutes, followed by hydro-extraction, tumble drying and conditioning in a standard atmosphere.

2.4.4 LUBRICATION

In order to produce a smoother fabric surface(9,34,120), polyethylene glycol (PEG) having molecular weights of 1000, 4000 and 6000 respectively were applied as water soluble lubricants.

The aqueous solutions of 5% of PEG were prepared in warm water (i.e. 60°C) and treatments were carried out at the same temperature to prevent any deposition of lumpy particles of the glycol (especially PEG 6000) on the fabric surface.

Application of PEG to fabric was carried out with agitation for 30 minutes, followed by hydro-extraction, tumble drying, and calendering on the Hoffman Press.

2.4.5 ROUGHENING

In order to roughen fabric surfaces with an intention of increasing the resistance to sliding, chemical and physical modifications of fabric surfaces were carried out. The chemical treatment consisted of the application of Syton(34,85,107-109). The physical modification entailed the use of a roller abrader.

(i) Syton Treatment (Chemical): Syton W30, which was a 30% colloidal dispersion of silica in water, supplied by Monsanto Chemical Co Ltd, was used. The physical properties of Syton W30 are given in Table 2.6.

Application consisted of an immersion of the fabric into a solution of Syton diluted to 1% concentration. Because of the large specific surface of Syton ($70m^2/g$), only a low concentration and liquor ratio (1:50) were required. The fabric was immersed into the solution for ten minutes at room temperature (20°C) with agitation, followed by hydro-extration and tumble drying. The fabric was subsequently calendered on a Hoffman Press and

Table 2.6

Physical Properties of Syton W30(85)

Properties	
Grade [1]	W30
Particle Size[2] (nm)	125
Density (Kg/m^3)	1200
pH	10
Silica (%)	30
Na_2O (%)	0.12
Specific Surface (m^2/g)	70
Viscosity (cP)	2

[1] Number represents concentration of silica in water.

[2] Approximate particle size based on light scattering

conditioned in a standard atmosphere for two weeks before tests were made.

(ii) Raising (Physical): A second method of roughening used a rotary emery roller (physical modification).

Briefly, the apparatus consisted of a wooden roller (30cm diameter) covered with a grade 150 carborundum paper. The test specimen was lapped round the roller at an angle of about 180°, and gripped at both ends by bulldog clips. The clips were movable (upward or downward) to increase or decrease the pressure between the roller and test specimen respectively. Raising was also carried out in a standard atmosphere (20°±2°C, 65±2%R.H.).

2.5 YARN FRICTION MEASUREMENT

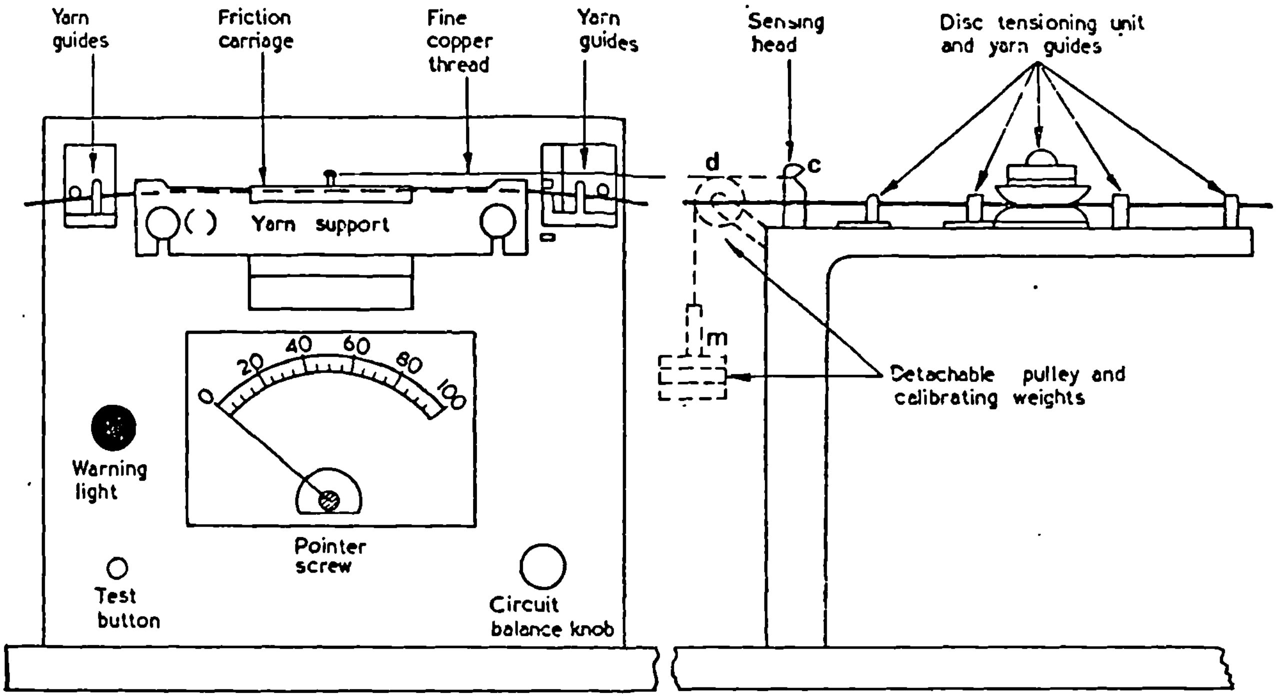
2.5.1 LINEAR METHOD

The Wira Linear Friction Tester was used in accordance with the B.S. specification(4), with some modifications in the method of test in order to permit the measurement of the frictional resistance between yarns instead of between metal and yarn.

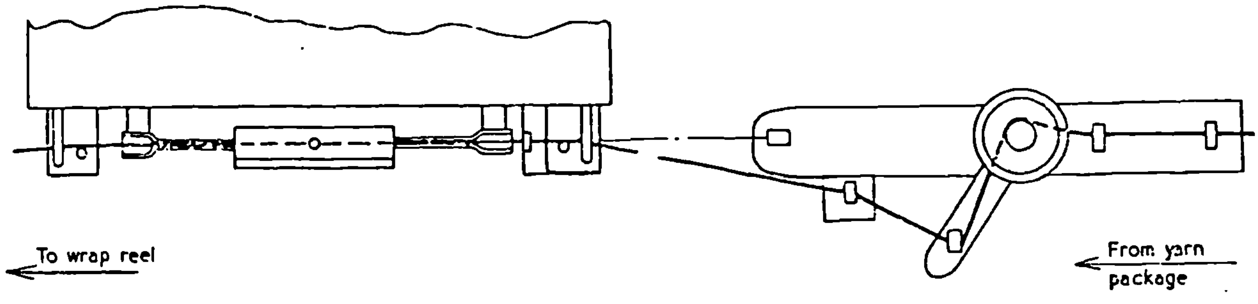
A yarn was drawn at a constant speed of 5cm/min, through the friction assembly by a Variac controlled winding drum (Figure 2.1). A friction carriage (mass 50g) rested on the running yarn, which in turn was supported by an aluminium frame mounted on the apparatus.

In order to achieve yarn-to-yarn contact, the inner surface of the carriage was first lined with a double-sided sellotape into which about six strands of yarns were secured as shown in Plate 1. The friction carriage was itself anchored to a fixed tension measuring device by a fine conductive wire, and balanced in a stable equilibrium by the running yarn.

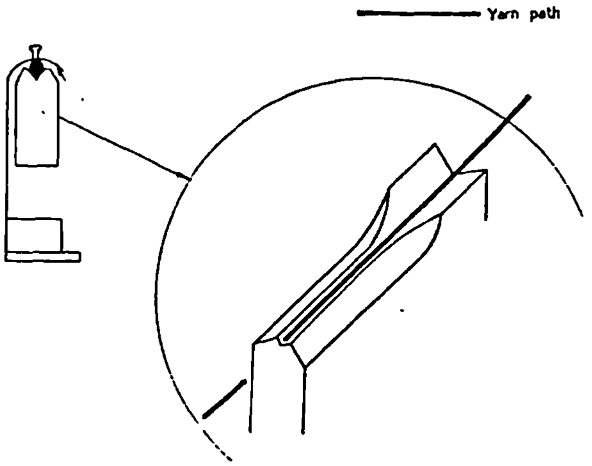
The yarn support consisted of a V-shaped groove cut along a narrow bevelled face of a metal as illustrated in the inset of Figure 2.1. The angle at the base of the groove was 90°. Four numbered yarns supports with grooves of different widths were employed for yarns



(a) Side elevation



(b) Plan



(c) Enlarged end elevation of friction carriage and groove

Figure 2.1

The Wira linear friction meter

Plate 1

Method of mounting yarns in the
inner surface of friction carriage
of a Wira linear friction meter

of various sizes as given in Table 2.7.

Table 2.7

Specification of yarn support

Yarn Support	Width at Top (mm)	Range of Yarn Count (Tex)
1	0.25	Below 30
2	0.50	30-95
3	0.75	96-200
4	1.00	Over 200

In addition to the correct choice of yarn support, the yarns under test were properly pre-tensioned. This ensured that yarn did not slip out of the groove during test. This pre-tensioning was made in accordance with the B.S. specification(4), namely:

Yarn below 45 Tex disc 1
Yarn between 45-90 Tex disc 1 + 2
Yarn above 90 Tex disc 1 + 2 + 3.

2.5.2 CAPSTAN METHOD

The frictional resistance between two yarns was measured by a capstan assembly shown in Figure 2.2. A yarn from the supply package was first pre-tensioned by a "ball and socket" type of tension device (a) followed by a disc tensioner (b). These enabled the input tension to be varied by ±0.5g. The input tension (T_1) was

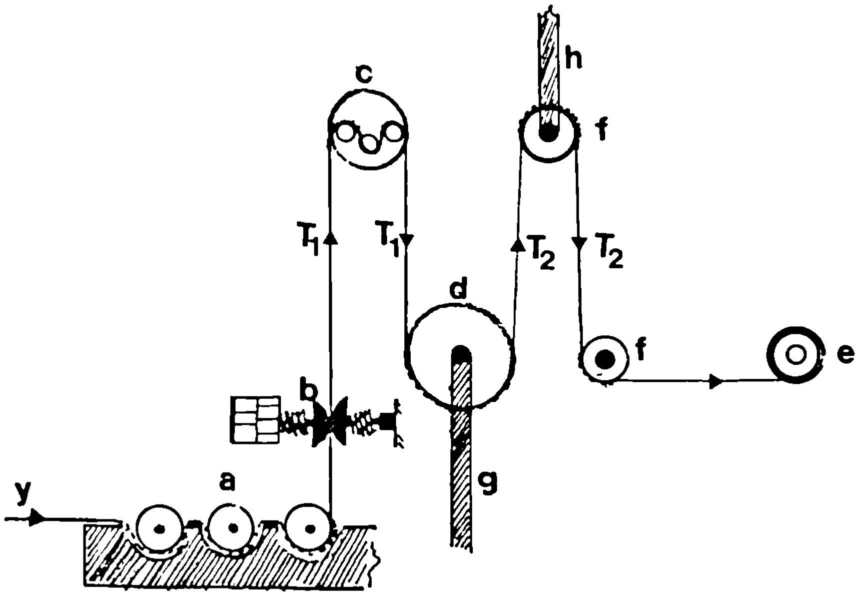


Fig 2·2

Assembly for yarn friction measurement on a capstan, (yarn speed 5 cm/min, temperature and humidity of test 20±2°C, 65±2% respectively)

y = yarn from supply package (cone), a = ball and socket tension device, b = spring-disc tension device, c = Rothchild tension meter, d = fixed friciton surface, e ≐ winding drum,. f = frictionless pulley, g = fixed support, h = attachment to the Instron load cell.

measured by the Rothchild Tension Meter (c). The yarn was then passed over the friction surface, and the output tension (T_2) was measured by an Instron Tensile Tester (Model 1122) by a pulley arrangement as shown in Figure 2.2. Both the Tension meter and the Instron recorders enable the input and output tensions respectively to be recorded.

In this case the friction surface consisted of a perspex cylinder (d) of 6cm outer diameter and 0.4cm thickness. A narrow slot (0.2cm wide and 0.2cm deep) was cut in the rim of the cylinder so that the effective diameter was 5.6cm. Two layers of yarns were wound in the slot, and the free ends of the yarns were secured by a double sided Sellotape. This ensured that the free ends of the yarn did not interfere with the running yarn.

2.5.3 CALIBRATION

The Wira linear yarn friction meter was calibrated in accordance with the B.S. specification(4). Briefly, this consisted of lifting the light weight pulley (d) to the calibration position as shown in Figure 2.1(a). A special disc holder (m) attached to the tension sensing head (c) enabled weights to be added (i.e. increased tension). The pen deflection corresponding to the tension increment was recorded. A typical calibration curve is shown in Figure 2.3.

The frictional resistance was estimated from the

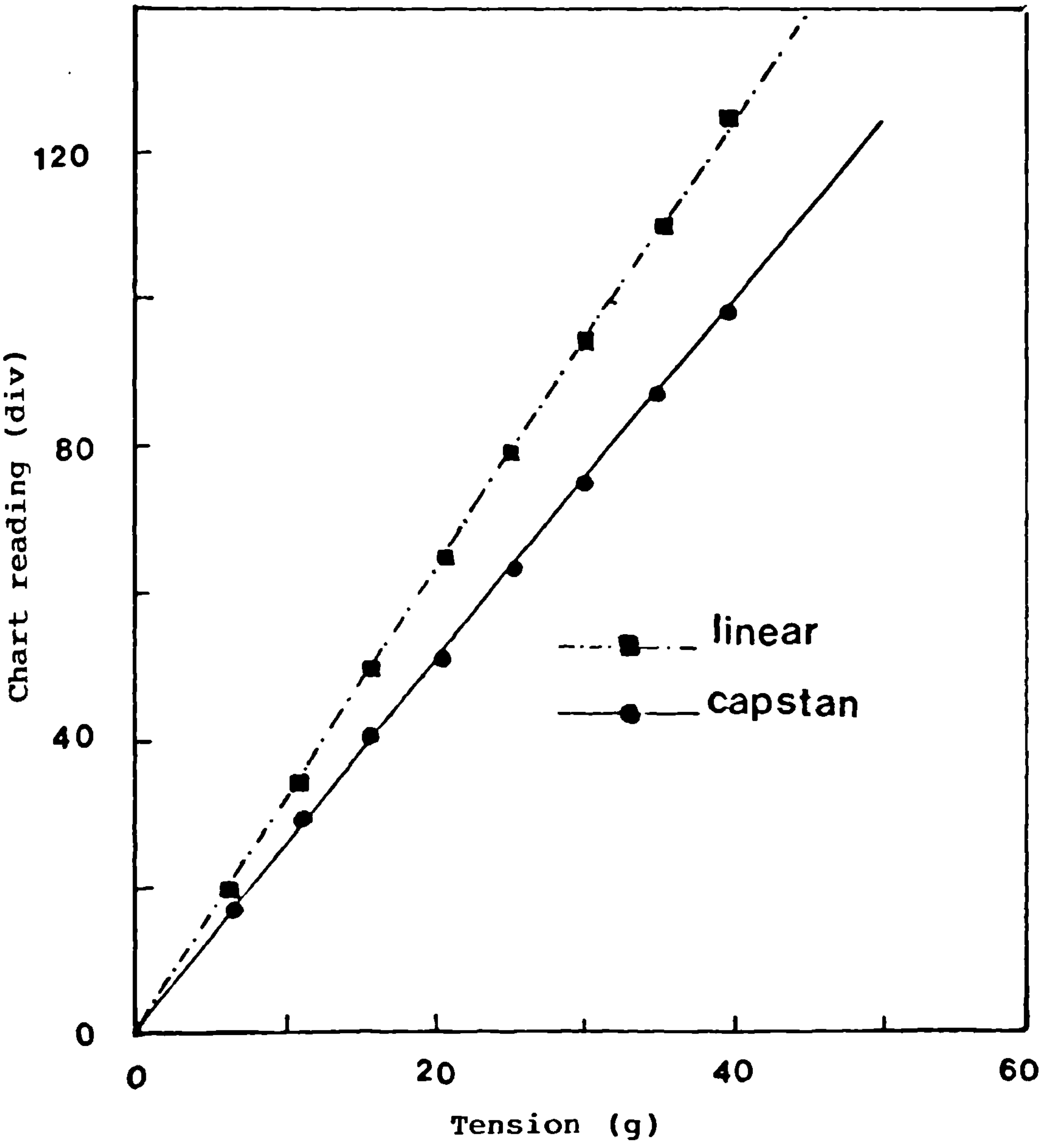


Figure 2.3

Typical calibration curves of the linear and capstan yarn friction meters

calibration equations

linear Y = 1.60X

Capstan Y = 1.28X

Y = Chart readings, X = tension

calibration equation, and the normal reaction corresponded to the mass of the carriage plus any additional weight added to it.

For the capstan friction meter, the tension meter and the Instron were calibrated in the running position by hanging weights over a loop of yarn(118). A typical calibration curve of the Rothchild Tension Meter is also shown in Figure 2.3.

2.6 FABRIC FRICTION

For fabric friction measurements, an Instron Tensile Tester (Model 1122) fitted with an appropriate friction assembly, i.e. aluminium platform, in accordance with the ASTM procedure was used(3).

The principle of measurement was based on the rectilinear motion of a sled over a horizontal platform (52cm x 15cm). A light wooden sled (8cm x 5cm), weighing 25g (i.e. pressure $63N/m^2$), was used. The sled was pulled at a constant speed of 5cm/min by the Instron cross-head by means of an inextensible towing yarn, passing over a frictionless pulley as shown in Figure 2.4. Both chart speed (5cm/min) and full scale deflection (50g - 200g) were selected to give the maximum reproducible frictional resistance, coefficient of friction and amplitude of the stick-slip motion.

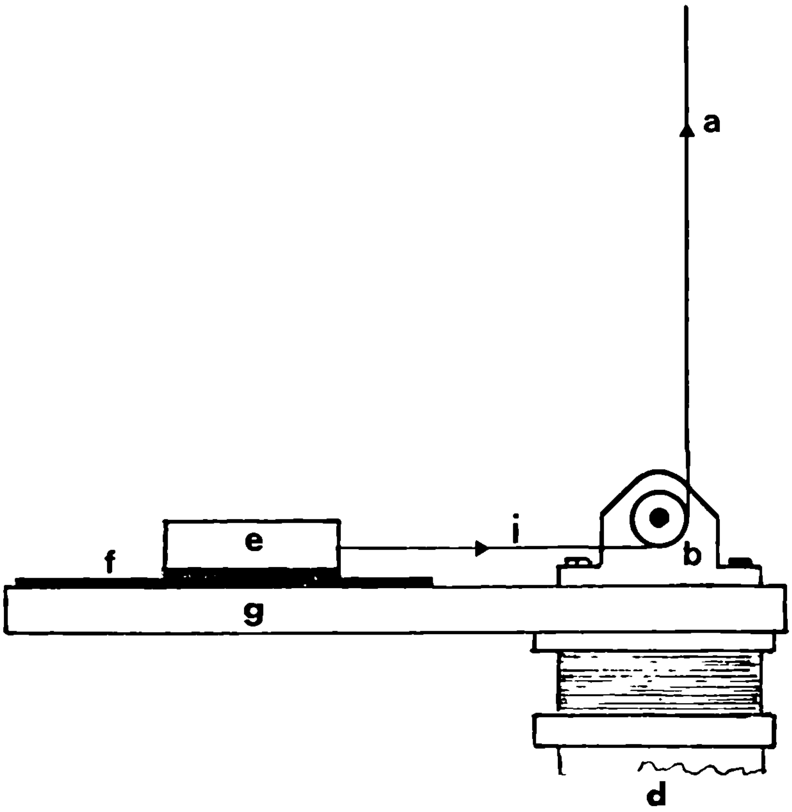


Fig 2.4

Sketch of the fabric friction measurement on a flat horizontal platform.

a = to Instron load cell, b = frictionless pulley, i = inextensible towing cord, e = sled (covered with fabric), f = fabric specimen, g = horizontal platform, d = connection to bottom jaw,

2.6.1 TEST PROCEDURE

The frictional resistance between two fabrics was measured by mounting a rectangular specimen (30cm x 10cm) on a horizontal platform over which a sled covered with an identical fabric was traversed. The fabric on the platform was smoothed by hand and held under a slight tension by bull-dog clips, this ensured that fabric did not wrinkle or buckle during the test. The fabric specimen mounted on the sled was also slightly tensioned and fastened on the upper surface of the sled by a double-sided Sellotape. Two directions of orientation, i.e. warp on warp, weft on weft, motion were employed. Fresh samples were used for all tests and a total of five tests (face and back) were made on each fabric specimen, except where otherwise stated.

2.6.2 EXPRESSION OF RESULTS

The frictional parameters enumerated in this section were determined in accordance wth the procedures of several other investigators, namely: Carr et al(7), Grosberg et al(30), Hearle and Husain(34), Ngai89) and Ohsawa et al(93,94).

(i) Frictional resistance: Both static and kinetic frictional resistance were determined directly from the friction trace. The highest peak at the beginning of motion was taken as the static frictional resistance (Fs)(7,94). The mean of peaks and troughs (equivalent to drawing a straight line through the middle of the stick-slip pulses) was taken as the kinetic frictional resistance (Fk)(34,94).

(ii) Coefficient of friction: The coefficient of friction (μ) was based on the simple linear relation between the friction resistance (F), and normal load (N) (i.e. $\mu = F/N$)(7).

(iii) Frictional index and constant: It has been shown in Chapter 1 that the friction properties of fabrics do not obey the simple Amonton's law, and that there is a non-linear relation between frictional force and applied load(7,44,88,93,131). However the results may be expressed in the form of a power equation(7,93,131):

$$F = KN^n \qquad (1.10)$$

where F = frictional resistance per unit area (g/cm²)

N = normal pressure (g/cm²)

K = friction constant (g/cm²)+

n = friction index

\+ Note that the values of K will be different in other units.

Equation 1.10 may be written as

$$\log_{10}F = \log_{10}K + n \log N \qquad (2.1)$$

Using the regression analysis technique, we may write(30,89)

$$Y = c + mX \qquad (2.2)$$

where $Y = \log_{10}F$

$X = \log_{10}N$

$C = \log K$

$m = n$

Thus
$$C = \frac{(\Sigma Y)(\Sigma X^2) - (\Sigma X)(\Sigma XY)}{a(\Sigma X^2) - (\Sigma X)^2} \qquad (2.3)$$

$$m = \frac{a(\Sigma XY) - (\Sigma X)(\Sigma Y)}{a(\Sigma X^2) - (\Sigma X^2)} \qquad (2.4)$$

where a = number of observations.

The values of C(K), and m(n) was calculated using the H.P. Olivetti Computer in the F.T.R.U.

iv Coefficient of friction (Capstan)

This was calculated from the following relation:

$$\frac{T_2}{T_1} = e^{\mu\Theta} \qquad 2.5$$

$$\mu = \frac{\text{In}T_2/T_1}{\Theta} \qquad 2.6$$

where T_1 = input tension

T_2 = output tension

Θ = angle of lap (3.14 radian)

(v) Amplitude of frictional resistance: This was taken as the height (i.e. peak to trough) of the stick-slip pulses exluding the first peak. It is denoted by F_A and the unit is that of force (i.e. gf).

(vi) Number of peaks: The number of distinctive peaks in 5cm traverse of sled was counted(34). This was very laborious and time consuming, particularly in woven fabrics with very high sett or surface hairiness.

(vii) Mean deviation of kinetic friction: This is a measure of the oscillation of the kinetic value above or below the mean value(19) (Fr).

2.7 SURFACE IRREGULARITY MEASUREMENTS

2.7.1 ROLLER (INSTRON) METHOD

The novel accessory used is shown in Plate 2. Basically this consisted of a tapered brass rod fitted with a freely rotating wheel roller. The roller surface was made of polished stainless steel in order to minimise friction between the roller and the test surface.

The brass arm was connected to an Instron (Model 1122) in such a manner that it was inclined to the horizontal, i.e. the test surface at an angle of 45°, as shown in Plate 2(a). As the Instron cross-head traversed upward, the roller moved forward, i.e. towards the cross-head. A downward traversal of the cross-head corresponded to the backward movement, i.e. away from the cross-head.

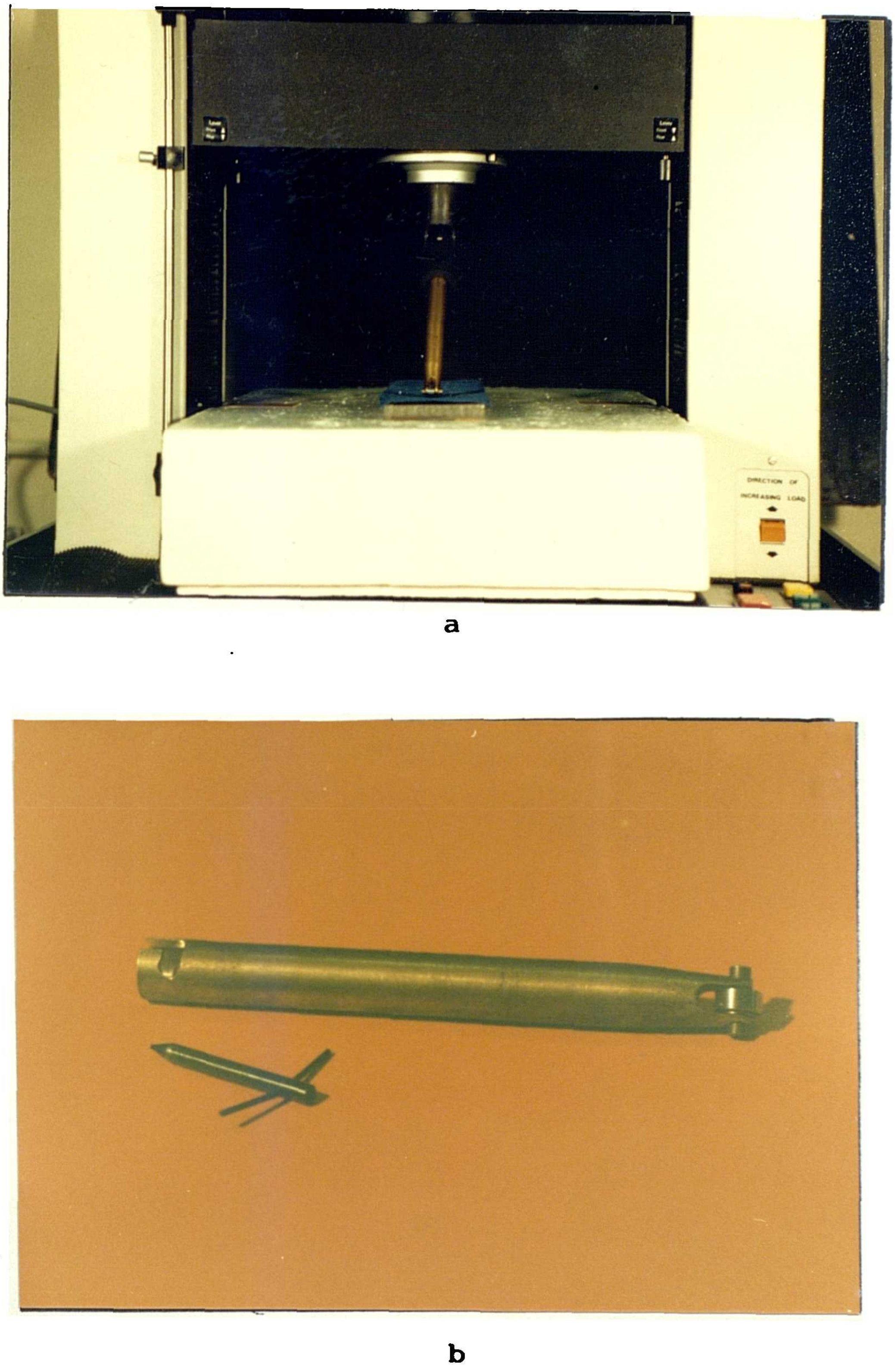


Plate 2

Instron (roller) surface contour apparatus

(a) assembled

(b) components

The length of stroke in both directions was 5cm. Both the choice of the angle of inclination (45°), and the length of stroke were made partly for convenience, and partly to minimise the geometric effect of the apparatus. A high speed pen sensitivity response enabled the deflection of the roller by surface irregularities to be accurately recorded.

One difficulty with the measurement of the surface irregularities of fabrics by the Instron technique was the effect of geometry of the linkage. The systematic change in movement caused the Instron trace to be slightly inclined to the horizontal, thus resulting in an accompanying systematic change in the amplitude. An analysis of this effect is given in Appendix 2.

2.7.2 STYLUS METHOD

In order to access the irregularities on fabric surfaces, thickness and changes in thickness along the line of probe and under a constant pressure were measured. The main feature of this apparatus consisted of a stainless steel pin (e) as shown in Figure 2.5, and Plate 3. The pin was fastened on to a rubber strap. This was in turn glued on to a transducer finger. The finger was itself mounted on the tension sensing head of a Rothchild Tension Meter, in such a way that the stylus was perpendicular to the fabric surface (see Figure 2.5).

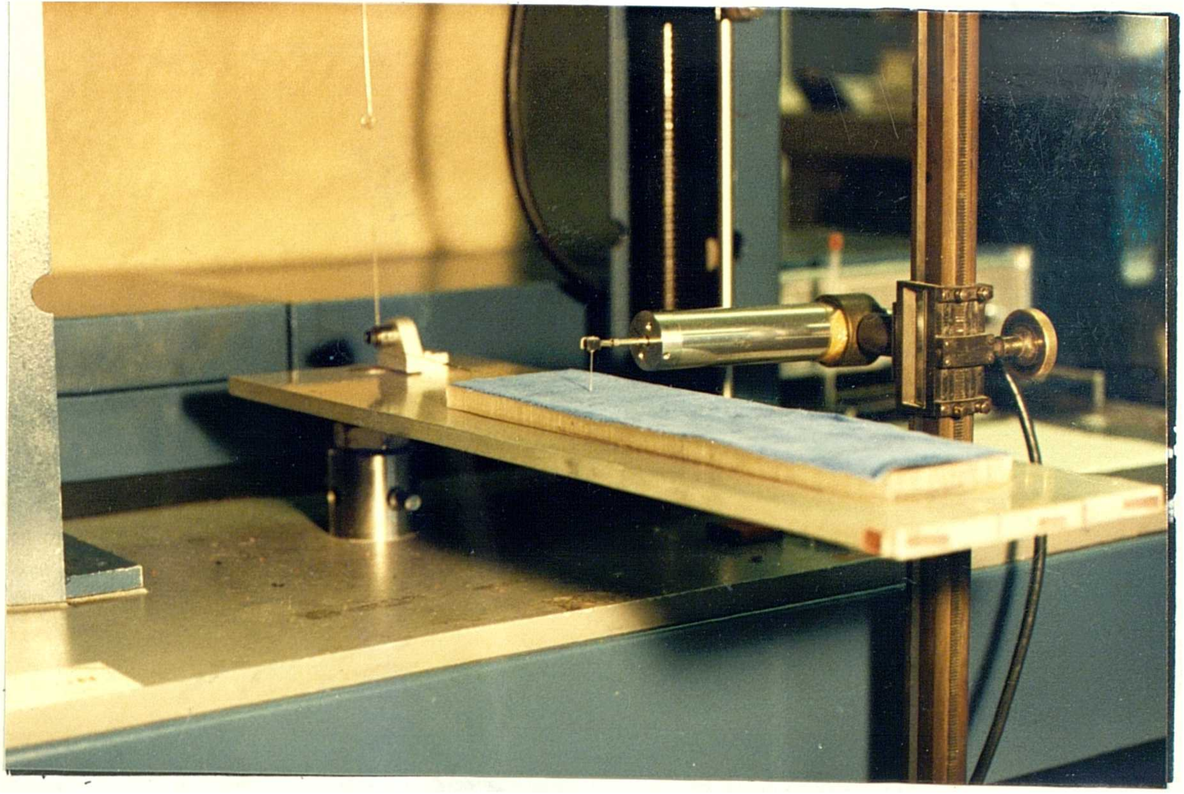
In order to exercise some control over the vertical movement of the stylus, and hence the pressure exerted on the fabric underneath, the cylinder of the tension sensor (c) was mounted on a travelling retort. This can be raised or lowered manually as required. A built-in damping facility in the Rothchild Tension Meter served to filter out any signal arising from a possible vibration of the stylus.

Before tests were made, the stylus mounted vertically over the test specimen was slowly lowered, until both the stylus and the fabric surfaces met, and a 1% of full scale deflection was registered by the pen. This arbitrary procedure ensured that contact was reasonably positive.

A fabric specimen (20cm x 6cm) was mounted on a perspex block (30cm x 10cm) under a slight tension. The edges of the specimen were fastened by a double-sided Sellotape, and the fabric smoothened by hand. These prevented wrinkle during test.

The perspex block was then traversed forward at a constant velocity of 2cm/min by the Instron cross-head. Use of the tension meter and a graphic recorder enable pen sensitivity to be magnified 100 times on the former, and 10 times on the latter. Use could similarly be made of a 50 times speed sensitivity of the chart. These features enabled more sensitive measurements to be made.

a



b

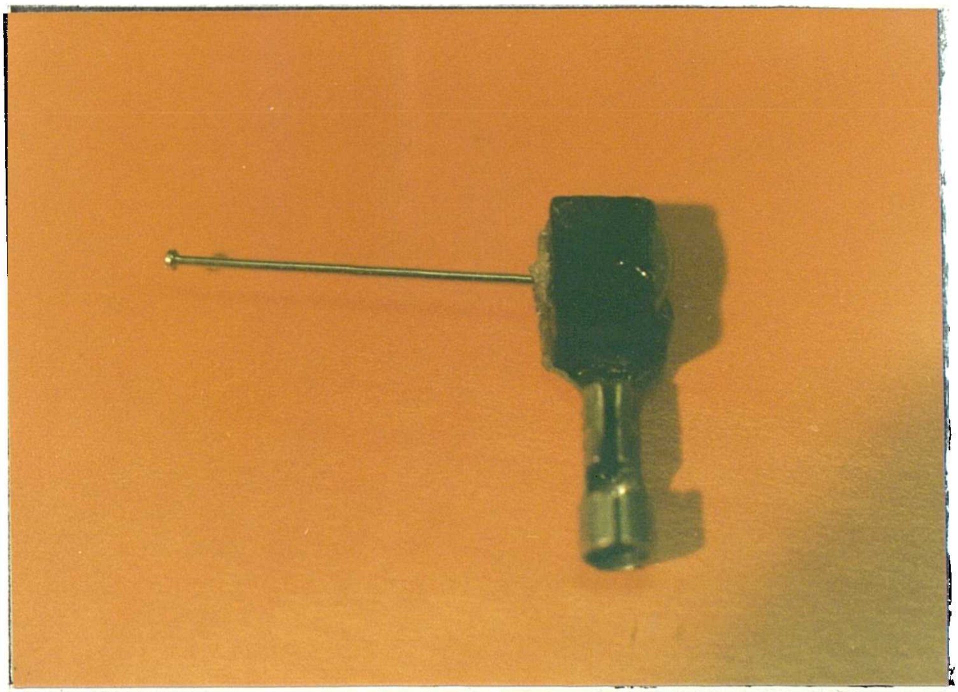


Plate 3

Stylus surface contour apparatus

(a) showing the stylus and fabric specimen
(b) stylus

Legend to Figure 2·5

a = Chart Recorder
b = Rothchild Tension Meter
c = Transducer
d = Travelling Retort Stand
e = Stylus
f = Perspex Sample Holder and Fabric
g = Horizontal Platform
h = Towing Cord
i = To Instron Top Jaw

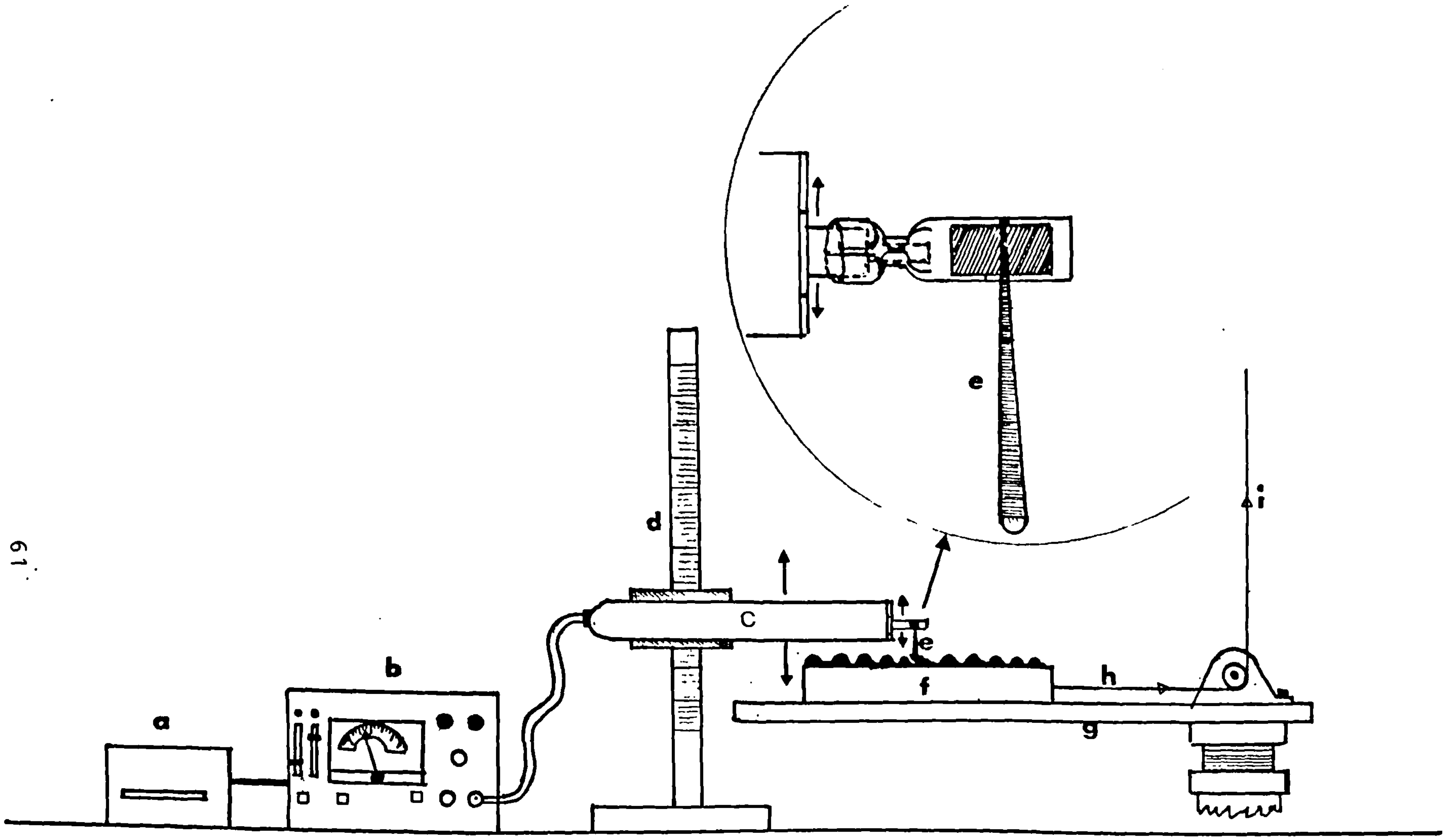
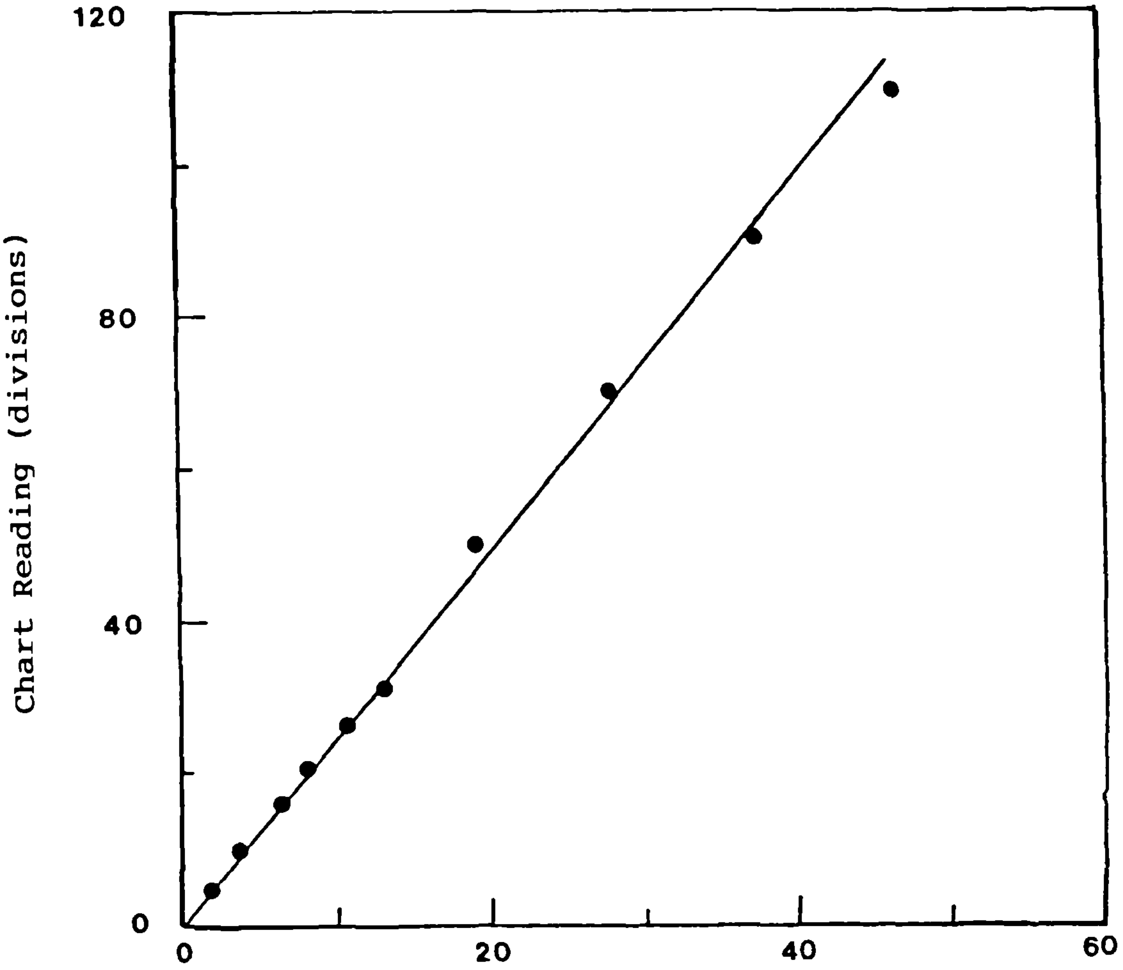


Fig 2.5

Sketch of the apparatus (stylus) used in the evaluation of surface profile of fabrics.
(Not to scale, see legend on page 60)



Load (g)

Figure 2.6

Calibration curve of the stylus probe

Calibration equation

$Y = 1.24X$

Y = chart reading

X = load (g)

2.7.3 CALIBRATION

This apparatus was calibrated by lowering the stylus on to a Mettler weighing balance (Type PE200). The pen deflections corresponding to the indicated loads (pressure) were recorded. A typical calibration curve is shown in Figure 2.6.

2.8 OTHER OBJECTIVE MEASUREMENTS

2.8.1 MICROSCOPIC (OPTICAL) MEASUREMENT

In order to determine the relative protrusion of yarn crowns (structure) from the plane of fabric surface, a cross-sectional examination of fabrics was made using a projection microscope. A fabric specimen was sandwiched between two faces of perspex blocks in such a manner that the section of fabric was uniformly displayed. The image was projected on to a screen on which a calibration graticule was superimposed, enabling numbers and dimensions of, for example, peaks, ribs, cords, etc., to be measured.

2.8.2 LATERAL AIR FLOW

The air flowing laterally across the surface of a fabric was measured on the Shirley Air Permeability Apparatus.

Briefly, a circular fabric specimen (7.5cm diameter) was sandwiched between a sheet of rubber and a perspex plate of the same dimensions. The perspex with an air hole of 3cm diameter was mounted on the apparatus, and made air-tight by means of Vaseline. Another perspex plate (without air hole) and a load was put on the rubber, so that the pressure on the fabric underneath was about $1 g/cm^2$. The essence of the low pressure was to ensure that the protruding structure is not unduly compressed or flattened.

Measurements were then made in accordance with the standard method of air permeability testing(4).

2.8.3 COMPRESSION MEASUREMENT

For compression tests(15), an Instron Tensile Tester (Model 1122), fitted with an appropriate compression load cell was used. This model enabled thickness and thickness changes to be magnified 100 times on the chart, while use could similarly be made of a x10 load sensitivity. Both features enabled more sensitive measurements to be made.

The rate of compression was such that one loading cycle took approximately one minute to complete. Compression was defined as the decrease in intrinsic thickness with an appropriate increase in pressure; intrinsic thickness being the thickness of the space occupied by a fabric subjected to barely perceptible pressure. This was measured by compressing a fabric until 1% of full scale deflection, corresponding to a pressure of 0.4KPa.

The sample was removed, and the "empty space" was compressed until the faces of the plate met. This distance between the displacement on the chart adjusted for scale gave the intrinsic thickness. Compressibility was defined as the ratio of compression/intrinsic thickness, expressed as a percentage.

2.9 SUBJECTIVE ASSESSMENTS (SMOOTHNESS)

For subjective assessments of fabric smoothness, the paired comparison technique was used. A panel of ten judges, 9 female and 1 male, within the age group 21 to 50 years, was asked to rank the fabrics. Each judge did two tests of paired comparisons and was answering the pertinent question such as "which is rougher?" or "which is deeper ridge?" In one test judges were allowed to see the fabrics since this is usually the case commercially. In another test, a pillory box was used to prevent the judges from seeing the samples and thus decisions were based on touch alone. A period of two weeks was allowed between tests to eliminate any possible memory effect. All samples were mounted on a stiff card, and judges were asked to draw their fingers over the surface of the fabric. The method of scoring and statistical analysis are given in Appendix 3. All tests were conducted in a quiet room maintained at a temperature of 20°C and relative humidity of 65%.

CHAPTER 3

GENERAL INVESTIGATION

ABSTRACT

A general investigation of frictional properties of fabrics was carried out. The dependence of the coefficient of friction, frictional resistance, number of peaks in the stick-slip traces, amplitude of resistance and the difference between static and kinetic frictional forces upon experimental variables (pressure, velocity, number of traverses, etc) are demonstrated.

Subjectively, fabrics with similar (different) values of coefficient of friction yield different (similar) tactile sensations of smoothness. Objectively, an examination of the stick-slip motion shows a good linear relation between the number of peaks and yarn sett (woven fabrics) or number of ribs (knitted fabrics). A relation also exists between the amplitude of the stick-slip motion and structural protrusions, i.e. twills, ribs. These structural features are also detectable visually and tactually. A linear relation between fabric friction (smoothness) and compressibility (softness) is demonstrated. The larger the value of the difference between static and kinetic frictional forces, the larger the compression and the softer the fabric.

3.1 INTRODUCTION

In addition to systematic yarn interlacings such as those found in plain, twill, or rib fabrics, woven fabrics may be smooth (filament yarn)(7,93,94,137) or hairy (staple yarn)(7,90,91,122). Any protrusion may be expected to alter the resistance to motion detected when the fabric surface is stroked either tactually by a human subject or rubbed mechanically by another fabric.

From the perusal of the literature in Chapter 1, many of the previous investigations dealt almost exclusively with the coefficient of friction(7,13,35,60,87,90-92,122,133,137). In view of the diverse nature of fabric surfaces, and the fact that the normal pressure (load) and frictional resistance are not always in direct proportions(7,93,133), the coefficient as such may be inadequate for surface characterisation, for example degrees of smoothness or roughness.

In the present investigation, several other frictional parameters such as frictional resistance (static and kinetic), number of peaks, amplitude of resistance, and the difference between static and kinetic frictional resistance were evaluated. The influence of experimental variables for example, normal pressure, velocity, number of traverses and the nature of sled surface on these frictional parameters was also investigated. A standard method of measurement that gave the best discrimination between samples, and a reasonable reproducibility of results was used in subsequent tests.

The fabric samples employed in this first case study were fairly diverse, and represented a wide range of structures, for example woven, knitted and non-woven, and physical properties for example mass, thickness, hairiness, and compressibility. They represented fabrics which were commercially available within their class, and which had been used by several other investigators in the Fibre and Textile Research Unit(14-18,33,120,124-126). Some details of these fabrics are given in Chapter 2 (Table 2.2).

3.2 EXPERIMENTAL VARIABLES

In addition to the influence of fibre content, yarn and fabric structures and finishing treatments which will be considered in later chapters, fabric friction is also affected by experimental conditions. These include normal pressure(7,90-93,93,131), velocity of sliding(90-92,131), number of traverses(13,33), nature of sled surface(13,83,87,136) and temperature and relative humidity(90). Apart from the frictional resistance and coefficient of friction, the effects of these variables on other frictional parameters, i.e. number of peaks, amplitude, etc, are not frequently scrutinised. They are therefore considered in the ensuing discussions using Case 1 fabrics.

3.2.1 NORMAL PRESSURE

The effect of normal pressure on the frictional properties of fabrics (Case 1) is shown in Table 3.1. The coefficient of friction diminished with an increase in the normal pressure. This is in accord with the results of several other workers(7,90-93,98,131). The magnitude of coefficient of friction, particularly at relatively higher pressure (650N/m^2), is comparable with those recently reported for woven fabrics by Carr et al(7), and for knitted fabrics by Yoon et al(136). This result would be expected according to Wilson(131), because of the visco-elastic properties of these materials, whereby the apparent area of contact increased with load but less rapidly than the load. This would imply that the value of the friction index (n) in the relation $F=KN^n$ lies between 0-1(7,48-53,131).

Reference to Table 3.1 shows that the frictional resistance (kinetic) consistently increased as the normal pressure increased. In order to test Wilson's hypothesis i.e. the relation between the frictional index n, and asperity contacts, and to demonstrate the validity of the relation $F=KN^n$, a plot of the frictional resistance per unit area against the normal pressure was carried out. A typical result is shown in Figure 3.1. This indicates an excellent linear correlation ($r^2=0.97-1$). By means of a regression analysis, as detailed in Chapter 2, the values of the friction constant (K) and index (n) were

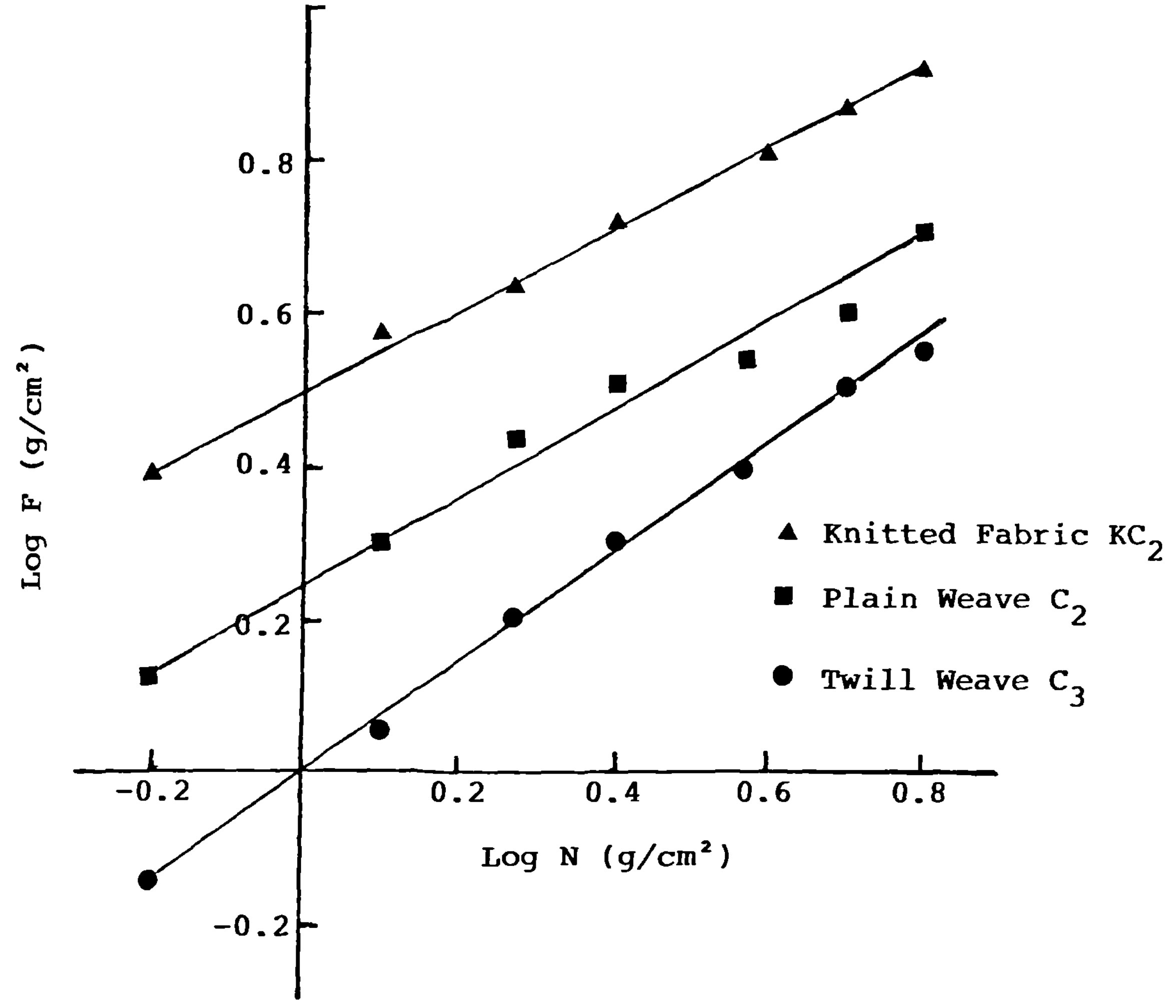


Fig 3.1

Effect of normal pressure (N) on the kinetic frictional resistance per unit area (F) of cotton fabrics (weft along weft motion)

Table 3.1

Effect of normal pressure on the frictional parameters of fabrics

(velocity = 5cm/min, number of traverse = 1, time = 3 min, surface = fabric/fabric)

Fabric Code*		μ_K**			F_K			F_N			F_A			F_S-F_K		
		1^+	2	3	1^+	2	3	1^+	2	3	1^+	2	3	1	2	3
C_2	P	2.28	1.24	0.82	57	124	205	30	33	8	2	4	5	6	8	30
	T	2.08	1.30	0.80	52	130	200	39	23	0	2	2	5	4	20	40
C_3	P	1.28	0.80	0.56	32	80	140	39	37	31	3	6	12	14	18	16
	T	1.36	0.80	0.56	34	80	140	32	39	19	4	6	8	15	10	36
W_1	P	1.72	1.40	0.77	43	140	186	18	18	2	2	3	4	9	16	22
	T	1.68	1.10	0.98	42	110	244	12	11	3	2	4	4	3	8	44
W_2	P	2.28	1.68	1.25	57	168	312	16	7	5	3	6	8	9	20	40
	T	2.20	1.60	1.20	55	160	300	12	6	5	2	4	8	8	16	52
W_6	P	1.84	1.20	1.12	46	120	280	6	2	0	2	2	4	10	26	48
	T	1.80	1.30	0.69	45	130	172	9	0	0	1	2	4	4	6	40
KC_2	C	3.20	1.72	1.20	80	172	300	21	19	8	4	8	8	6	12	36
	W	3.40	2.12	1.33	85	212	332	23	14	6	3	8	8	10	12	12
KC_{71}	C	2.64	1.36	0.98	66	136	244	20	14	14	3	4	4	12	14	16
	W	2.64	1.26	0.70	66	126	176	24	22	21	3	4	4	14	14	20
KW_{120}	C	2.24	1,38	1.12	56	138	280	14	5	3	2	2	4	2	12	36
	W	2.20	1.34	1.01	55	134	252	14	15	6	3	4	4	4	16	36

*See fabric details in Table 2.2

$^+$Mean of 5 tests C.U. < 10%

**See lists of symbols

Column	Pressure (N/m²)
1	63
2	250
3	630

calculated. The results are given in Table 3.2, the values of n ranged between 0.50-0.87. This is comparable with those found by Wilson (0.57-1.06)(131), Ohsawa and Namiki (0.85-1.07)(93), and more recently by Carr et al (0.70-0.94)(7). The value of the constant K was dependent upon the unit of pressure(88), and was generally negatively correlated with the exponent(7,93,127-129,131). The latter relation has been attributed to structural interlocking(93), fibre cohesion(127-129) and the mode of deformation of the asperities (visco-elastic)(9,131).

Apart from the influence of the normal pressure on the coefficient of friction, and frictional resistance, other frictional parameters were equally affected. Reference to Table 3.1 will also show a decrease in number of peaks, but the amplitude of resistance and the value of $F_s - F_k$ both increased with an increase in normal pressure. In some cases such as fabric C_2 and W_6, the stick-slip motion disappeared altogether at relatively higher pressure (650N/m²). The reason for this may be ascribed to a smoothing of the fabric due to compression and structural flattening.

3.2.2 VELOCITY OF SLIDING

An increase in the velocity of sliding implies a decrease in the time of contact between the sliding members(5,6,44). Since textile materials in general and fabrics in particular are visco-elastic(8,44,80), their

Table 3.2

The frictional parameters of fabrics derived from the relation $F=KN^n$, where F=frictional resistance (g/cm^2), N=normal pressure (g/cm^2), K=friction constant (g/cm^2), n=friction index.

*Fabric Code		Static		Kinetic	
		**K	n	K	n
C_2	P	0.31	0.55	0.28	0.52
	T	0.26	0.61	0.25	0.55
C_3	P	0.16	0.52	0.06	0.58
	T	0.13	0.66	0.01	0.70
W_1	P	0.21	0.65	0.17	0.63
	T	0.19	0.87	0.15	0.86
W	P	0.35	0.76	0.30	0.75
	T	0.34	0.79	0.28	0.79
W_6	P	0.29	0.73	0.20	0.80
	T	0.26	0.59	0.20	0.57
KC_2	W	0.49	0.55	0.45	0.53
	C	0.55	0.51	0.50	0.53
KC_{71}	W	0.39	0.52	0.33	0.53
	C	0.43	0.50	0.36	0.52
KW_{120}	W	0.28	0.76	0.26	0.73
	C	0.31	0.68	0.26	0.67

*See fabric details in Tables 2.2 and 2.5

**Unit of K (g/cm^2)

P = warp along warp motion

T = weft along weft motion

W = wale along wale motion

C = course along course motion

frictional properties are expected to be time dependent(8,44).

As shown in Table 3.3, the number of peaks, amplitude of resistance, and F_s-F_k all diminished from their initial values as the velocity of sliding increased. However, there was no consistent change in the magnitude of the coefficient of friction. Nishimatsu and Sawaki(92) recently reported an initial decrease, followed by an increase in the coefficient of friction as the velocity was increased.

If it is assumed at the moment (and this is demonstrated in Sections 3.3.2 and 3.3.3) that the number of peaks, and amplitude of resistance are dependent on fabric structure, among other things, then a further investigation of the influence of velocity on these parameters would be useful. The knitted fabrics with distinctive ridges of ribs were used, these were slightly stretched and tested along the course direction. The objectives were to correlate the number of peaks with the number of ribs, and to observe the influence of velocity on the agreement.

As shown in Table 3.4, it is interesting to note that a 100 fold increase in velocity (i.e. 0.5-50cm/min) resulted in different degrees of changes in the number of peaks and amplitude, which were in turn dependent upon fabric structure. In the case of fabric KC_2 where the courses were fine, and closely spaced, the number of peaks diminished rapidly (-77%), and moderately (-39%)

Table 3.3

Effect of velocity of sliding on the frictional parameters* of fabrics

(normal pressure 0.63g/cm², number of traverse=1, time of loading 3 min, surface fabric/fabric)

Velocity cm/min / Fabric		μ_K			F_K			F_N			F_A			F_S-F_K		
		5	100	500	5	100	500	5	100	500	5	100	500	5	100	500
C_2	P	2.28	2.28	1.64	57	41	-	30	20	8	2	3	-	6	2	-
	T	2.08	1.80	2.00	52	45	50	39	22	10	2	2	1	4	5	12
C_3	P	1.28	1.52	1.20	32	38	30	39	19	10	3	3	2	14	4	6
	T	1.36	1.40	-	34	35	-	32	21	-	4	3	-	15	2	-
W_1	P	1.72	1.68	1.60	43	42	40	18	9	11	2	2	1	9	0	3
	T	1.68	1.80	1.88	42	45	47	12	9	5	2	2	1	3	2	3
W_2	P	2.28	2.28	2.20	57	57	55	16	8	4	3	2	1	9	3	3
	T	2.20	2.32	2.52	55	58	63	12	7	3	2	2	1	8	4	1
W_6	P	1.84	1.80	1.80	46	45	45	6	3	3	2	2	1	10	0	0
	T	1.80	1.84	2.08	45	46	52	9	10	3	1	2	2	4	9	4
KC_2	W	3.20	2.84	3.12	80	71	78	21	19	7	4	3	2	6	2	2
	C	3.40	3.32	3.68	85	83	92	23	12	7	3	3	3	10	0	1
KC_{71}	W	2.64	2.92	2.72	66	73	68	20	15	5	3	3	2	12	2	3
	C	2.64	2.84	2.64	66	71	66	24	15	6	3	2	1	14	2	6
KW_{120}	W	2.24	2.08	2.44	56	52	61	14	7	3	2	2	1	2	1	2
	C	2.20	2.08	2.20	55	52	55	14	15	15	3	2	4	4	7	0

*See Chapter 2

Table 3.4

Effect of sled velocity on the number of peaks and the amplitude of resistance of fabrics

(pressure = 63N/m^2, traverse = 1, surface, fabric/fabric)

Velocity (cm/min)	Number of Peaks/5cm			Amplitude(gf)		
	*KC$_2$	KC$_{71}$	KW$_{120}$	KC$_2$	KC$_{71}$	KW$_{120}$
	(50)	(26)	(13)			
0.5	48	26	13	4	3	4
1.0	45	26	13	4	2	4
2.0	37	28	13	4	2	4
5.0	38	26	13	4	2	4
10.0	32	25	13	4	2	3
20.0	19	22	13	2	2	3
50.0	11	16	13	1	2	2

*See fabric details in Table 2.5.

Values in parenthesis are the number of ribs (courses) across the direction of motion.

in the case of fabric KC_{71}, whereas the number of peaks remained constant irrespective of any increase in velocity in the case of fabric KW_{120} with largest size of courses (ribs). It may be concluded that the larger the size of the rib, the smaller the effect of velocity on the number of peaks. The amplitude remained fairly stable for the three fabrics until the velocity was of the order of 20cm/min when a reduction was obtained.

3.2.3 NUMBER OF TRAVERSES

As shown in Table 3.5, successive traverses of the sled over the fabric surface caused a decrease in the magnitude of the coefficient of friction, resistance to motion, number of peaks, amplitude of resistance and the value of F_s-F_k. These results may be attributed to surface polishing, i.e. compacting and aligning of the surface hairs in the direction of motion.

When both fabrics on the horizontal platform and sled were reversed end-to-end, i.e. turned through 180°, the ensuing intermeshing of hairs resulted in an increase in the resistance to motion.

3.2.4 NATURE OF SLED SURFACE

The coefficient of friction of some plain weave fabrics is shown in Table 3.6. Three sled surfaces (fabric/fabric, rubber/fabric and perspex/fabric) were

Table 3.5

Effect of number of traverse on the frictional properties of fabrics

(normal pressure=63N/m², velocity=5cm/min, time of loading=3min , surface=fabric/fabric)

Fabric Code*		μ_K			F_K			F_N		F_A			F_S-F_K		
		1	10	11**	1	10	11**	1	10	1	10	11**	1	10	11**
C_2	P	2.28	1.92	2.20	57	48	55	30	26	2	2	4	6	3	12
	T	2.08	2.00	2.24	52	50	56	39	20	2	1	1	4	2	6
C_3	P	1.28	0.88	1.40	32	22	35	39	18	3	1	5	14	4	9
	T	1.36	1.20	1.88	34	30	47	32	-	4	1	3	15	8	19
W_1	P	1.72	1.40	1.80	43	35	45	18	10	2	1	3	9	2	2
	T	1.68	1.68	1.88	42	42	47	12	11	2	1	1	3	2	19
W_2	P	2.28	2.16	2.60	57	54	65	16	6	3	1	4	9	1	2
	T	2.20	2.16	2.48	55	54	62	12	6	2	1	1	8	1	4
W_6	P	1.84	1.68	2.20	46	42	55	6	4	2	0	3	10	0	8
	T	1.80	1.68	2.20	42	41	55	9	6	1	1	1	4	2	8
KC_2	W	3.20	3.20	3.48	80	80	87	21	20	4	3	5	6	1	3
	C	3.40	2.36	2.60	85	89	65	23	22	3	2	3	10	1	3
KC_{71}	W	2.64	2.12	2.92	66	53	73	20	15	3	3	4	12	0	2
	C	2.64	2.28	2.80	66	57	70	24	12	3	2	2	14	8	9
KW_{120}	W	2.24	2.16	2.25	56	54	57	14	10	2	3	3	2	0	3
	C	2.20	2.12	2.12	55	53	53	14	14	3	1	1	4	2	2

*See fabric details in Table 2.2.
**Both the fabrics on the sled, and that on the horizontal platform reversed end-to-end

Table 3.6

Effects of sled surfaces on the coefficient of friction of fabrics

(Normal pressure=470N/m^2*, velocity=5cm/min,

number of traverse=1, time of loading=3 min, 20°C,65%R.H.)

Fabric Code		Coefficient of Friction					
		Static			Kinetic		
		Fabric	Rubber	Perspex	Fabric	Rubber	Perspex
C_2	P	0.74	0.88	0.19	0.57	0.83	0.17
	T	0.82	0.81	0.15	0.66	0.78	0.15
C_3	P	0.53	0.81	0.27	0.37	0.78	0.25
	T	0.59	0.76	0.21	0.44	0.72	0.16
W_1	P	0.81	0.83	0.25	0.68	0.80	0.25
	T	0.85	0.83	0.17	0.70	0.79	0.16
W_2	P	1.09	0.94	0.22	0.92	0.91	0.22
	T	1.14	0.94	0.23	0.96	0.93	0.23

*Recommended for plastics(3)

employed. The normal pressure (470N/m^2) recommended for plastic testing(3), and the one most frequently used by many investigators(12,20,33,60,93,94,120) was used in order to enable the comparisons of results to be made.

It would be seen that the coefficient of friction using perspex sled was significantly lower than those of fabric/fabric and rubber/fabric. The coefficient of friction using rubber sled are usually, but not always, higher than when fabric sled was used. This agreed with a recent finding by Yoon et al(136) for knitted cotton and polyester/cotton blended fabrics.

Generally fabric/fabric provided the most sensitive surface, and gave the best discrimination. One possible reason for this is that when similar fabrics were tested against themselves, the surface protuberances such as yarn crown, twill, ribs and cords, fitted together rather nicely. The perspex gave the best reproducibility but the discrimination was poor. For this reason it was decided that all subsequent tests would be made using the fabric/fabric technique.

From the foregoing, fabric friction is sensitive to small variations in experimental conditions. A glance at Tables 3.8 - 3.11 will show the magnitude of changes in the frictional parameters as experimental variables were systematically altered. As shown in Table 3.8, a tenfold increase in normal load at constant area of sled and other factors had produced a decrease of between -34 to -87% in coefficient of friction, and

Table 3.8

Changes in frictional properties as a result of tenfold increase in normal load (25-250g) with respect to the frictional properties at standard condition*

Fabric Code		Changes in Frictional Properties (%)					
		μ_S	μ_K	F_S	F_K	F_N	F_A
C_2	P	-60	-60	+260	+250	-73	+70
	T	-53	-60	+360	+300	-100	+150
C_3	P	-70	-60	+210	+270	-18	+300
	T	-60	-50	+300	+370	-41	+100
W_1	P	-59	-87	+320	+320	-90	+100
	T	-55	-42	+540	+480	-77	+100
W_2	P	-40	-40	+510	+540	-63	+100
	T	-40	-42	+480	+480	-50	+300
W_6	P	-36	-34	+440	+450	-100	+300
	T	-55	-58	+270	+250	-100	+100
KC_2	W	-66	-67	+240	+230	-67	+30
	C	-68	-66	+220	240	-77	+50
KC_{71}	W	-69	-47	+210	+240	-21	+33
	C	-79	-76	+110	+130	-19	+33
KC_{120}	W	-46	-50	+450	+400	-54	+300
	C	-52	-55	+380	+350	-77	+200

* Standard condition (load = 25g, area = $40cm^2$, velocity = 5cm/min, time of loading = 3 min, number of traverse = 1, temp = 20°C, r.h. = 65%)

- decrease in property

+ increase in property

Table 3.9

Changes in frictional properties as a result of tenfold increase in area of sled (4-40cm^2) with respect to the frictional properties at standard condition

Fabric Code		Changes in Frictional Properties (%)					
		μ_S	μ_K	F_S	F_K	F_N	F_A
C_2	P	+100	+120	+100	+120	0	+300
	T	+100	+140	+110	+104	-7	+300
C_3	P	+75	+86	+75	+86	-3	+100
	T	+110	+110	+110	+110	-9	+150
W_1	P	+66	+64	+66	+64	-5	-
	T	+109	+100	+109	+100	+17	+100
W_2	P	+97	+90	+97	+90	-25	+150
	T	+100	+100	+100	+110	-	-
W_6	P	+74	+68	+77	+68	-	+100
	T	+120	+114	+120	+114	+40	+100
KC_2	W	+207	+200	+207	+200	+31	+300
	C	+135	+138	+135	+138	+16	+300
KC_{71}	W	+110	+167	+110	+167	+11	+200
	C	+95	+133	+95	+133	+7	+200
KC_{120}	W	+73	+76	+73	+76	0	+100
	C	+88	+107	+88	+107	-7	-25

Table 3.10

Changes in frictional properties as a result of tenfold increase in velocity (5-50cm/min) with respect to the frictional properties at standard condition

Fabric Code		Changes in Frictional Properties (%)					
		μ_S	μ_K	F_S	F_K	F_N	F_A
C_2	P	+24	+32	+24	+32	-73	-66
	T	0	+4	0	+4	-64	-100
C_3	P	-23	-14	-23	-17	-72	-100
	T	-	-	-	-	-	-
W_1	P	-14	-5	-14	-5	-39	-100
	T	+6	+12	6	12	-58	-100
W_2	P	-12	-2	-12	-2	-79	-100
	T	+8	+21	+8	+15	-79	-100
W_6	P	-6	+5	6	5	-67	-100
	T	-7	+4	-7	+4	-79	0
KC_2	W	+8	+15	+8	+15	-75	-33
	C	+8	+11	+8	+11	-70	0
KC_{71}	W	-10	-3	-10	-3	-75	-33
	C	-12	-3	-12	-3	-70	-100
KW_{120}	W	-7	7	-7	7	-75	-100
	C	-11	0	-11	0	0	+33

Table 3.11

Changes in frictional properties as a result of ten traverses with respect to the frictional properties at standard condition

Fabric Code		Changes in Frictional Properties (%)					
		μ_S	μ_K	F_S	F_K	F_N	F_A
C_2	P	-20	-16	-20	-16	-13	0
	T	-10	-11	-10	-11	-26	-100
C_3	P	-26	-24	-26	-24	-46	-100
	T	-27	-14	-27	-14	-10	-100
W_1	P	-18	-13	-18	-13	-44	-100
	T	-10	-5	-10	-5	-9	-100
W_2	P	-19	-14	-19	-14	-50	-67
	T	-11	-7	-11	-7	-50	-100
W_6	P	-7	-2	-7	-2	-56	-100
	T	-10	-5	-10	-5	-33	0
KC_2	W	-7	0	-7	0	0	0
	C	-8	-2	-8	-2	+9	0
KC_{71}	W	-34	-21	-34	-21	-25	-25
	C	-13	-10	-13	-10	-37	0
KC_{120}	W	-9	-5	-9	-5	-33	0
	C	-9	-5	-9	-5	+8	-100

-21 to -100% in the number of peaks, and an increase of +110 to +540% in resistance, and +33 to +300% in the amplitude of resistance.

Referring to Table 3.9, a similar tenfold increase in the area of sled at constant normal load (mass assisted load) gave an increase of about +66 to +207% in coefficient of friction, and a similar value for frictional resistance. The increase in amplitude was between +100 to +300%. The changes in number of peaks were not very consistent in all fabrics. But they decreased by about -9% or less for woven fabric and increase by +40% or more for knitted fabrics.

As stated earlier, there were no consistent changes in coefficient of friction and resistance to motion (Table 3.9). Perhaps these inconsistencies were due to a see-saw effect, where one property, for example hairiness, tends to increase the resistance to sliding, and the decrease in the time of contact, and the visco-elastic nature of fabric deformation tends to decrease frictional resistance(5,6,8,44,80). In spite of these complications, a consistent decrease in the number of peaks (-79% or less) and amplitude (-100% or less) was obtained.

Reference to Table 3.11 will show that the magnitude of all frictional parameters under scrutiny diminished as a result of ten successive traverses. In spite of the lower pressure (63N/m^2) employed in this investigation, a decrease of up to -100% in amplitude of resistance was obtained. Generally, the amplitude of resistance, number of peaks and frictional resistance are the most sensitive to experimental variations. It is therefore likely that these parameters are better indicators of frictional properties than the coefficient of friction.

3.3 FRICTIONAL PARAMETERS

3.3.1 COEFFICIENT OF FRICTION

An examination of the data in Table 3.12 will show that the thin knitted cotton fabric KC_2 possessed a higher coefficient of friction, and offered a greater resistance to motion than the thin woven cotton fabric C_2 although tactually no obvious difference in smoothness was noted when these fabrics were stroked. A similar comparison between a relatively thicker knitted cotton fabric KC_{71}, and a twill cotton fabric C_3 indicated that in this instance the former offered a greater resistance to motion and felt rougher and more "ridgy" than the latter.

A comparison of fabrics C_2, W_2 and KW_{120} provided some interesting results. Quantitatively, the frictional resistance and the coefficient of friction of these fabrics were similar. Qualitatively, a tactual and/or visual examination would reveal some differences in fibre content (cotton and wool), fabric construction (woven and knitted), fabric structure (plain weave and rib knit), yarn sett (high and low) as well as in the density of surface hairiness. Compressionally, the thicker, hairier samples felt softer than the thinner cotton fabrics(15).

The agreement (positive correlation)(12,33,91,120,122) or disagreement (negative correlation)(35,60,87) between coefficient of friction and fabric smoothness is well documented. Dreby(12) stated that for fabrics with approximately similar physical properties, the one with a lower coefficient of friction would be the smoother fabric. Thorndike and Varley(91) also noted that fabrics

Table 3.12

Frictional parameters of fabrics (Case 1)

(Normal pressure = 0.63g/cm², velocity = 5cm/min, traverse = 1, 20°C 65% R.H.)

Fabric Code*		Frictional Parameters**						
		μ_S	μ_K	F_S	F_K	F_N	F_A	F_S-F_K
C_2	P	2.52	2.28	63	57	30	2	6
	T	2.24	2.08	56	52	39	2	4
C_3	P	1.84	1.28	46	32	39	3	14
	T	1.96	1.36	49	34	32	4	15
W_1	P	2.08	1.72	52	43	18	2	9
	T	1.80	1.68	45	42	12	2	3
W_2	P	2.64	2.28	66	57	16	3	9
	T	2.52	2.20	63	55	12	2	8
W_6	P	2.24	1.84	56	46	6	2	10
	T	1.96	1.80	49	45	9	1	4
KC_2	W	3.44	3.20	86	80	21	4	6
	C	3.80	3.40	95	85	23	3	10
KC_{71}	W	3.12	2.64	78	66	20	3	12
	C	3.20	2.64	80	66	24	3	14
KW_{120}	W	2.32	2.24	58	56	14	2	2
	C	2.36	2.20	59	55	14	3	4

* See fabric details in Table 2.2 and 2.5

P = warp over warp motion

T = weft over weft motion

** See frictional parameters on page xv

W = wale over wale motion

C = course over course motion

with lower coefficients of friction were ranked smoothest by a panel of judges. However, Hoffman and Beste(35) and Morrow(87) and several other workers(60,84) who found a negative correlation between the coefficient of friction and smoothness expressed doubts if this quantity can describe adequately the tactile sensations of smoothness.

It must therefore be concluded at this stage that the coefficient of friction on its own may not be the sole or best indicator of fabric smoothness or roughness.

3.3.2 NUMBER OF PEAKS IN THE STICK-SLIP TRACES

The number of peaks per 5cm sled traverse (fabric/fabric) is shown in Table 3.12. Considering the knitted fabrics, the number of peaks for motion of cord across cord was plotted against the number of courses. A good linear relation was obtained as shown in Figure 3.2. For the woven fabrics in the group, i.e. C_2, C_3, W_1 and W_2, it was assumed that the motion of sled (or finger) along the warp (weft) direction implied that the main barrier to motion was offered by the "ridges" of weft (warp) yarns. (This assumption is further proved to be valid in Chapter 6.) Therefore the number of peaks when traversing along the warp (weft) was plotted against the weft (warp) thread sett as shown in Figure 3.2. This also shows a linear relation with some degrees of scatter, perhaps because of some other factors, for example, hairiness.

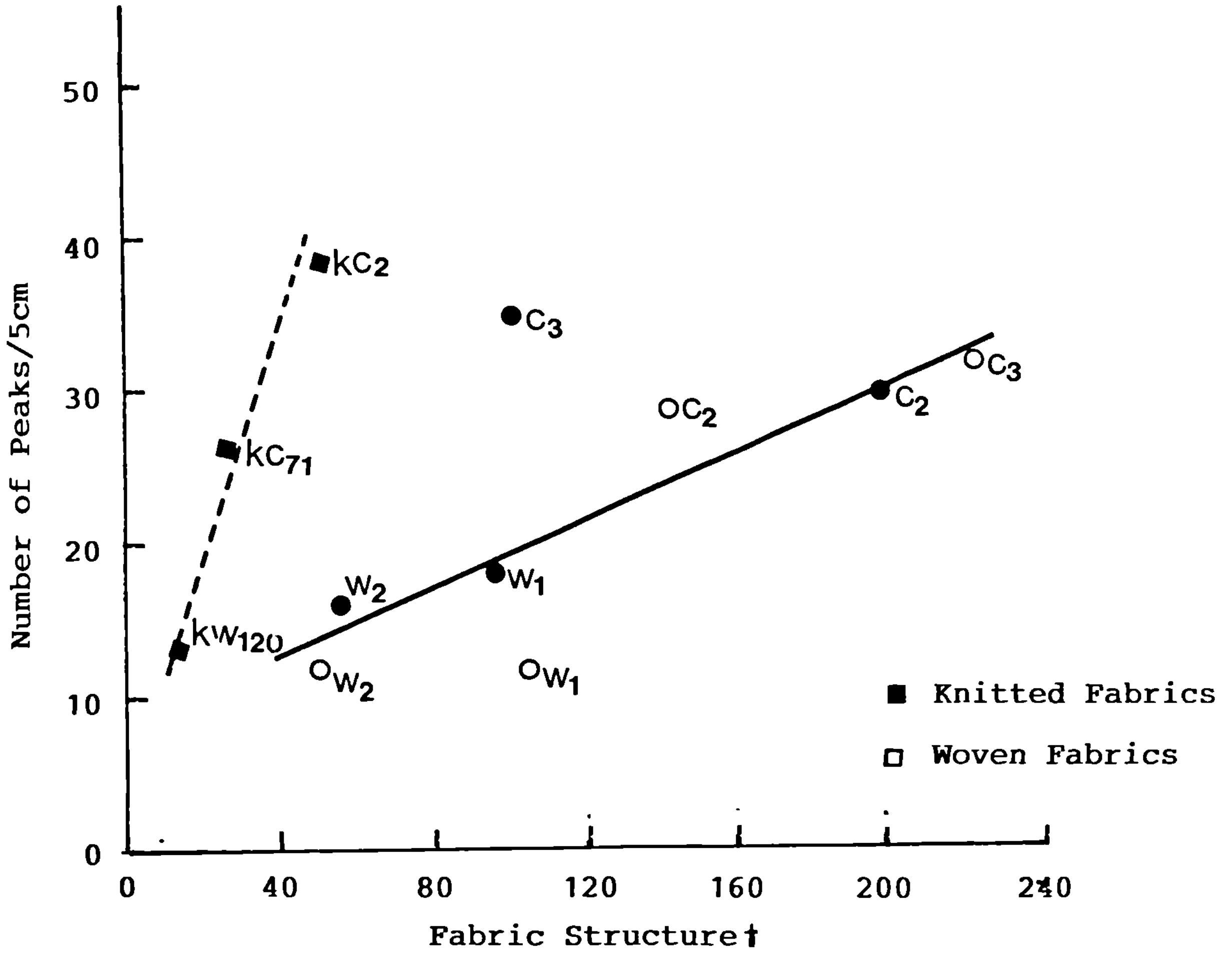


Fig 3.2

Relation between number of peaks in stick-slip motion and fabric structure †(Threads/5cm in woven fabrics*, courses/5cm in knitted fabrics).

*Filled signs = warp on warp motion

Empty signs = weft on weft motion

A comparison between the results for knitted and woven fabrics (Figure 3.2) will show a better agreement between the number of peaks and fabric structure in the case of the knitted fabrics. This might be expected if the distinctive ridges of courses intermesh during sliding. The process of shearing these interlocking structures resulted in clear peaks. In woven fabrics where yarn sett is high, interlocking is not as pronounced. The presence of surface hairs, particularly in fabric W_2 may also conceal the yarn profile. These factors resulted in the relatively poor agreement between the number of peaks and yarn sett.

Tactually, the fingers could discriminate between and within the knitted and woven structures, but the discrimination is poorer within woven fabrics.

3.3.3 AMPLITUDE OF RESISTANCE

It may be postulated that the amplitude of the stick-slip motion should increase if the relative height of yarn crowns or the amount of surface fuzz increase(19, 121). In this case, it was found that the twill fabric (C_3) and the knitted fabrics (KC_2, KC_{71}, KW_{120}) with obstrusive yarn profiles (twill or rib) yielded relatively high amplitudes. Similarly, the wool fabric W_2 with surface hairs also gave a higher amplitude than fabrics W_1 and C_2 with plane surfaces. When the fabrics were stroked, differences in ridginess of the knitted, and hairiness of the wool fabric W_2 were detectable.

3.3.4 DIFFERENCES BETWEEN THE STATIC AND KINETIC FRICTIONAL FORCES (F_S-F_K)

It has been pointed out from the perusal of literature in Chapter 1 that the difference between the static and kinetic frictional forces, i.e. F_S-F_K affect the handle of materials(5,6,10,25,34,78,88,95,107-109).

Despite the number of references, there are few experimental studies concerned with the verification of this hypothesis. Consequently it was considered firstly here and again in subsequent chapters.

According to Röder(107-109), a large difference between the values of static and kinetic frictional forces is more likely to give a soft and smooth handle. Quantitatively, this may imply a relatively higher initial fricative resistance to motion (F_S), followed by smooth sliding, i.e. lower kinetic fricative resistance to motion (F_K). A higher value of the former (F_S) may arise from two factors, namely:

1. higher tendency of mechanical interlocking of surface structure such as cords (see Chapter 4),
2. higher fabric compression (bedding or bow-wave effect).

Referring to Table 3.12, the data of F_S-F_K (i.e. mean of warp and weft) was plotted against fabric com-

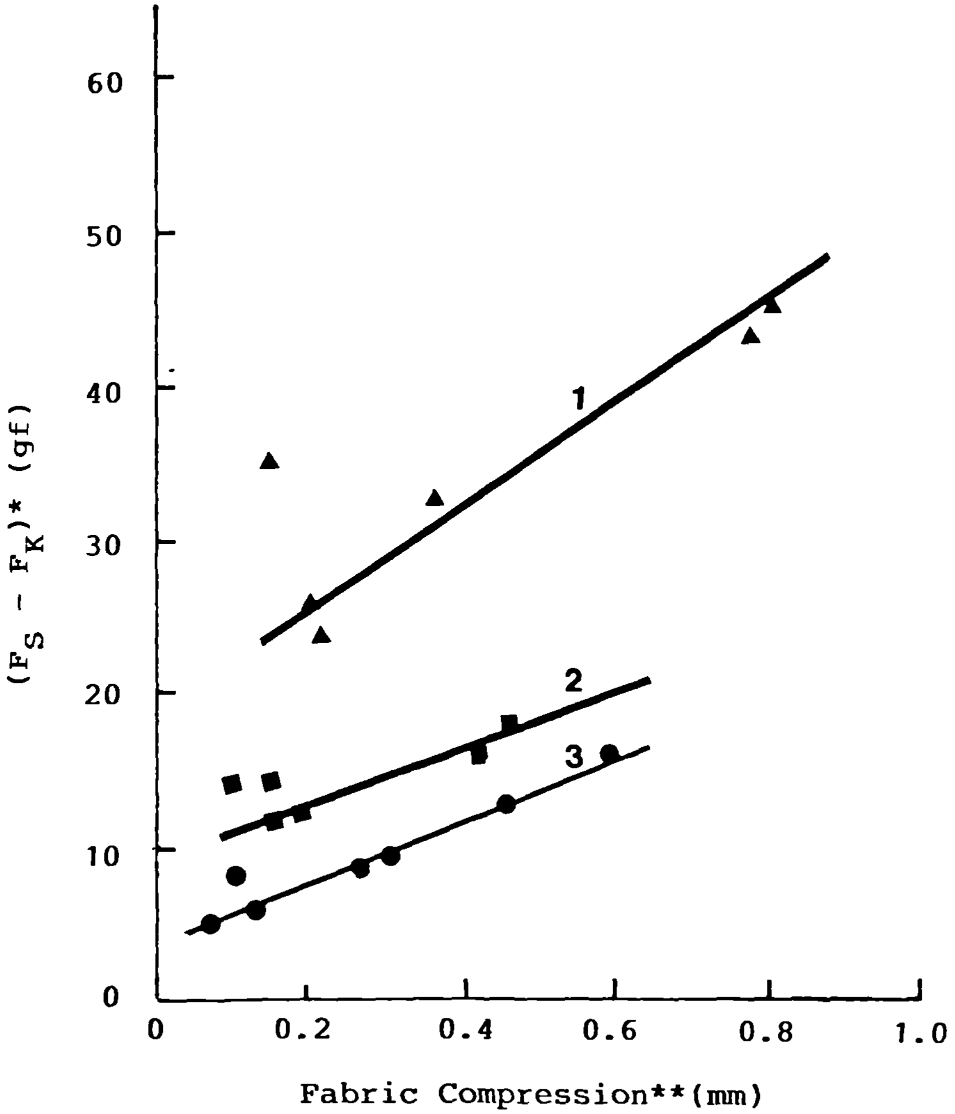


Fig 3.3

Relation between $(F_S - F_K)^*$ and Fabric Compression**

Pressure	$F_S - F_K^*$	Compression**
1	63Pa	2KPa
2	250Pa	4KPa
3	650Pa	20KPa

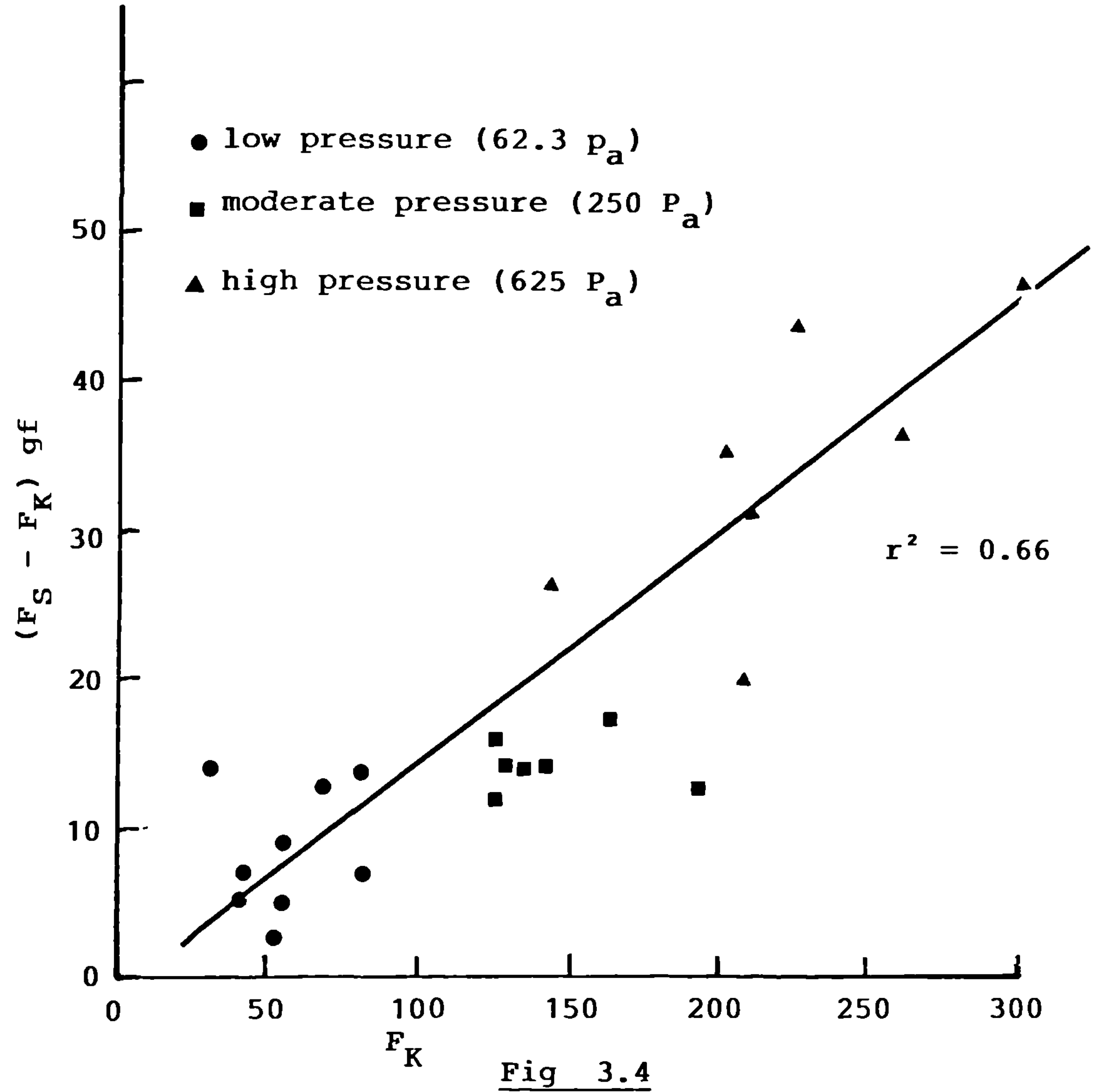


Fig 3.4

Relation between F_S-F_K and F_K under a low (62.5P_a), moderate (250P_a) and high pressure pression, under similar pressures (2, 4, 20KPa) reported by Elder et al(15)*. As shown in Figure 3.3, a fairly good linear relation was obtained. This implied that fabrics with higher compression also gave relatively higher values of F_S-F_K. A plot of the values of F_S-F_K against the values of F_K is shown in Figure 3.4. This gave a wide scatter with a correlation coefficient of only 0.66. This might indicate that a higher value of F_S-F_K is also associated with a higher value of F_K, and this is in turn dependent upon the normal pressure.

It may be inferred from these results that fabrics with higher magnitudes of F_S-F_K and lower value of F_K may be described as soft and smooth fabrics. This inference also agrees with Röder's(107-109) and Hearle and Hussain's(34) conclusions, namely, that larger (smaller) differences between the values of F_S-F_K yielded soft and smooth (harsh) handle.

3.4 CONCLUSIONS

1. Fabric friction is affected by a large number of factors. Care is necessary in the choice of conditions of test. A relatively low pressure, i.e. 63N/m², velocity 5cm/min, and only one traversal gave a reasonably good reproducibility, i.e. coefficient of variation was less than 10%. The discrimination between samples was better when similar fabrics were tested against themselves.

2. Objectively, fabrics may offer a similar (different)

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*Footnote: Pressures were comparable to those applied on fabrics during subjective assessments of softness(15).

fricative resistance to motion, and possess a similar (different) coefficient of friction, subjectively these fabrics may be tactually different (similar). This may imply that these quantities may not be the sole indicator of fabric smoothness or roughness.

3. A critical examination of the stick-slip motion shows that the number of peaks, the amplitude and the value of F_S-F_K are well correlated with some pertinent fabric properties such as yarn sett, structural protuberances and fabric compressibility respectively.

4. Where other frictional properties (F_N, F_A, F_S-F_K) are approximately the same, the fabric with the lower coefficient of friction is usually the smoother fabric.

CHAPTER 4

FABRIC STRUCTURE

ABSTRACT

Taking a case of a plain weave fabric, Case 2, where the weft yarn sett is systematically increased, a systematic increase in the fricative resistance to motion is demonstrated. This is greater for weft-over-weft motion than for warp-over-warp. The greater warp crimp producing a "knuckle effect" could be the explanation, although the diminishing spaces between the weft threads could also be a factor.

In another case (Case 3) involving a series of pile type woven fabrics, an increase in the height of fibre tufts produces an increase in the resistance to motion and also the amplitude of the stick-slip motion. A good linear relation exists between the number of peaks and the number of cords. The size of cords, and the degree of spacing between them may have enhanced structural interlocking and intermeshing of fibre pile.

The frictional properties of some knitted fabrics are also shown to be related to those of their component yarns (Case 4). Yarns with higher coefficient of friction give fabrics whose coefficients of friction are also higher. Frictional properties are again influenced by structure for example loop size, and surface hairiness.

4.1 INTRODUCTION

Structurally, the protrusion of yarn crowns, and fibre tufts from the plane of fabric surface are two factors that influence fabric smoothness(119) and frictional properties(93,94,122,131,137).

In a recent investigation(124-126), changes in fabric quality have been predicted from a systematic variation in woven fabric structure. One of the cases considered was a systematic increase in yarn sett, with yarn count constant. This variation in fabric construction would be expected to alter the yarn crimp (surface boundaries) and consequently alter fabric smoothness, and presumably the frictional properties. Since this hypothesis was not tested at the time, it is considered in this work as Case 2. Some details of these fabrics may be found in Table 2.3.

Another case (Case 3) was examined in which the height, width and spacing of the fibre pile were increased, and changes in frictional properties were observed (see fabric details in Table 2.4).

In the fourth case (Case 4) the frictional properties of wool, cotton and acrylic yarns and fabrics were measured, the purpose being to compare the influence of fibre content and also yarn and fabric friction. Some details of yarns are given in Table 2.1, and details of fabrics may be found in Table 2.5.

In this study (Case 4), the frictional properties of yarns unravelled from the knitted fabrics were compared with those of their original yarns, i.e. before knitting, no significant changes were found despite the inherent tendency to kinkiness of the residual loops. This had presumably been successfully reduced as a result of tension application. A plain and rib knitted structures were employed in this study. The natural propensity, particularly of the plain knit, to skew was overcome by wet relaxation as described in Section 2.4.1.

The hypothesis in case 4 was that yarns with higher (lower) coefficient of friction would yield fabrics whose coefficients of friction are also higher (lower), fabric structure and finish being held constant.

With these case studies, it is hoped to demonstrate quantitatively at least the effects of fibre content, yarn and fabric structure on the frictional properties of fabrics.

4.2 CASE 2: PLAIN WEAVE FABRICS

4.2.1 FRICTIONAL PROPERTIES

The frictional properties of the plain weave fabrics (case 2) are shown in Table 4.1. It will be seen that an increase in the density of weft yarn sett has given a systematic increase in the frictional resistance. This is greater for weft-over-weft motion than for warp-over-warp. An increase in yarn crimp producing a knuckle

Table 4.1

The influence of increasing weft yarn sett on the frictional properties of plain weave cotton fabrics

Fabric* Code	Frictional Parameters**				
	F_S	F_K	F_N	F_A	F_S-F_K
C_6 P	54	49	23	2	5
T	60	51	20	4	9
C_7 P	60	53	22	2	7
T	66	56	29	2	10
C_8 P	67	58	26	2	9
T	70	62	27	2	8
C_9 P	66	56	30	2	10
T	75	67	30	2	8
C_{10}P	69	60	33	2	9
T	78	70	33	2	8

* See fabric details in Table 2.3

** F_S = Static frictional resistance (gf)

F_K = Kinetic frictional resistance (gf)

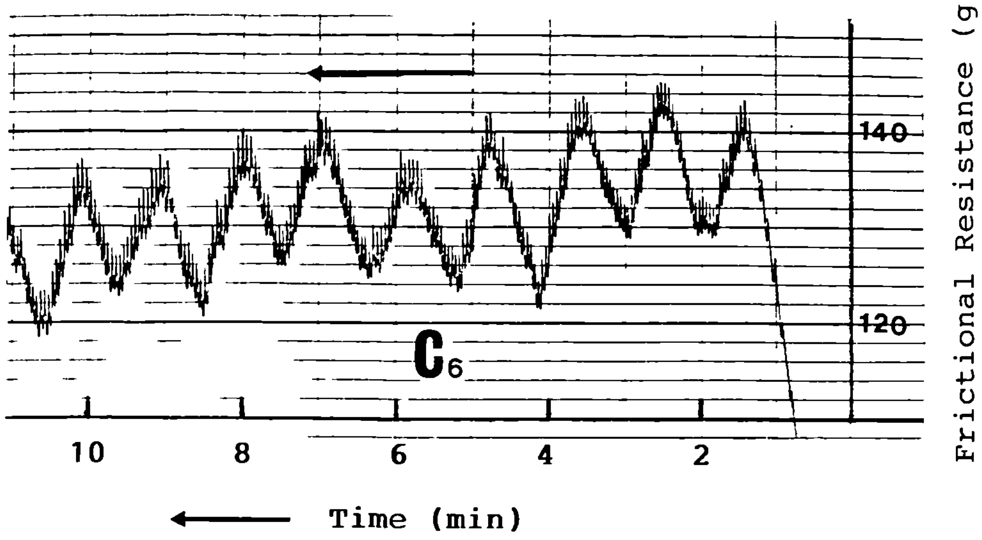
F_N = Number of peaks/5cm sled traverse

F_A = Amplitude of stick-slip (gf)

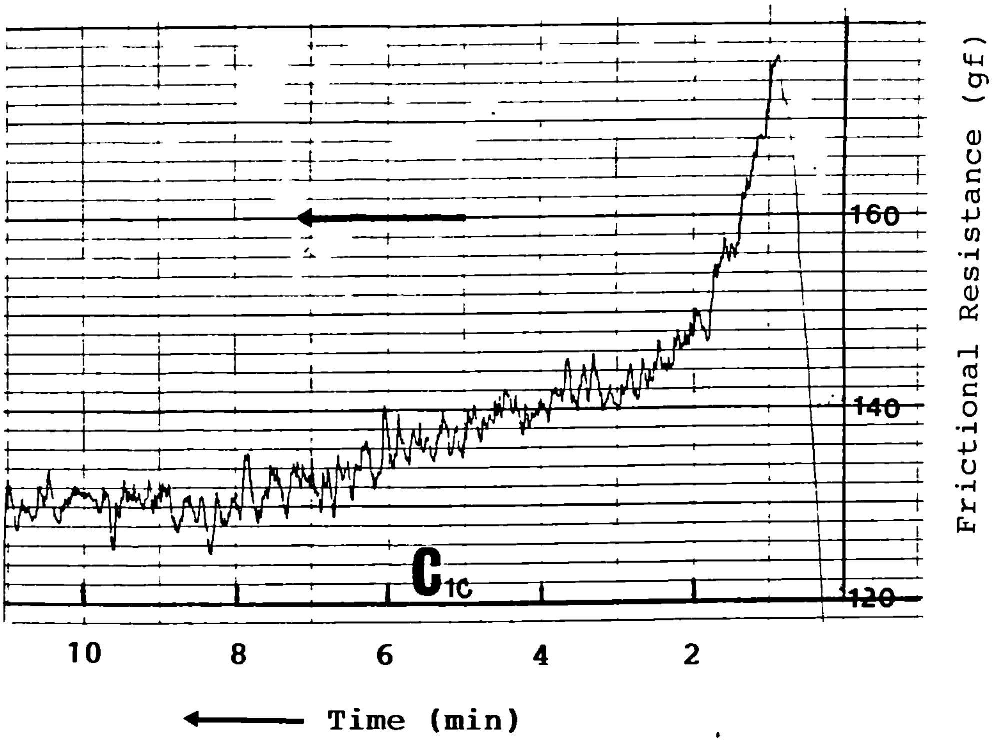
F_S-F_K = Difference between the static and kinetic frictional forces (gf) effect could be an explanation for this, although the dimishing spaces between the weft yarns could also be a factor.

Zurek et al(137) have recently reported similar results for some filament fibre-fabrics. A greater fricative resistance to motion was also found in the direction perpendicular to the axes of yarns with greater crimp. For example, a greater crimp in the warp yarns gave a greater (lower) resistance along the weft (warp) direction. These authors(137) explained that the knuckles of the rubbing and rubbed fabrics engaged, and relative motion was therefore restrained. Consequently, the resistance to motion along the weft direction was greater. From this model, some lateral mobility of the yarns may be envisaged, particularly if the spacing between yarns is reasonably wide, and if the contact between the mating fabrics is reasonably positive. For this purpose, a normal pressure of $375N/m^2$, and sled speed of 2cm/min was employed. Typical friction traces of fabric C_6 (wider yarn spacing) and fabric C_{10} (narrower yarn spacing) are shown in Figures 4.1 (a) and (b) for warp-over-warp motion and weft-over-weft motion respectively.

A distinctive plateau of peaks in fabric C_6 particularly in the warp direction, is an evidence of lateral shifting of the weft yarns. A similar but less pronounced effect was also obtained in the weft direction. An examination of the traces produced by fabric C_{10} will



Fabric C_6



Fabric C_{10}

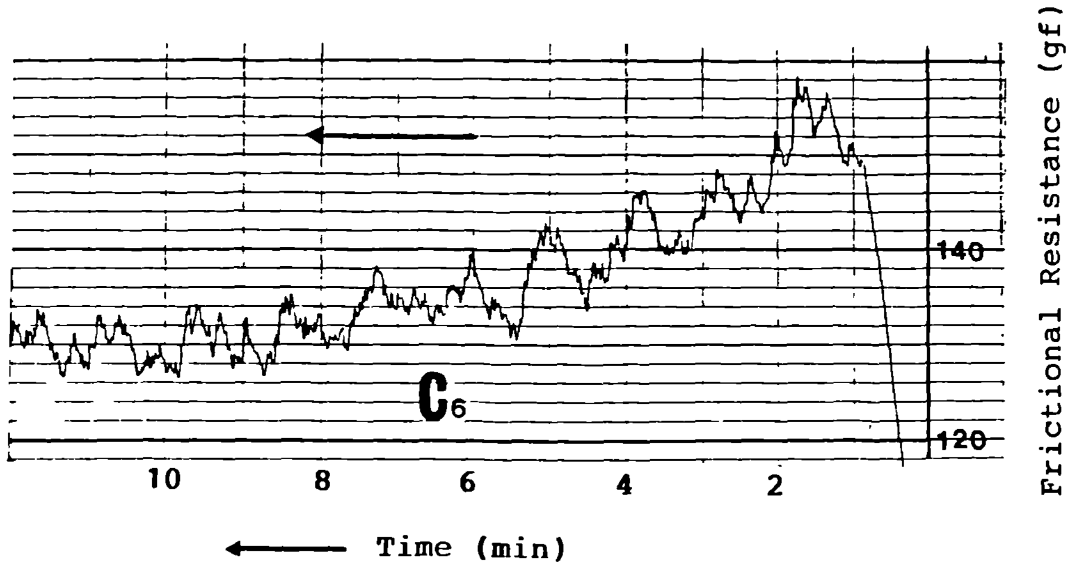
Fig 4.1(a)

Typical friction traces of woven cotton fabrics C_6 and C_{10} showing the effect of lateral mobility of weft yarns in a system of warp over warp motion.

(Arrow indicates direction of traverse.)

(Normal pressure = 375N/m², velocity of sled = 2cm/min.)

Fabric C_6



Fabric C_{10}

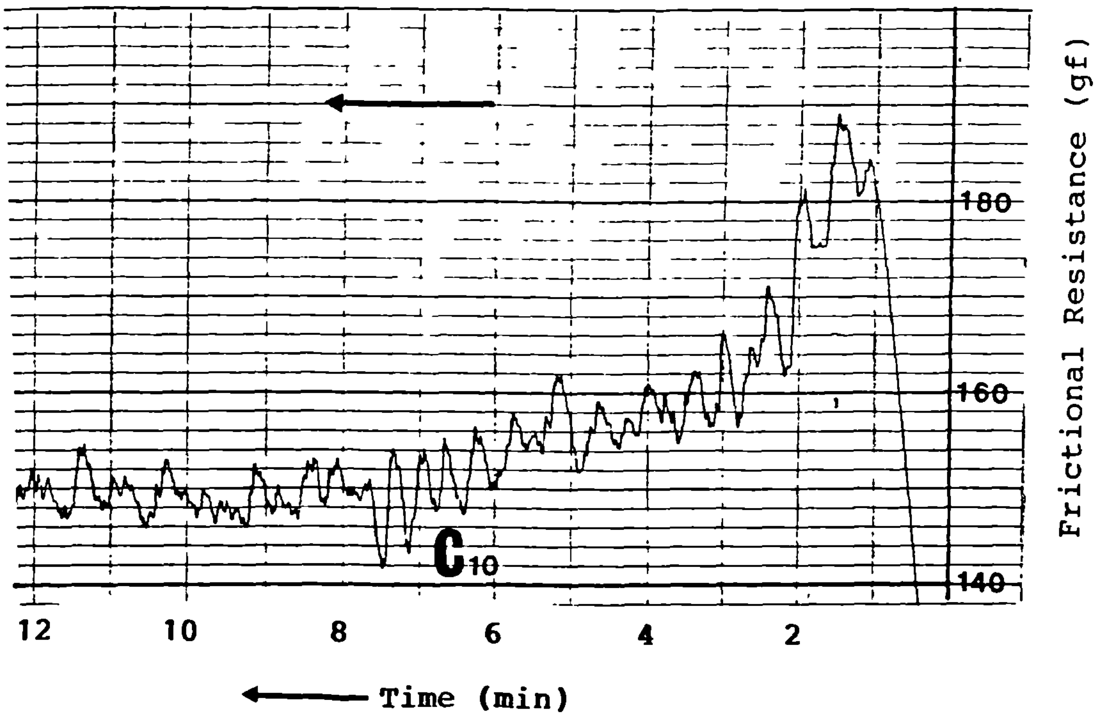


Fig 4.1 (b)

Typical friction traces of woven cotton fabrics C_6 and C_{10} show the effects of lateral mobility of warp yarns in a system of weft over weft motion. (Arrow indicates direction of sled traverse.) Normal pressure 375 N/m^2, velocity of sled 2 cm/min show that the effect of yarn mobility was minimal. This may be because of the narrow spacing between yarns.

It will appear from the foregoing that the fricative resistance to motion in a woven fabric is perhaps more complex than Zurek et al(137) had supposed. It was therefore thought that a further geometrical and theoretical considerations would be useful.

4.2·2 GEOMETRICAL CONSIDERATIONS

The frictional properties of woven fabrics may be interpreted in relation to surface smoothness and texture from the geometric consideration of their component yarns(93,94,137).

According to the adhesion theory(5,6), the overall frictional resistance between two bodies (fabric/fabric) is composed of two terms, namely:

1. the adhesion term (which is related to the true area of contact)(5,6,66),
2. the ploughing term (which is related to the relative height of surface asperities)(5,66,121).

In a plain weave fabric the ratio of the surface area of the warp and weft yarns is expressible by the fabric balance, i.e. the ratio of cover factors of warp and weft(32,94). When yarn crimp (i.e. surface boundaries) are taken into consideration, the relation between fabric balance and cover factor is given by(94):

$$B\lambda = \frac{P_P(1 + C_T)\sqrt{T'_T}}{P_T(1 + C_P)\sqrt{T'_P}} \qquad 4.1$$

The height of protruded yarn crowns from an arbitrary plane of fabric can also be estimated(137), using Peirce relation(102,103). This is also given by:

$$H_C = \tfrac{1}{2}\{(h_P - h_T) - (h_P + h_T)((\delta - 1)/(\delta + 1))\} \qquad 4.2$$

where $\delta = \sqrt{T'_P/T'_T}$

where $B\lambda$ = fabric balance

P = yarn spacing i.e. 1/threads/cm

C = yarn crimp

h = crimp amplitude

T' = yarn linear density (Tex)

Subscripts P and T refer to warp and weft respectively. The derivation of these relations (equation 4.1 and 4.2) are given in Appendix 1.

Considering a case of woven fabrics, where the weft sett was systematically increased, the geometrical configuration of yarn, i.e. crimp, spacing, crown height, area of contact (fabric balance) will all change.

4.2.2.1 YARN CRIMP

As shown in Figure 4.2, and Plates 4 and 5, both warp and weft yarn crimp increase with an increase in the density of weft yarn sett. This increase in crimp

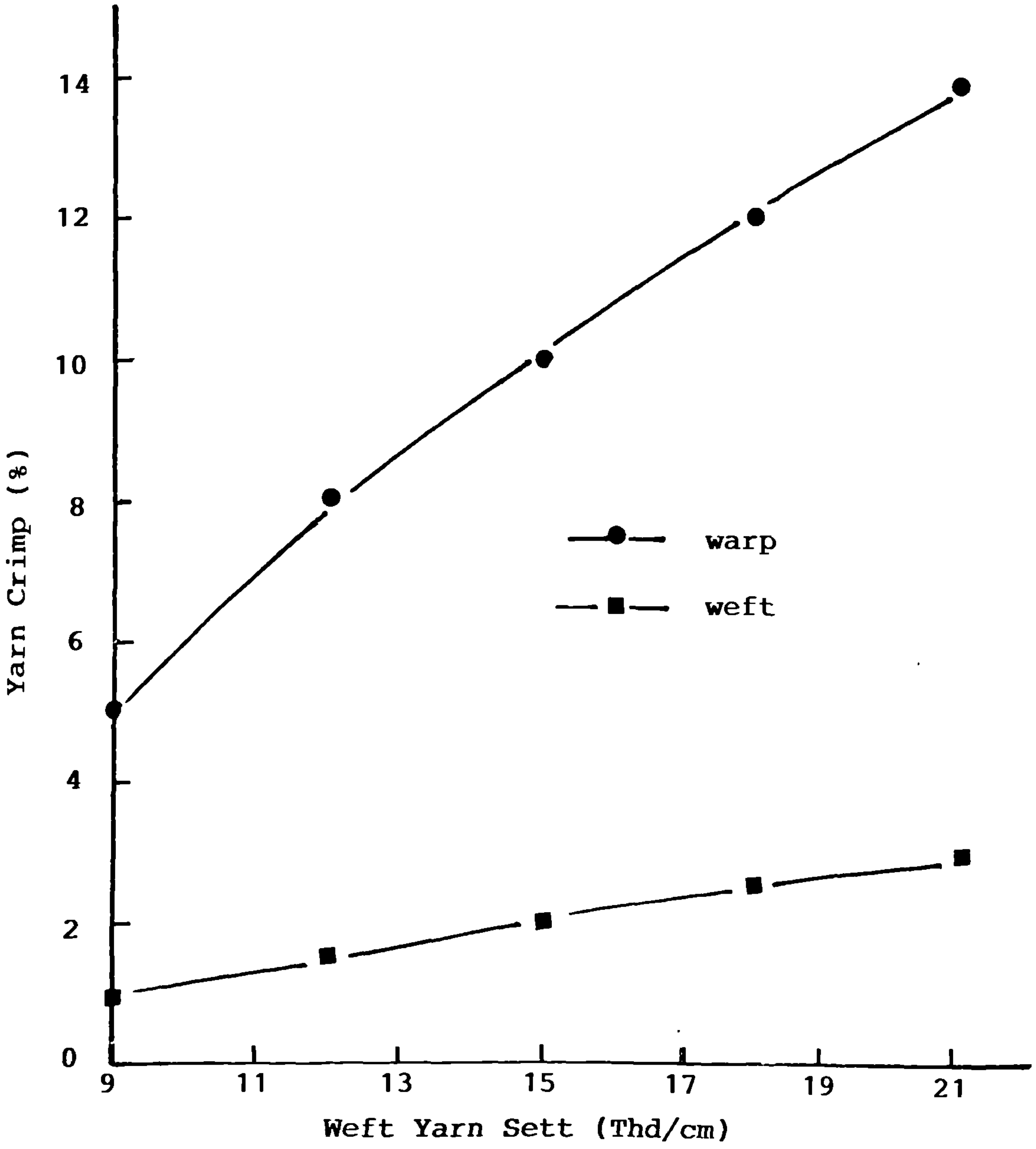
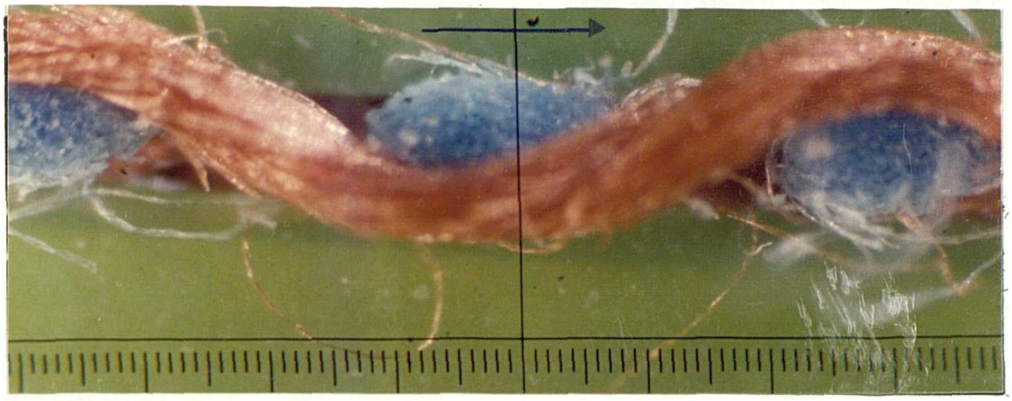


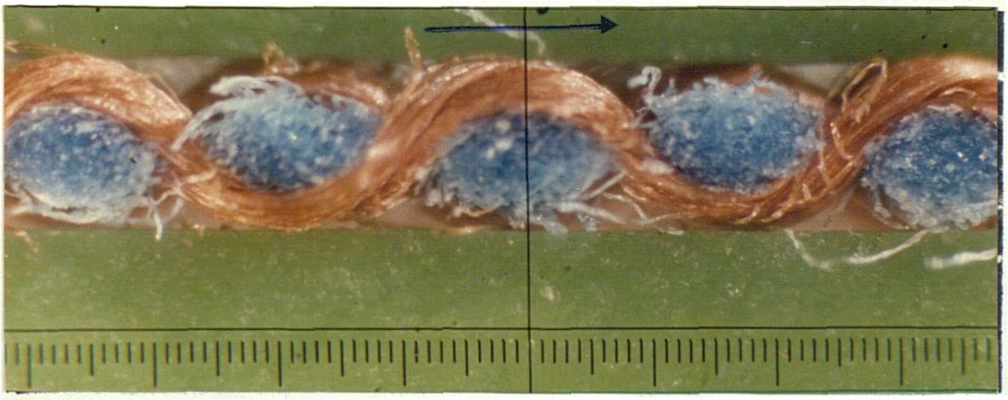
Fig 4.2

The influence of increasing weft yarn sett on the yarn crimp



Fabric C_6

Fabric C_8

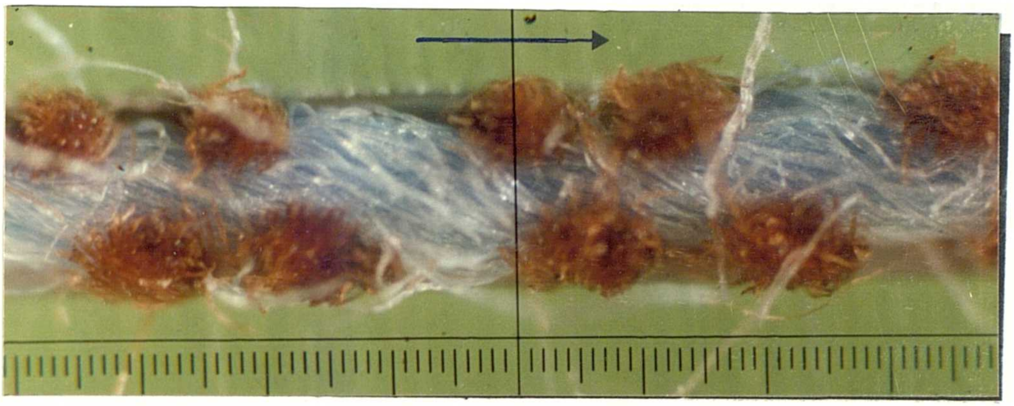


Fabric C_{10}

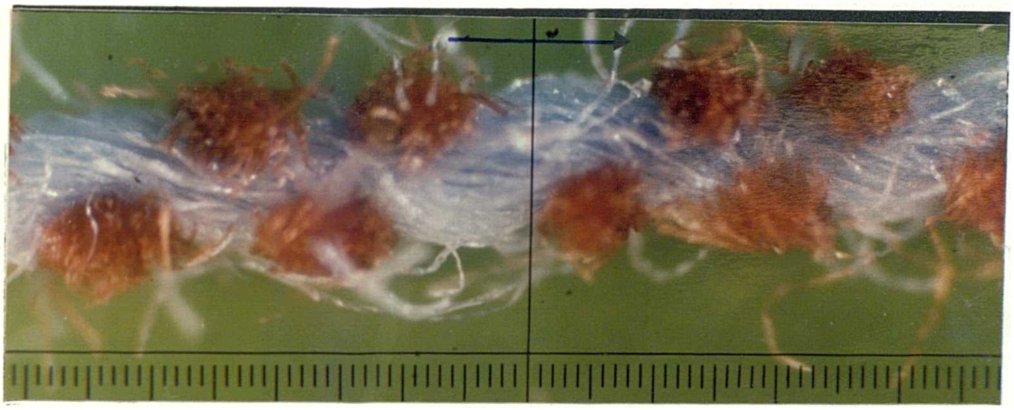
Plate 4

The influence of increasing weft yarn sett on warp crimp

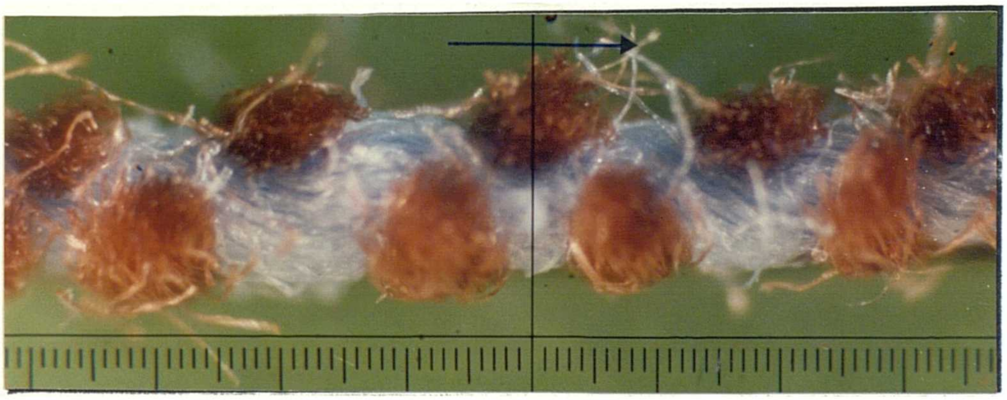
arrows indicate warp direction



Fabric C_6



Fabric C_8



Fabric C_{10}

Plate 5

The influence of increasing weft yarn sett on weft crimp
arrows indicate weft direction

is greater in the warp than in the weft yarns. Firstly the greater tension imposed on the weft yarns, during weaving, secondly their greater stiffness because of their higher linear density (30,31), are likely reasons.

4.2.2.2 YARN SPACING

As shown in Figure 4.3, the weft yarn spacing (1/threads/cm) decreased with a systematic increase in the density of weft yarn sett. The warp yarn spacing which might be expected to remain constant actually increased. The latter effect is attributable to the denting and lifting plan during weaving. For example, an insertion of four ends per dent frequently causes the yarns to group together, particularly at lower sett (30-32) as shown in Plate 6 (a). As the density of weft sett was increased, migration of yarns occurred, and the spacing between warp yarns increased.

Reference to Plate 6 and the previous Plates 4 and 5 will show some differences in colour contrast. This is probably due to a slight variation in specimen illumination during preparation, but the variation in the film processing may also be another reason. In spite of these differences, Plate 6 is the plan, and Plates 4 and 5 are respectively cross-sections of the warp and weft yarns of the same fabrics.

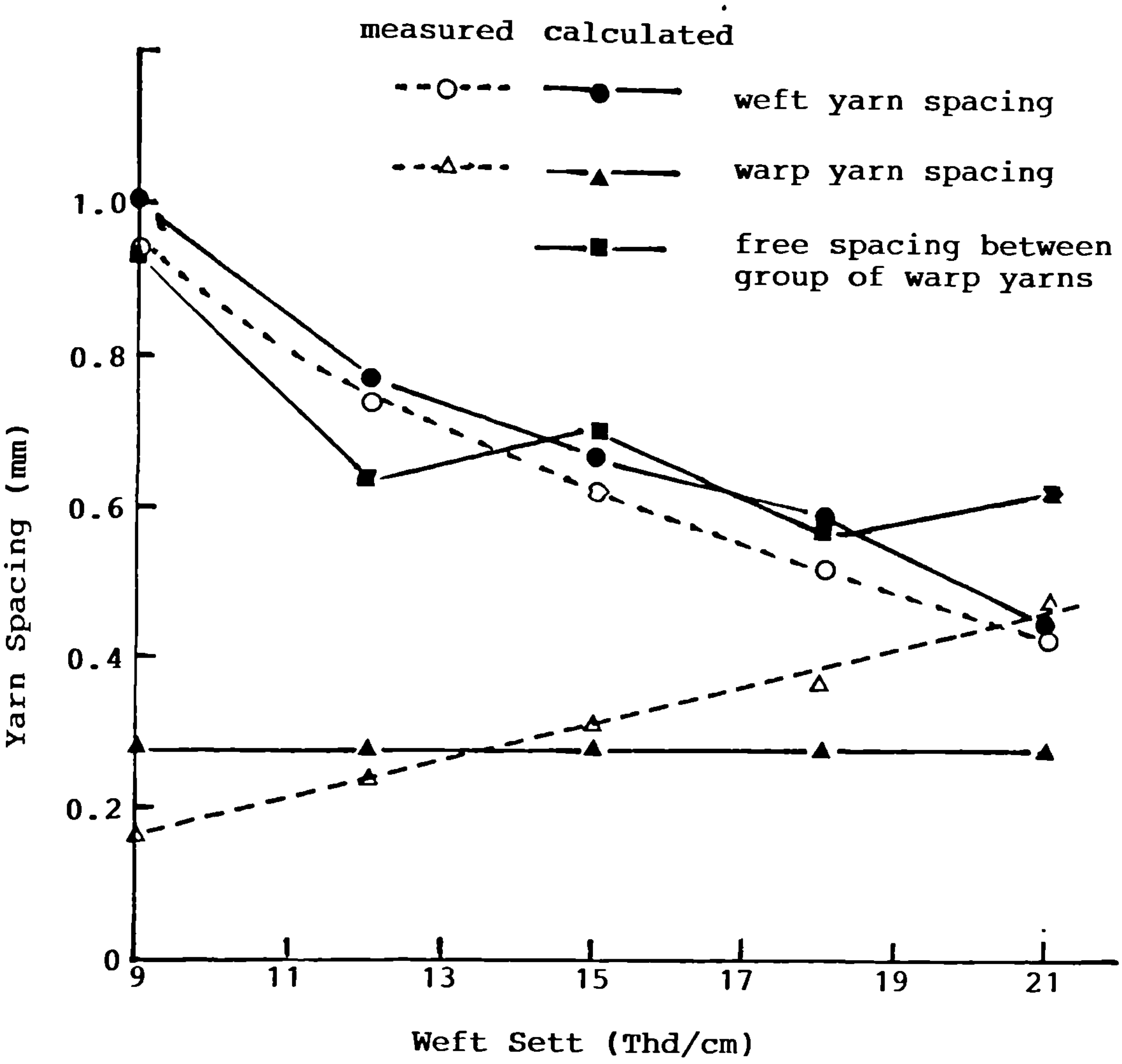
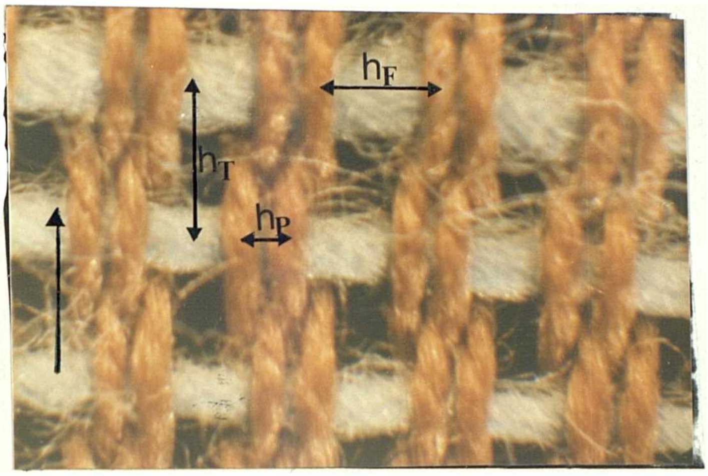
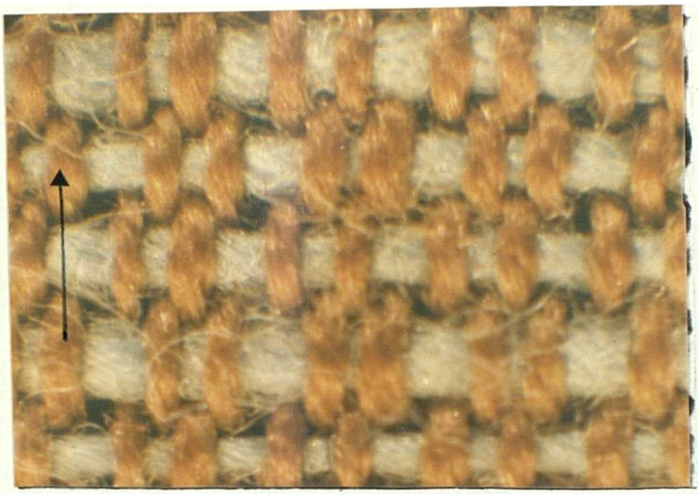


Fig 4.3

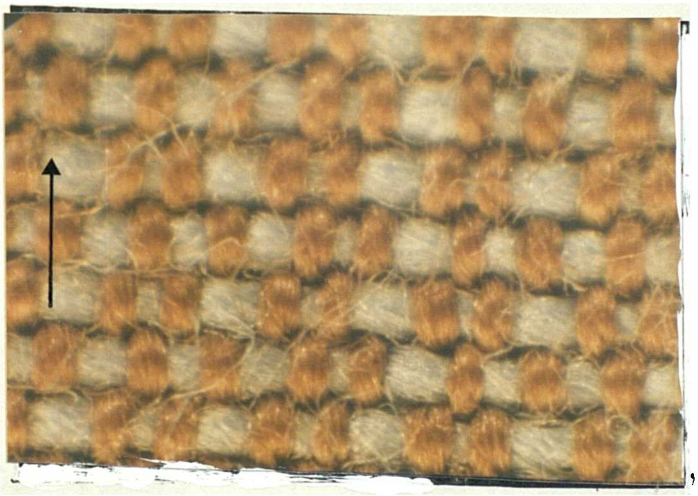
The influence of weft sett on yarn spacing



Fabric C_6



Fabric C_8



Fabric C_{10}

Plate 6

The effect of increasing weft sett on yarn spacing (warp and weft) arrows indicate warp direction

h_P: Warp spacing
h_T: Weft spacing
h_F: Free spacing (warp)

4.2.2.3 CROWN HEIGHT

In spite of an increase in yarn crimp, as the density of weft sett was increased, the magnitude of yarn crown height showed a consistent decrease (Table 4.2). The surface of the fabric also felt smoother and more regular. The diminishing values of yarn crown height may be due to a decrease in the modular length of warp yarns(100), but the diminihsing difference between the crimp balance in the two sets of yarns is a more likely reason(19). As shown in Table 4.2, the agreement between theoretical and calculated crown height is reasonable.

In spite of the declining crown height, little or no change in amplitude was obtained (Table 4.1). However, the number of peaks of the stick-slip motion when rubbing along warp is linearly correlated with weft yarn sett, as shown in Figure 4.4. This also confirms earlier findings in case 1.

4.2.2.4 FABRIC BALANCE

The relative area of contact between two fabrics is expressed by fabric balance(94). Theoretically, the fricative resistance to motion should increase if the relative area of contact (fabric balance) increased. The data (F_K) in Table 4.1 was plotted against the fabric balance ($B\lambda$) estimated from equation 4.1, as shown in Figure 4.5. A systematic increase in the fricative resistance to motion was obtained as the fabric balance

Table 4.2

Geometric parameters of plain weave cotton fabrics

Fabric* Code	Calculated Values[1] (mm)			Experimental Values[2] (mm)		
	**H_P	H_T	H_C	H_P	H_T	H_C
C_6	0.54	0.30	0.12	0.53	0.22	0.16
C_7	0.53	0.31	0.11	0.53	0.28	0.13
C_8	0.52	0.33	0.10	0.47	0.33	0.07
C_9	0.50	0.33	0.09	0.46	0.33	0.06
C_{10}	0.43	0.31	0.06	0.42	0.32	0.05

* See fabric details in Table 2.2

** H_P = Height of warp yarn protrusion

H_T = Height of weft yarn protrusion

H_C = Crown height

[1] Calculated from equation 4.2

[2] Measured on the microscope

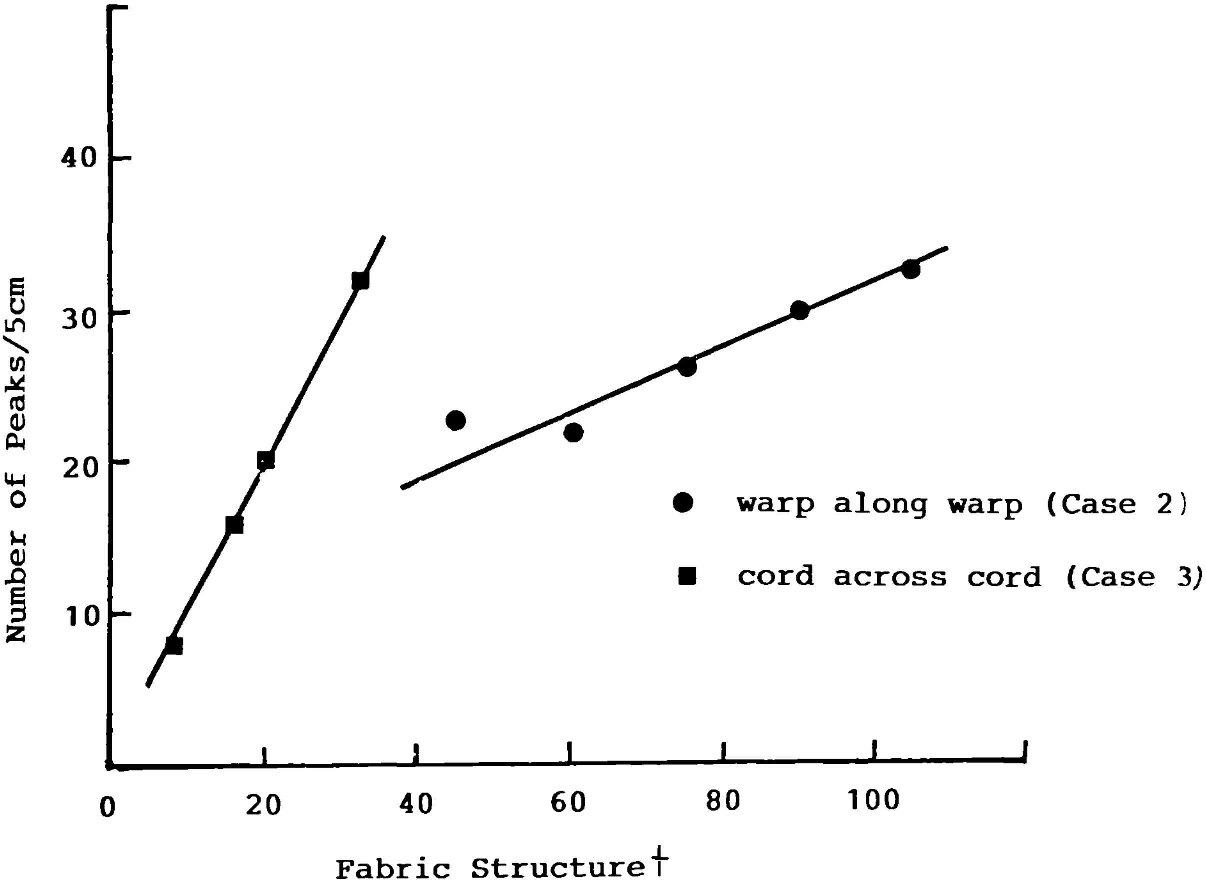


Fig 4.4

Relation between the number of stick-slip peaks and fabrics structure †(number of threads/5cm in plain weave fabrics, and number of cords/5cm in weft pile fabrics)

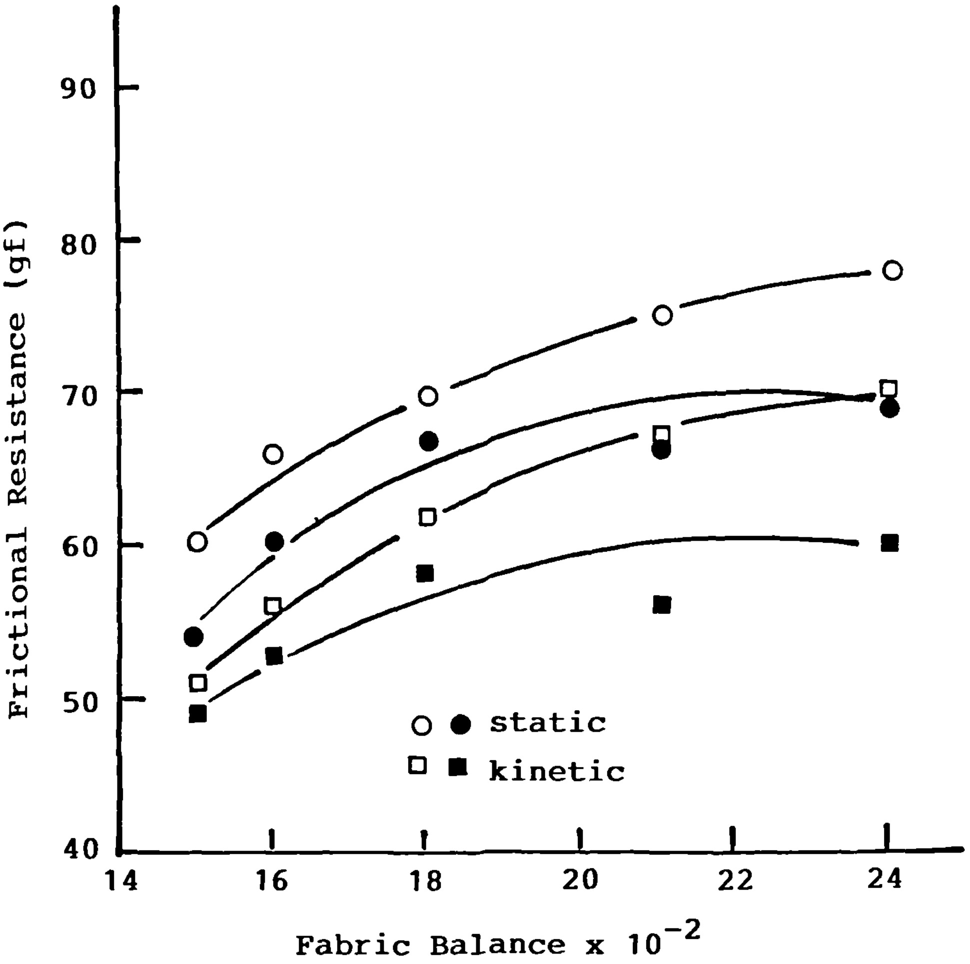


Fig 4.5

Relation between fabric balance and frictional resistance (filled signs = warp on warp motion, empty signs = weft on weft motion) was increased. A similar relation can also be shown between the resistance to motion and yarn sett. For this reason, the former is more of mathematical than technological importance, hence the latter is used in this work.

4.2.3 CONCLUSIONS

The frictional resistance of a plain weave fabric has been shown to be sensitive to small changes in yarn geometry produced by alterations in yarn crimp, thread spacing, crown height and fabric balance. The results for case 2 fabrics agree broadly with those for the woven fabrics used in case 1, namely a frictional resistance in the region of 30-80gf.

4.3 WEFT PILE FABRICS (CASE 3)

4.3.1 FRICTIONAL PROPERTIES

Like the woven and knitted fabrics considered in cases 1 and 2 and elsewhere(93,94,131), the cords (case 3) also show some anisotropy in their frictional properties. For example, an inspection of Table 4.3 shows that the frictional resistance (static and kinetic) amplitude of resistance, and the values of F_S-F_K are greater, but the number of peaks is consistently lower for motion of cord-across-cord. This directional effect is also detectable visually and tactually as discussed in Chapter 6. It

Table 4.3

The influence of fabric structure on the frictional properties of weft pile cotton fabrics

*Code	**Frictional Parameters									
	Face-to-face					Back-to-back				
	F_S	F_K	F_N	F_A	F_S-F_K	F_S	F_K	F_N	F_A	F_S-F_K
C_{12} 1	132	126	64	2	6	66	52	44	1	20
2	134	132	63	2	2	60	50	51	1	10
C_{13} 1	74	66	40	1	8	66	58	43	1	8
2	100	84	32	3	16	65	56	40	2	9
C_{14} 1	97	78	41	1	9	78	60	42	1	18
2	122	108	20	11	14	72	58	40	2	14
C_{15} 1	80	78	40	1	2	72	63	41	2	9
2	142	116	16	25	26	76	60	40	2	26
C_{16} 1	102	78	40	1	24	60	52	41	2	8
2	158	122	8(8)	37	36	80	60	40	2	20

* See fabric details in Table 2.3

1 = cord along cord motion

2 = cord across cord motion

** F_S = static frictional resistance(gf)
F_K = kinetic frictional resistance(gf)
F_N = number of peaks/5cm sled traverse
F_A = amplitude of resistance (gf)

will be noted that the magnitude of frictional resistance is approximately twice that of the plain weave fabrics reported earlier. However, unlike the woven fabrics, in which the frictional properties were very similar on both sides of the fabric, i.e. face-to-face and back-to-back, the resistance face-to-face is significantly higher than back-to-back in all the weft pile fabrics considered.

The amplitude of the stick-slip motion was plotted against the cord height in Figure 4.6. As expected, the amplitude increases for cord across cord motion and remains fairly constant for cord along cord. This clearly shows that this quantity is related to the height of protuberances on the fabric surface.

Reference to Figure 4.4 also shows a very good linear relationship between the number of peaks in the stick-slip motion, and the number of cords (for cord across cord motion). The agreement is similar to that found in the knitted fabrics (case 1 Figure 3.2) but better than woven fabrics. As stated before, the degree of spacing, and the size of cords which in turn enhance interlocking and intermeshing of fibre pile must be responsible.

4.3.2 FRICTION TRACES

An important characteristic of corduroys in general is the ridginess of fabric surface(30). An examination of the friction traces such as those shown in Figure 4.7 enables such features to be characterised objectively,

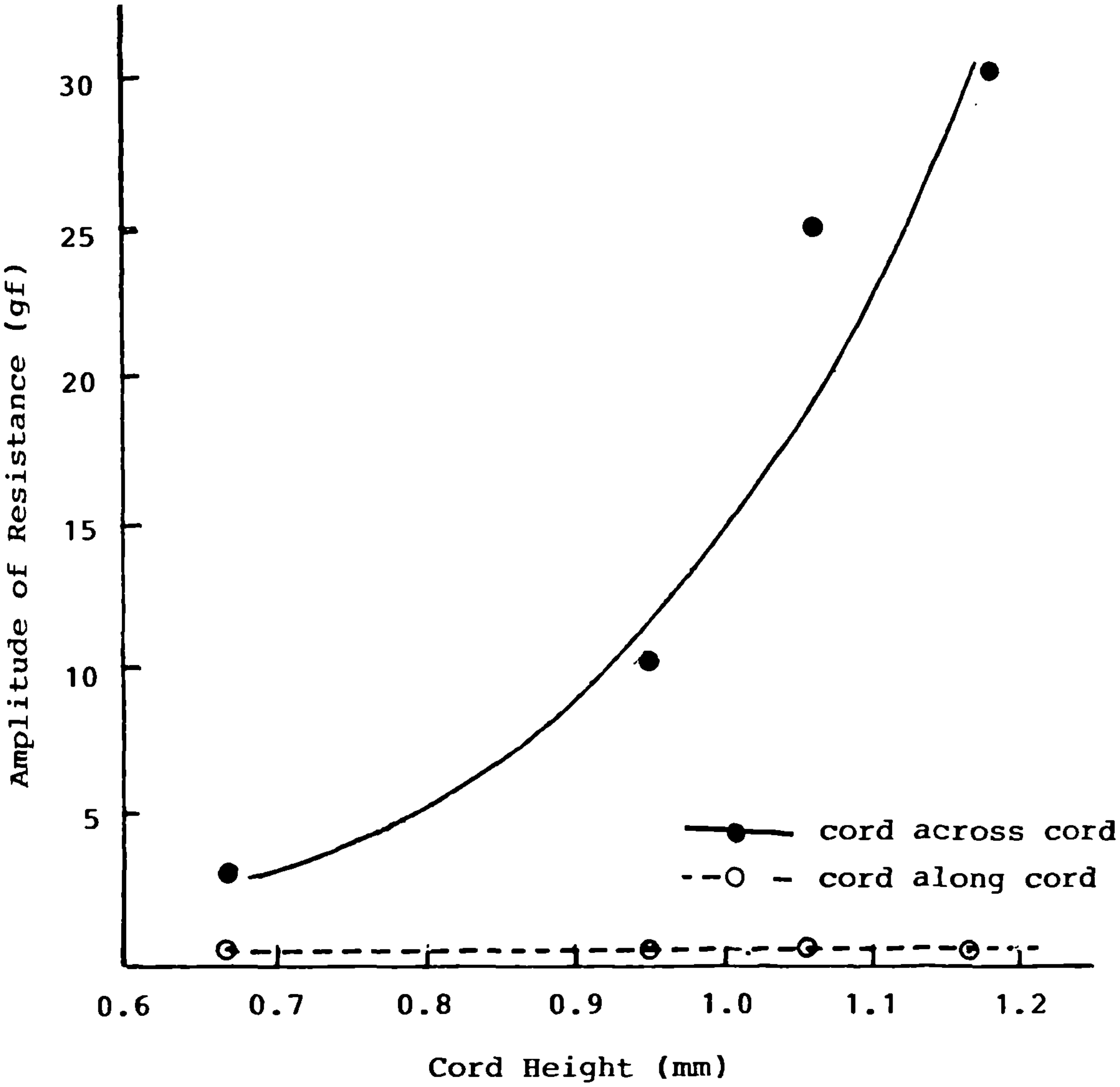
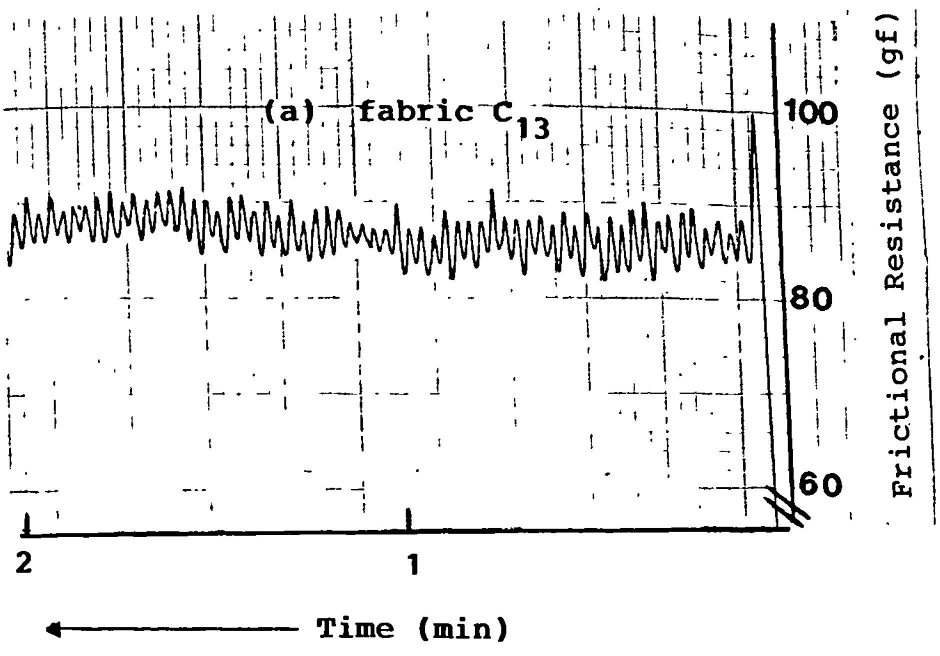


Fig 4.6

The influence of cord height on the amplitude of frictional resistance



(b) fabric C_{16}

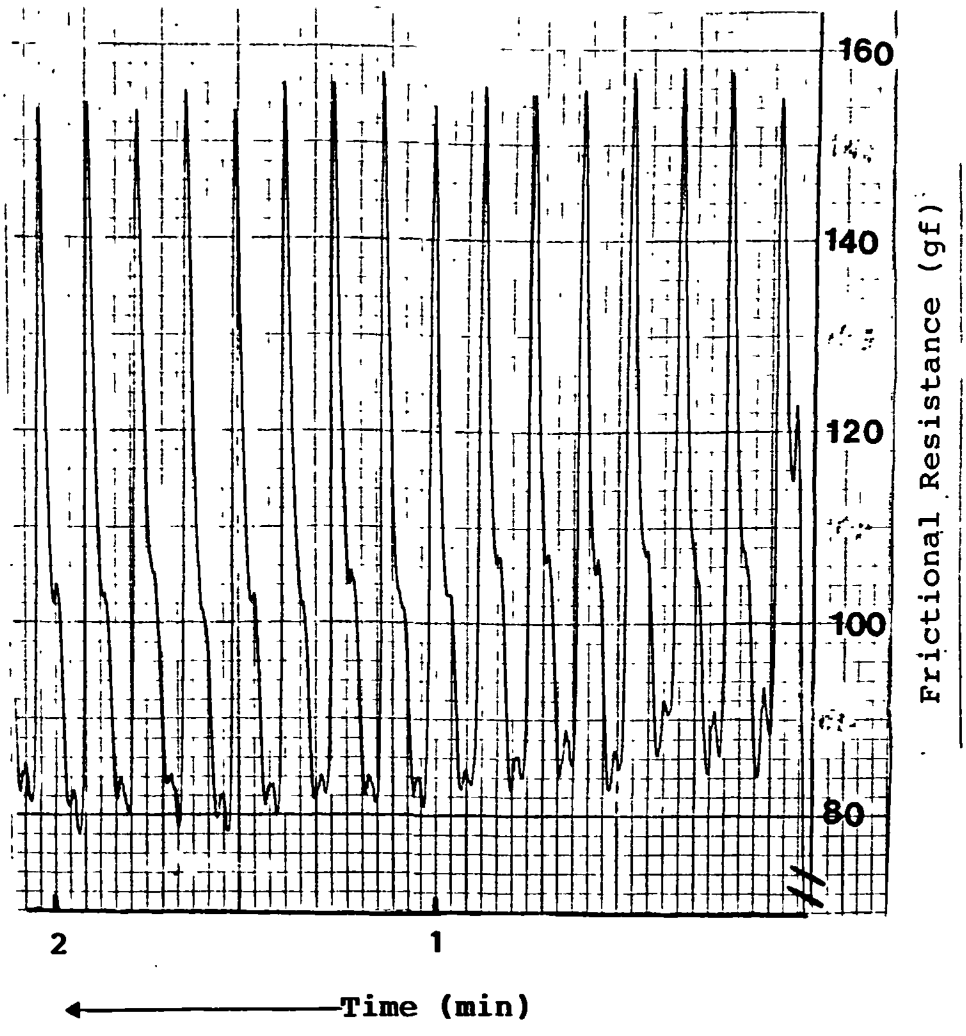


Fig 4.7

Typical friction traces of weft pile cotton fabrics (C_{13} and C_{16}) for cord across cord motion. (Arrow represents the direction of motion) and related to fabric handle and texture. These traces are examples of regular stick-slip traces discussed in Section **1.5**.

If it is assumed for the moment that fabric C_{13} is smoother than fabric C_{16}, (and this is shown in Chapter 6), then the following observation may be made of smooth textures. The number of peaks is relatively greater, but the resistance to motion, amplitude and the value of F_S-F_K are lower (fabric C_{13}), than those found in rough surfaces(121) (fabric C_{16}). This agrees with the findings of Hearle and Husain(34), namely when the magnitude of F_S-F_K is low, the number of peaks is large, and the handle is smoother.

4.3.3 CONCLUSIONS

The fricative resistance to motion, amplitude and number of peaks shows clear relationship with fabric structure. The magnitude of resistance is about twice greater, and the amplitude may be up to ten times greater than those found in most woven fabrics.

4.4 CASE 4: KNITTED FABRICS

4.4.1 FRICTIONAL PROPERTIES

The results for case 4 fabrics are shown in Tables 4.4 and 4.5 for plain and rib-knitted fabrics respectively. It may be seen that the frictional resistance

Table 4.4

Frictional properties of plain knitted fabrics in the dry and wet relaxed states*

Fabric Code	Frictional Parameters				
	F_S	F_K	μ_S	μ_K	F_N
KW_{71} (o) W	62	55	2.39	2.10	30
C	62	55	2.37	2.11	32
KW_{71} (s) W	62	53	2.38	2.02	34
C	55	51	2.11	1.97	29
KC_{71} (o) W	49	39	1.90	1.50	28
C	52	39	1.99	1.52	24
KC_{71} (s) W	57	49	2.18	1.87	28
C	59	49	2.26	1.90	27
KA_{71} (o) W	37	30	1.43	1.15	30
C	39	32	1.51	1.23	32
KA_{71} (s) W	30	24	1.17	0.93	36
C	39	28	1.49	1.06	35

* See Section 2.4.1

(o) = dry relaxed state

(s) = wet relaxed state (scoured)

W = wale along wale motion

C = course across course motion

<u>Table 4.5</u>

Frictional properties of rib knitted fabrics in the dry and wet relaxed states*

Fabric Code		Frictional Parameters				
		F_S	F_K	μ_S	μ_K	F_N
KW_{120} (o)	W	54	48	2.06	1.86	14
	C	57	52	2.19	1.98	14
KW_{120} (s)	W	44	40	1.71	1.53	13
	C	47	44	1.80	1.70	14
KC_{120} (o)	W	48	44	1.84	1.68	15
	C	49	47	1.88	1.82	16
KC_{120} (s)	W	54	48	2.08	1.86	15
	C	58	52	2.22	1.98	15
KA_{120} (o)	W	42	37	1.63	1.42	18
	C	43	36	1.69	1.40	17
KA_{120} (s)	W	47	41	1.84	1.58	17
	C	49	43	1.90	1.65	17
KV (o)	W	47	45	1.87	1.71	15
	C	52	44	1.99	1.68	16

* See Section 2.4.1

(o) = dry relaxed state

(s) = wet relaxed state (scoured)

W = wale along wale motion

C = course across course motion

varies depending upon structure, state and fibre content. It may also be noted that the results are not necessarily consistent. Thus while the plain structure offers greater fricative resistance in the case of wool fabrics, the opposite is the case for the acrylic fabrics. The values for cotton may be said to be neutral in this respect. The changes between the dry- and wet-relaxed states mirror these for structure, although to a lesser extent. Finally, as far as fibre content is concerned, wool fabrics offer slightly greater resistance than cotton fabrics, both offering more resistance than acrylics. Visually and tactually the fabrics can be discriminated between and this point will be examined later in Chapter 6.

4.4.2 COMPARISONS OF YARN AND FABRIC FRICTION

The coefficients of friction of yarns are shown in Table 4.6, it will be seen that the coefficients of friction rank according to fibre content in descending order, namely: wool, viscose rayon, cotton and acrylic fibres. The values are similar in magnitude to those quoted in the literature(57,97). The coefficients of friction measured by the capstan assembly are significantly greater than those measured on the Wira linear friction meter. This is in accord with an earlier finding by Dodo(11), who compared the magnitudes of the coefficients of friction of cotton yarns measured by the Wira linear friction meter (flat) with those measured by the Shirley (cylindrical)

Table 4.6

Coefficients of friction of yarn-on-yarn

Fibre* Content	Coefficients of Friction			
	Capstan(1)		Linear(2)	
	static	kinetic	static	kinetic
Wool	0.88	0.78	0.47	0.43
Cotton	0.64	0.60	0.26	0.23
Acrylic	0.43	0.43	0.22	0.20
Viscose Rayon	0.78	0.73	0.39	0.33

* Yarn details in Table 2.1

(1) Capstan radius = 5.6cm
input tension = 10g±0.5
angle of lap = 3.4 rad.
yarn velocity = 5cm/min.

(2) Normal load = 50g.
yarn velocity = 5cm/min.

yarn friction meter. The former was consistently lower than the latter. This may be due to the geometric differences between the test surfaces, but other factors such as the input tension(38-44,110-115), the radius of capstan(79), and the angle of yarn lap(22-24) are known to increase the frictional properties of capstan-like assemblies.

The coefficients of friction of fabrics were plotted against those of their component yarns as shown in Figures 4.8 and 4.9 for plain and rib knitted structures respectively. It can be seen that fabric friction is consistently greater (by a factor of about 3x) than their component yarns. This is in accord with the results of other workers(20,137). Ferguson(20) attributed the higher fabric friction to a lower pressure (470N/m^2) used in fabric tests, which allowed snagging and catching of the protruded fibres and yarn structures. Zurek et al(137) explained that the greater structural complexity of fabrics may increase the tendency of interlocking and frictional resistance. The dissimilar geometry of the test surfaces, which are usually flat in the case of fabrics and cylindrical in the case of yarns, may also affect these comparisons.

However, again the ranking in descending order is wool, viscose rayon, cotton and acrylic fibre content which confirms the postulate made earlier, namely that fabric friction is related to yarn friction. The correlation is better between fabric and yarn friction

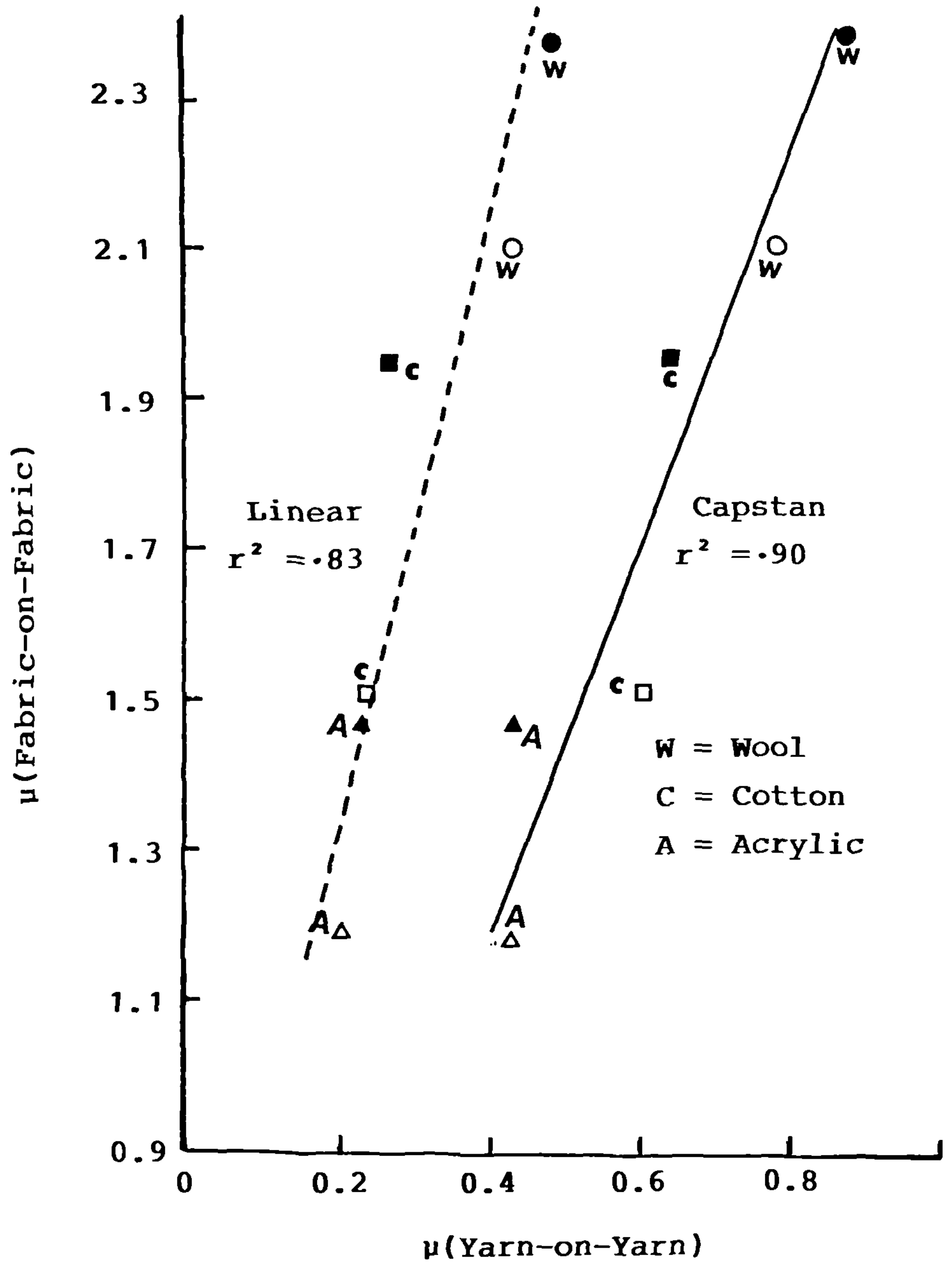


Fig 4.8

Relation between the coefficients of friction of plain knitted fabrics and their component yarns (filled signs = static, empty signs = kinetic). Measurements made in the dry relaxed state

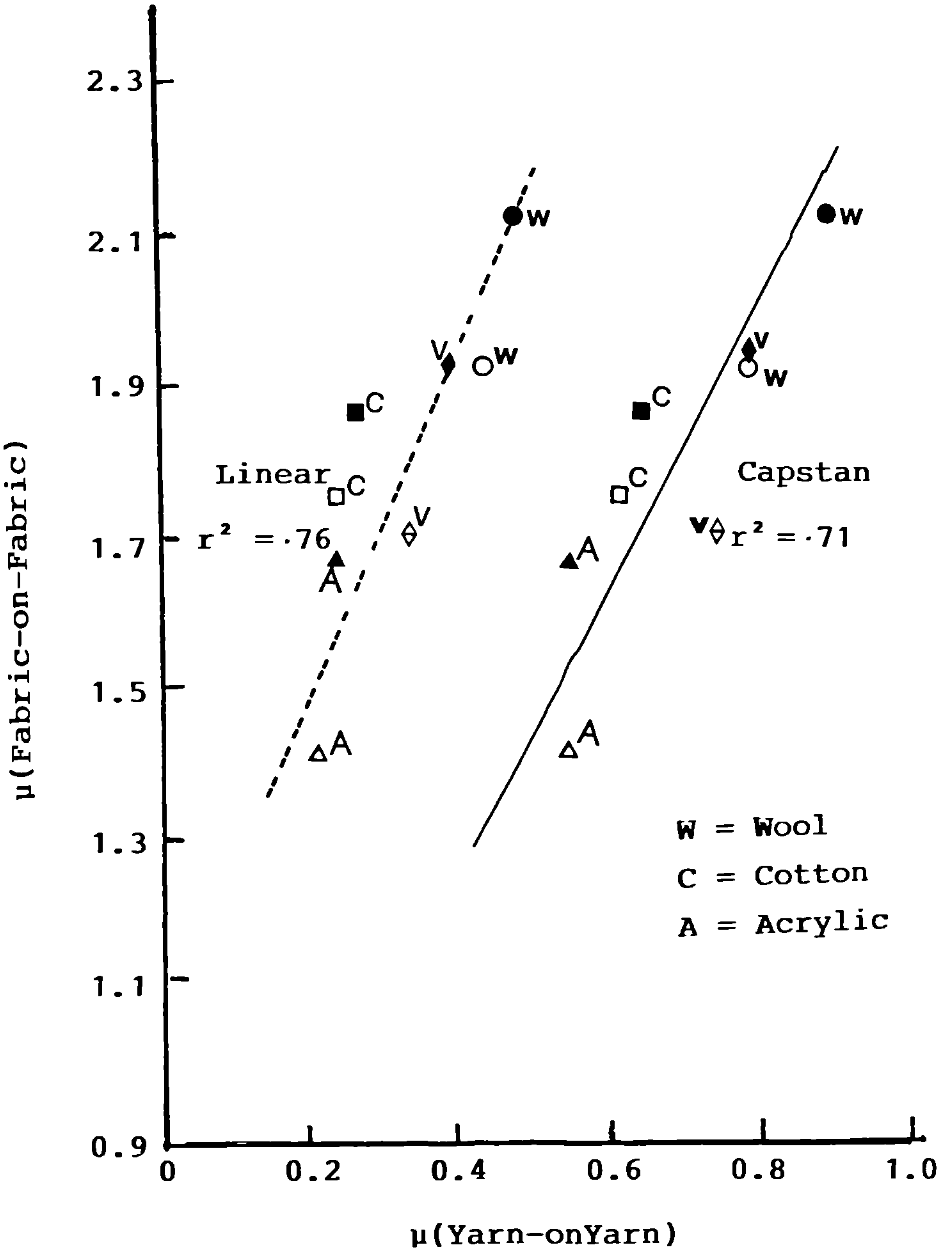


Fig 4.9

Relation between the coefficients of friction of rib knitted fabrics and their component yarns (filled signs = static, empty signs = kinetic) Measurements made in the dry relaxed state measured on a flat surface, despite experimental variables.

4.4.3 CONCLUSIONS

Fabric friction is approximately three times greater than those of their component yarns. Yarns with higher frictional properties gave fabrics whose frictional properties are equally higher.

The magnitude of the coefficient of friction measured on the capstan friction meter is about (2X) greater than those values obtained from the flat surface (linear friction meter). In both cases frictional properties of yarns are related to fibre content, and those of fabrics are influenced by loop size and surface hairiness.

Comparing this Case 4 with the previous Cases 2 and 3, it would be seen that a twofold increase in the density of yarn sett at constant yarn count also produces about twofold increase in yarn crimp but only about 22-37% increase in frictional resistance. Similarly a slight increase in the height of fibre pile (0·67-1.18mm) produces large changes in frictional resistance (2X) in weft pile fabrics.

CHAPTER 5

FINISHING TREATMENTS

ABSTRACT

Simulation of finishing treatments to knitted and woven cotton fabric substrates cause significant changes in their frictional resistance. The fabrics also felt smoother or rougher in accord with whether there had been a decrease or an increase in the resistance. Changes in other properties such as compression, air permeability and lateral air flow are also being reported.

5.1 INTRODUCTION

Finishing treatments are applied to textile substrates for several reasons. This may be to improve quality features such as handle, i.e. smoothness, softness, stiffness and stretchiness, or to enhance performance features such as crease resistance, dimensional stability and strength. The immediate objective here is to monitor changes in frictional resistance.

Inter-fabric friction is measurable as either static frictional resistance, related to the force required to cause movement, or the kinetic friction, related to the force required to maintain movement. The difference between these two resistances is associated with handle (107-109). For a scroopy handle for example, a higher difference between static and kinetic frictional forces are required. Thus with such a handle, the initial movement of a fabric against itself is difficult, but once achieved movement becomes easier.

It is possible to simulate finishing treatments that should increase or decrease the frictional resistance of fabrics and then to compare their handle.

A knitted fabric KC_2 and a woven fabric C_2 were used as controls in this case (Case 5). Details of these fabrics may be found in Chapter 2.

5.2 EFFECTS OF FINISHING TREATMENTS

5.2.1 SCOURING

Relaxation of stresses imposed on fibres, yarns and fabrics occurs during scouring and other wet treatments. This along with mechanical agitation causes structural consolidation, i.e. shrinkage which might in turn be expected to cause changes in fricative resistance to motion. In fact, examples have been shown previously in Chapter 4, but in this particular case (Table 5.1) it would be seen that scouring has produced small but consistent increases in frictional resistance especially for the knitted fabrics.

5.2.2 MERCERISATION

Mercerisation is an internal and surface modifier, it is usually applied industrially to cotton fabrics to

Table 5.1

Effects of chemical finishing treatments upon the frictional properties of knitted (KC_2) and woven (C_2) fabrics

Finishing Treatments	KC_2*				C_2**			
	F_S	F_K	F_S-F_K	F_A	F_S	F_K	F_S-F_K	F_A
Original	70	55	15	4	65	49	16	3
Scoured	80	63	17	5	69	52	17	3
Mercerised (N_aOH)	105	85	20	8	79	62	17	6
Softening (Softlan)	75	56	19	4	60	46	14	3
Lubrication (PEG 1000)	41	30	11	2	38	32	6	2
Lubrication (PEG 4000)	50	32	18	3	45	37	8	2
Lubrication (PEG 6000)	56	38	18	4	60	44	16	2
Syton	150	120	30	10	100	80	20	8

* See fabric details in Table 2.5

** See fabric details in Table 2.2

NaOH = Sodium hydroxide

PEG = Polyethylene glycol

improve dye uptake, absorbability, stretchiness and strength(9,123). The treatment is usually accompanied by an increase in fabric shrinkage(123) and some changes in the frictional properties may be expected.

Reference to Table 5.2 will show that the frictional resistance and amplitude of resistance have increased. Since the ease of compression did not increase, this may be attributed to an increase in the relative effective area of contact as a result of consolidation. It is also possible that changes in the peripheral boundaries of fibres substrate (from ribbon-like structure of native cotton to the cylindrical shape of a mercerised material (123)) may also increase the relative area of contact.

5.2.3 SOFTENING

Commercially, fabric softeners are applied to goods to make them more pleasing to the touch, for example to enhance the ease of compression and smooth texture.

Despite the increase in fabric smoothness and softness, and contrary to expectations, this treatment has produced a slight increase in frictional resistance, F_S-F_K and amplitude of resistance as shown in Table 5.1. Perhaps these changes were associated with easier compression and a bedding effect, but the orientation of the micelles of the finishing molecules on the fabric surface thus producing a hydrodynamic lubrication may also be an explanation.

Table 5.2

Effects of increasing the concentration of mercerising solution on the frictional properties of a plain knitted (KC_2) and woven (C_2) cotton fabrics

Concentration of Sodium Hydroxide (%)	KC_2*				C_2**			
	F_S	F_K	F_S-F_K	F_A	F_S	F_K	F_S-F_K	F_A
0	80	63	17	5	69	52	7	3
5	83	70	13	5	71	55	16	3
10	88	74	14	6	71	57	14	4
15	90	78	12	8	74	60	14	4
20	95	81	14	8	76	62	14	5
25	105	85	20	8	79	62	17	6

* See fabric details in Table 2.5

5.2.4 LUBRICATION

The objective of this treatment was to reduce both the static and kinetic frictional resistance with the intention of producing a smoother handle. As shown in Table 5.1, polyethylene glycol (PEG) lubricants produced large reductions in static and kinetic frictional resistances and amplitude but there was a progressive decrease in the magnitude of change as the molecular weight of the lubricant increased. The possible mechanism responsible for this is hydrodynamic lubrication. Treated fabrics therefore may have a thick lubricant layer on their surface (depending upon the number of carbon atoms involved in micelles formation) and lubricants or softeners may orientate themselves either parallel or perpendicular to the surface as discrete particles. Polyethylene glycol lubricants also serve as effective antistatic agents by promoting the formation of a condensed film of moisture on the fibre surface. Another reason is the increase in the viscosity of the lubricants as their molecular weight increased, and a possible increase in the tackiness of fabric surface. Olsen(97) has demonstrated in a study concerned with the application of five Newtonian oils to nylon fibre substrates, that a plot of frictional resistance versus the logarithm of viscosity of 2% solution of lubricant was linear. Hearle and Husain(34) have also reported a reduction in the coefficient of friction of rayon card webs treated with polyethylene glycol lubricants. These authors also found that the PEG treated samples yield a lower difference between the static and kinetic frictional resistances. An examination of Table 5.1 will also show a relatively lower difference between the static and kinetic frictional forces, particularly for the PEG 1000 on woven fabric substrate. The handle of this fabric also felt smoother and softer relative to the original sample, in accord with Hearle and Husain(34), Röder(107-109) and Morton and Hearle's(88) postulates.

5.2.5 CHEMICAL ROUGHENING (SYTON)

The frictional properties of materials are frequently modified by the deposition of colloidal silica or starch, in order to enhance inter-fibre cohesion during spinning or to impart transverse strength to non-woven articles(82). It is used in this investigation to increase both the static and kinetic frictional resistance in order to simulate a rough handle.

Reference to Table 5.1 and Figure 5.1 will show that Syton treatment produced a very large increase (>100%) in frictional resistance and amplitude particularly for the knitted fabric. This effect has been ascribed to micro-interlocking of silica deposit. Treatments discussed in Sections 5.2.1 - 5.2.5 produced changes in tacticity which corresponded to changes in the frictional resistance and amplitude.

5.2.6 PHYSICAL MODIFICATION (RAISING)

The raising of fabric surfaces by mechanical methods is well known, for example, brushing. In the present example an abrasive action was induced by rubbing as described in Chapter 2.

The increase in frictional resistance as time of rubbing continued is shown in Table 5.3. The increase in frictional resistance is appreciable particularly against the direction of the rotational rubbing. The amount of detritus also increased, the difference between the amount collected and the mass of the fabric (after *rubbing)* presumably represented the airborne dust. As the surface is raised the lateral air permeability increased probably due to the separation of plate and fabric surfaces by detritus (Table 5.4). The observation might be made that while the term roughening has been used in the frictional context, the raised fabrics actually felt softer because of the ease of compression of the raised fibres compared to the original hard yarn knuckles.

A comparison between the raised fabrics and the former weft pile fabrics discussed previously (Chapter 4), will show that the frictional resistance of the latter is about three to four times greater than the former raised fabrics.

The magnitude of changes in the frictional properties by the foregoing treatments upon the knitted and woven fabric substrates may be illustrated. Reference to

Table 5.3

Effects of physical raising on the frictional resistance of fabrics

Time	1^+			2^{++}		
(min)	$*F_S$	F_K	F_S-F_K	$*F_S$	F_K	F_S-F_K
0	28	23	5	28	23	5
1	35	30	5	33	28	5
3	38	34	4	35	30	5
5	42	37	5	37	33	4

$^+$ 1 Against hair (direction of rotational rubbing)

$^{++}$2 With hair (against the direction of rotational rubbing)

* Frictional parameters in (gf)

Table 5.4

Effects of raising on the physical properties of plain weave cotton fabric C_{11} (canvas)

Time of rubbing (min)	Mass of detritus (g)	Loss in fabric mass (g)	AP $cm^3/cm^2/cm/sec$	LAF cm^3/s
0	0	0	3.0	3.5
1	0.26	30	4.0	14
3	0.38	43	4.5	18
5	0.44	50	5.8	23

AP = Air Permeability (Conventional)
(Test Method B.S.11, 1974)

LAF = Lateral Air Flow

Figures 5.1 and 5.2 will show that consistent results were obtained with both the knitted and woven fabric substrates. Polyethylene glycol (PEG 1000) produced the greatest reduction in frictional resistance (-35 to -52%), amplitude (-33 to -60%), and F_S-F_K (-35 to -65%). The Syton treatment also produced the greatest increase in frictional resistance (+29 to +90%), amplitude (+100 to +167%), and F_S-F_K (+18 to +77%). Between these two extremes, it is worth noting that the amplitude of resistance was the most sensitive parameter to finishing treatments.

Finally, a comparison of the differences in handle of these fabrics by adapted signal detection technique as detailed in Chapter 6 was carried out. It would be seen from Table 5.5 that when the magnitude of the difference in frictional forces between the finished and original sample is less than ±10gf there was no obvious difference in the smoothness of fabrics.

Legend to Figures 5.1 and 5.2

A = Mercerised (sodium hydroxide)

B = Softened (Soflan for knitted, Comfort for woven fabric)

C = Lubricated (Polyethylene glycol 1000)

D = Lubricated (polyethylene glycol 4000)

E = Lubricated (Polyethylene glycol 6000)

F = Roughened (Syton)

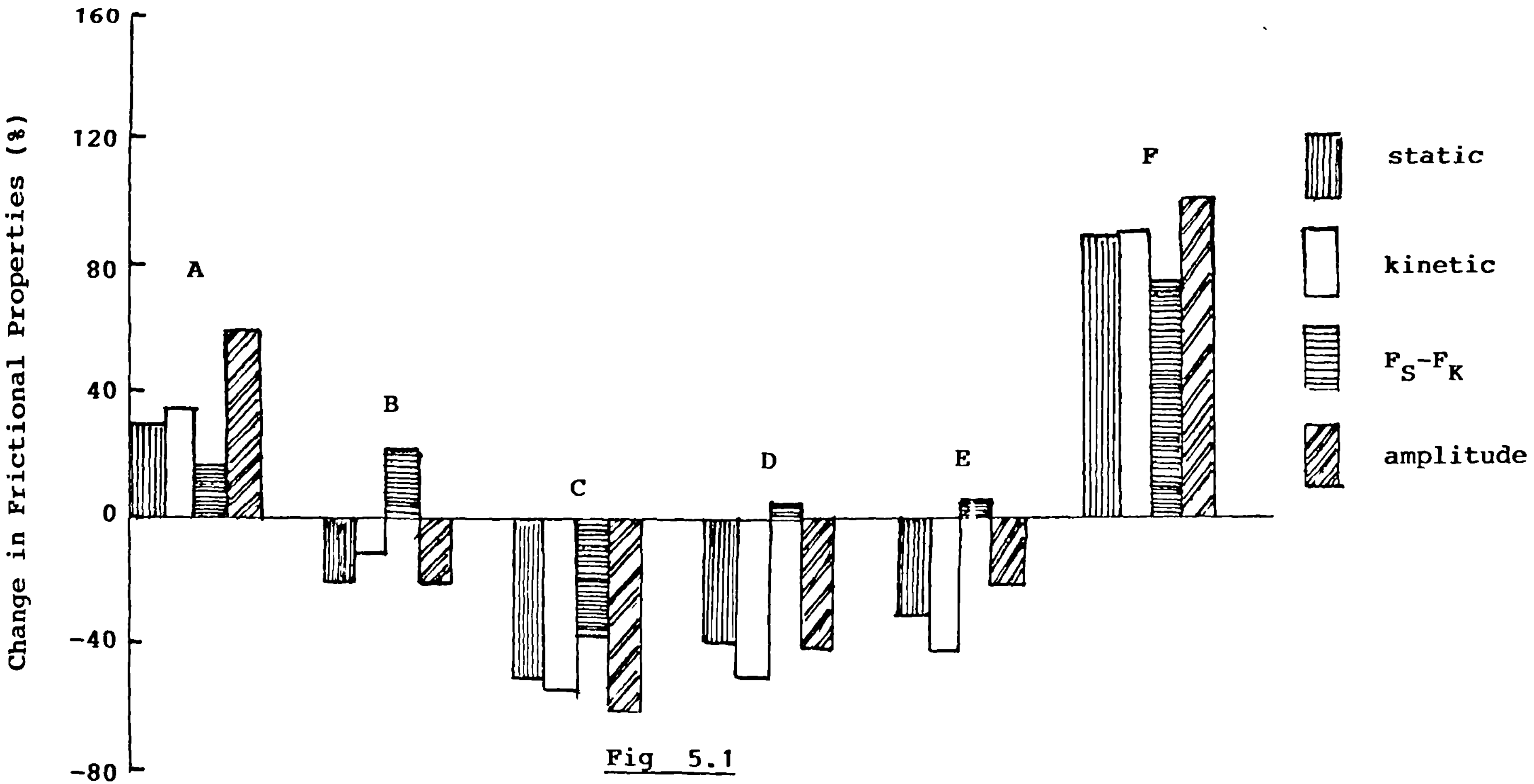


Fig 5.1

Magnitude of changes in frictional properties of knitted fabric with respect to the control scoured fabric.(KC$_2$)

*See legend of finishing treatments on page141 .

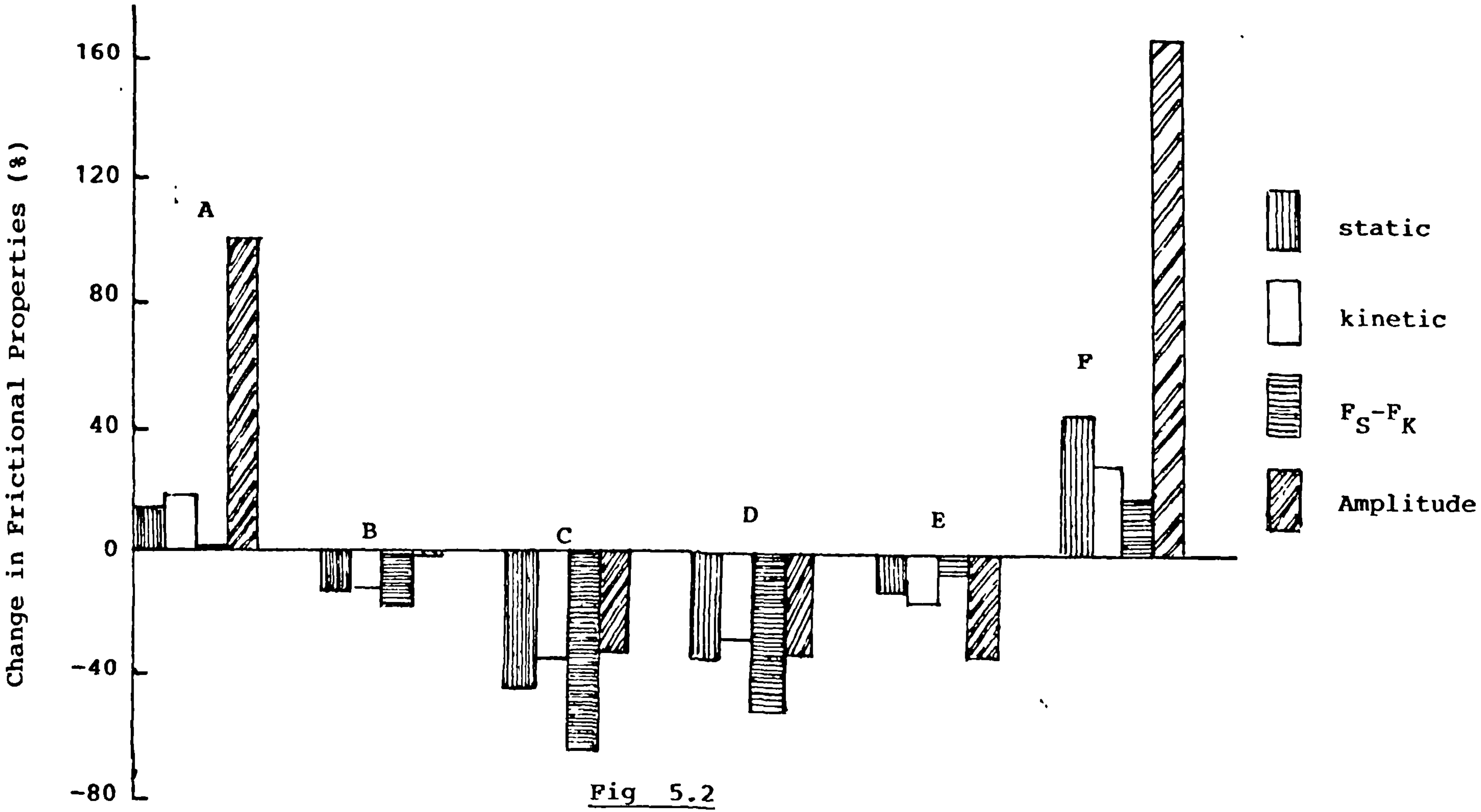


Fig 5.2

Magnitude of changes in frictional properties of woven fabric(C_2) with respect to the control scoured fabric.

*See legend of finishing treatments on page 141 .

Table 5.5

Differences in the magnitude of the frictional resistance of the original and finished fabrics and their handle (smoothness)

Finishing Treatments	Fabric KC_2			Fabric C_2		
	F_S	F_K	Diff$^+$	F_S	F_K	Diff$^+$
Scoured	+10	+8	Yes	+4	+3	No
Mercerised	+35	+30	Yes	+14	+13	Yes
Softened	+5	+1	Yes	-5	-3	Yes
Lubricated						
PEG 1000	-29	-25	Yes	-27	-17	Yes
PEG 4000	-20	-23	Yes	-20	-12	Yes
PEG 6000	-14	-17	Yes	-5	-5	Yes
Roughened						
Syton	+80	+65	Yes	+35	+31	Yes
Raising*	-	-		14 (9)	14 (10)	Yes

* Raising fabric C_{11} details in Table 2.2
value in parenthesis represents the frictional data against the direction of rotational rubbing

\+ Any difference between the handle of the original and finished fabric?

5.3 OTHER FINISHING TREATMENTS

Commercially, finished fabrics are frequently encountered in which the detail finishing treatments are not known. In such cases, evaluation of some physical properties may be useful. In this consideration a set of plain weave fabrics and knitted fabrics were finished externally by Unilever. The treatment consisted of scouring of both fabrics, a part of the woven fabrics was roughened by starch application, and a part of the knitted fabric was lubricated by a commercial fabric softener. Other details of treatment were not known.

The physical properties of these fabrics are given in Tables 5.6 and 5.7. For the woven fabrics, the starch application did not bear out any apparent solidity in fabric structure although an increase in stiffness (20%), and a decrease in compression (-54%), was observed. The coefficient of friction increased slightly (7%) and no change is stretchiness was observed. The resultant handle of the material was harsh. For the knitted fabric, a decrease in stiffness of about -52%, an increase in compression of about 44%, and an increase of about 35% in stretchiness was observed. Very little or no change in coefficient of friction was obtained although the lubricated sample was smoother and softer.

A comparison between the woven and knitted fabrics in the scoured states show that the knitted fabric was consistently softer, less stiff, and smoother than the

Table 5.6

Effect of roughening (starch) on physical properties of plain weave cotton fabrics

Physical Properties	Finishing Treatment	
	Scoured	Roughened
Mass (g/m^2)	188	188
Thickness$^+$ (mm)	0.40	0.42
Sett P (Thd/cm) T	27 22	27 22
Yarn Count P (Tex) T	35 45	35 45
Compression^{++} (mm)	0.13	0.06
Stiffness* (%)	283	339
Stretchiness** (%)	16	16
Coefficient of friction	1.06	1.14

+ Baty (pressure $35g/cm^2$)

++ Pressure $2KP_a$

* Drape coefficient

** Extension at 50N load (mean warp and weft)

Table 5.7

Effect of lubrication on physical properties of plain knit cotton fabrics

Physical Properties	Finishing Treatment	
	Scoured	Lubricated
Mass (g/m^2)	196	195
Thickness$^+$ (mm)	1.13	1.12
Courses/cm	14	14
Wales/cm	15	15
Yarn Count (Tex)	14	14
Compression^{++} (mm)	0.09	0.13
Stiffness* (%)	23	11
Stretchiness** (%)	26	35
Coefficient of friction	1.06	1.02

$^+$ Baty (pressure $35g/cm^2$)

$^{++}$ Pressure $2KP_a$

* Drape Coefficient (%)

** Extension at 50N load (mean of course and wales) woven fabrics. From these results, surface friction is the least sensitive to finishing treatments and stiffness and compression are more sensitive.

5.4 CONCLUSIONS

Simulations of finishing treatments such as lubricants produced large reduction (about 50%) in frictional resistance while deposits of silica in the interstices between yarns produced between 30-90% increase in resistance. The amplitude of resistance appears to be the best indicator in testing the effectiveness of finishing treatment. However, if the difference between the frictional resistance of two fabrics is less than ±10gf, it is unlikely in our opinion that their handle (smoothness) will be different.

CHAPTER 6

OTHER PHYSICAL MEASUREMENTS

ABSTRACT

Measurements of surface irregularities of fabrics by various methods in addition to friction is reported. It is demonstrated that the number of peaks of the roller, stylus and friction traces may be the best indicator of fabric smoothness. A negative correlation between this quantity and smoothness suggests that fabrics which yield more peaks are smoother than those with fewer peaks. This also agrees broadly with the results of lateral air flow.

In the field of subjective assessment, uncertainty about the terminology continues. Generally judges may find fabrics readily identifiable but finding the right descriptive adjective for these differences remains a problem. The correlations between other frictional, roller, stylus, lateral air flow parameters and fabric handle (smoothness) are also examined.

6.1 INTRODUCTION

Apart from the conventional friction measurements discussed previously, the vertical displacement of a probe (stylus or roller), resting on a fabric surface, where there is relative movement between the probe and the fabric is determined by the surface irregularities of the fabric in the vertical plane. Generally, there are two types of irregularities, namely:

1. Systematic variation as a result of uniform fabric structure, for example cords or ribs.
2. Random variation caused by uneven threads or thread spacing.

Hypothetically, a smooth plane surface would be expected to give a smooth trace (signal). If a fabric has a rippled surface of distinct periodicity, a regular and repetitive signal would be expected. The amplitude and pitch of such a signal would be dependent upon the height and width of the surface undulations respectively. Any random irregularities in, or the displacement of, yarns, or the presence of surface hairs, or uneven deposits of finishing agents might be expected to produce irregular signals. Changes in amplitude would be expected at the transition from thin to thicker places. Changes in pitch from irregular yarn spacing and snagging, the latter producing a lateral deflection of a stylus. Some differences would be expected between the signals obtained from a stylus, i.e. point contact and a roller with a larger circumferential contact. The stylus would be expected to be sensitive to small variations or protuberances on fabric surface which, because of a higher pressure ($43.7g/cm^2$) and flattening of asperities, may not be detected by the roller. It should be possible to establish some correlations between objective measurements of surface characteristics such as friction, roller, stylus, lateral air flow and optical (microscopic) measurement and subjective assessments. This is the purpose of this chapter. Some fabrics examined in the previous chapters are considered further.

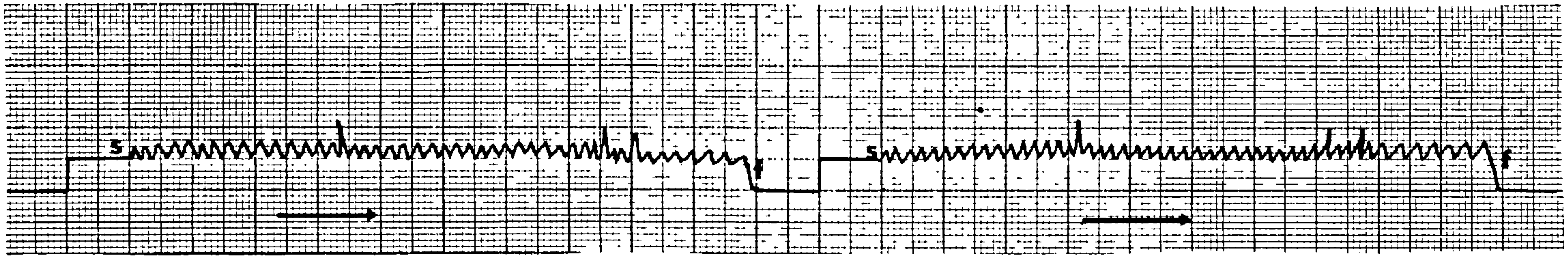
6.2 ANALYSIS OF SIGNALS PRODUCED BY ROLLER AND STYLUS METHODS

Typical signals obtained from the roller and stylus methods are shown in Figures 6.1, 6.2 and 6.3 for woven fabrics C_6 and C_{10} (Case 2), C_{13} and C_{16} (Case 3) and KC_{71} and KC_{120} (Case 4) respectively. Case 1 fabrics were not included in this consideration because of the randomness of the fabrics*. Similarly, the finished fabrics (Case 5) were not included primarily because the methods show poor discriminations between original and finished fabrics. It is likely that the changes caused by finishing treatments are larger internally than externally.

Referring to Figures 6.1 - 6.3, two repeats of the stylus trace corresponding to 5cm displacement of fabrics in the same direction are shown. A closer examination of Figure 6.2 (a) and (b) will reveal that the amplitude of the pulses diminished slightly on the second traversal. This may be due to the directional alignment of hairs in the direction of trace. A similar effect was observed with friction measurement of Case 1

*Preliminary experiments

fabric C_6 (less smooth)



fabric C_{10} (smooth)

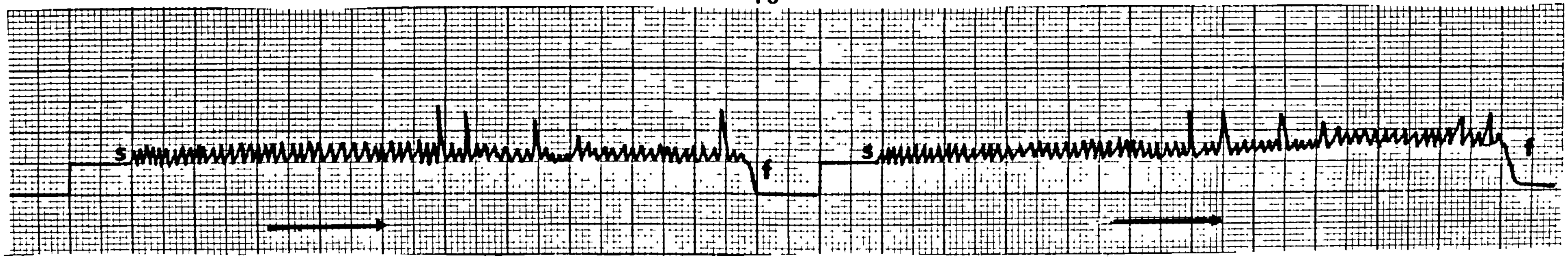


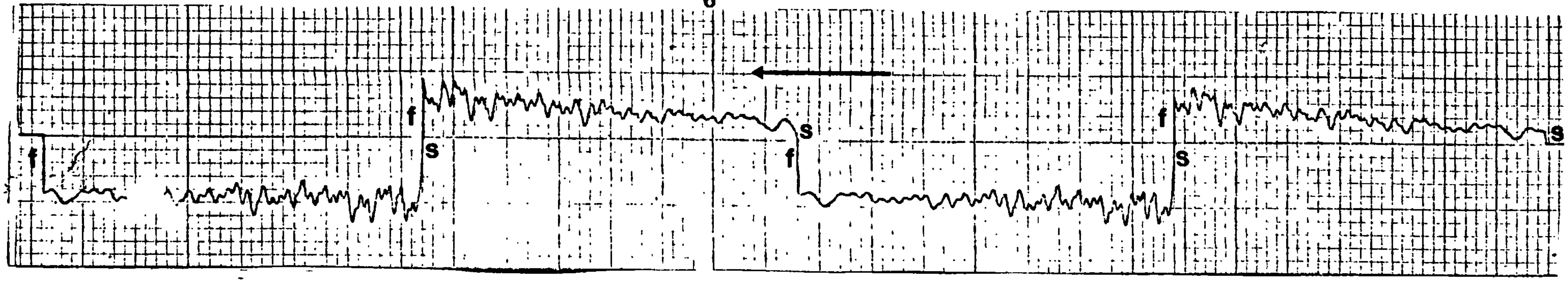
Figure 6·1(a)

Typical stylus traces of woven fabrics (Case 2)

Arrows indicate the direction of displacement of sample

s = starting point, f = finishing point

fabric C_6 (weft direction)



fabric C_6 (warp direction)

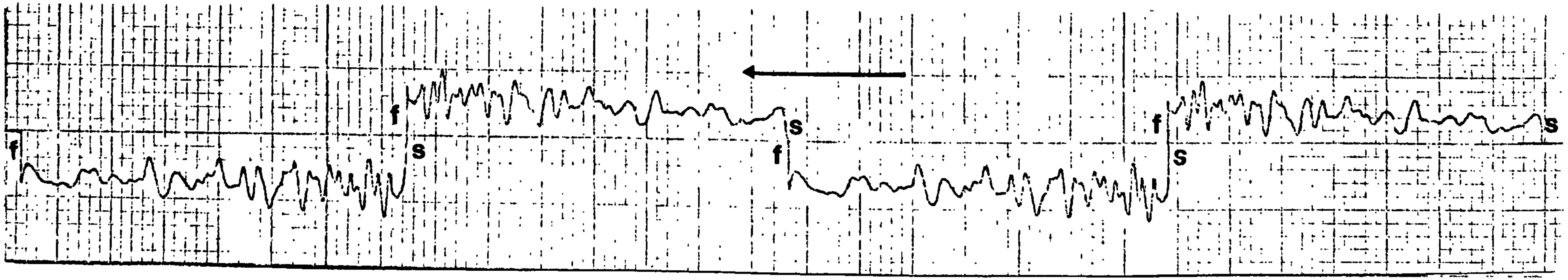


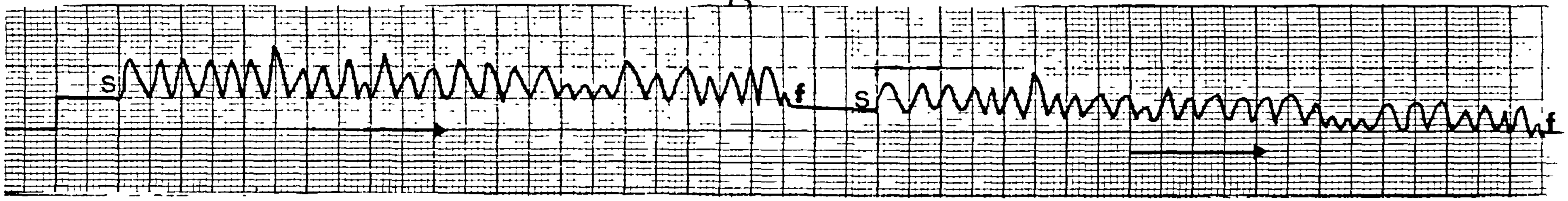
Figure 6.1(b)

Typical Roller traces of woven fabrics Case 2

Arrows indicate the direction of displacement of sample

s = starting point, f = finishing point

fabric C_{13} (smooth)



fabric C_{16} (less smooth)

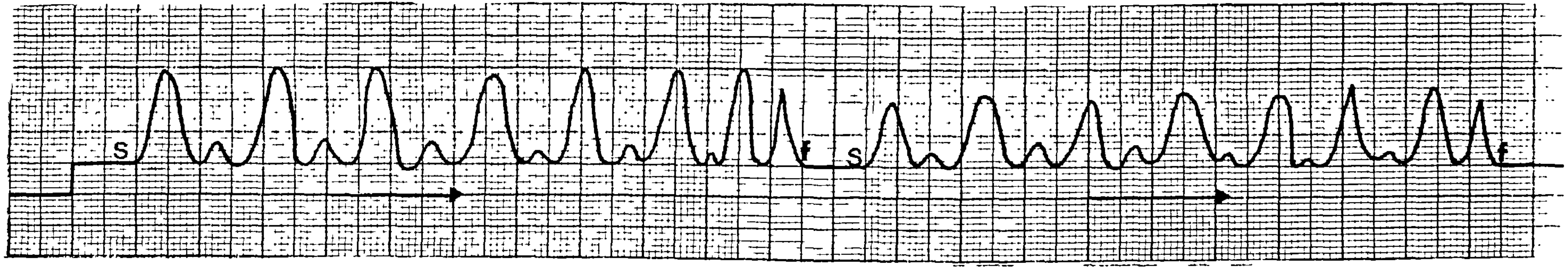


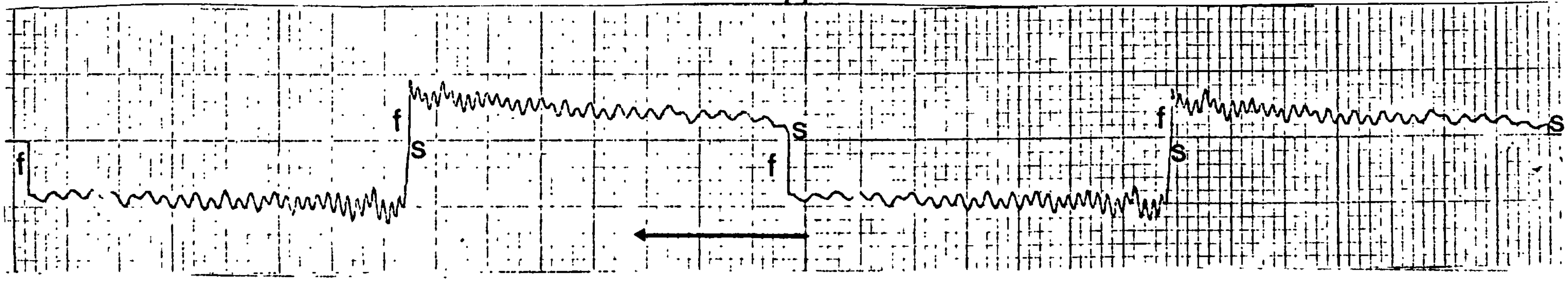
Figure 6.2(a)

Typical stylus traces weft pile fabrics (Case 3)

Arrows indicate the direction of displacement of sample

s = starting point, f = finishing point

fabric C_{13} (smooth)



fabric C_{16} (less smooth)

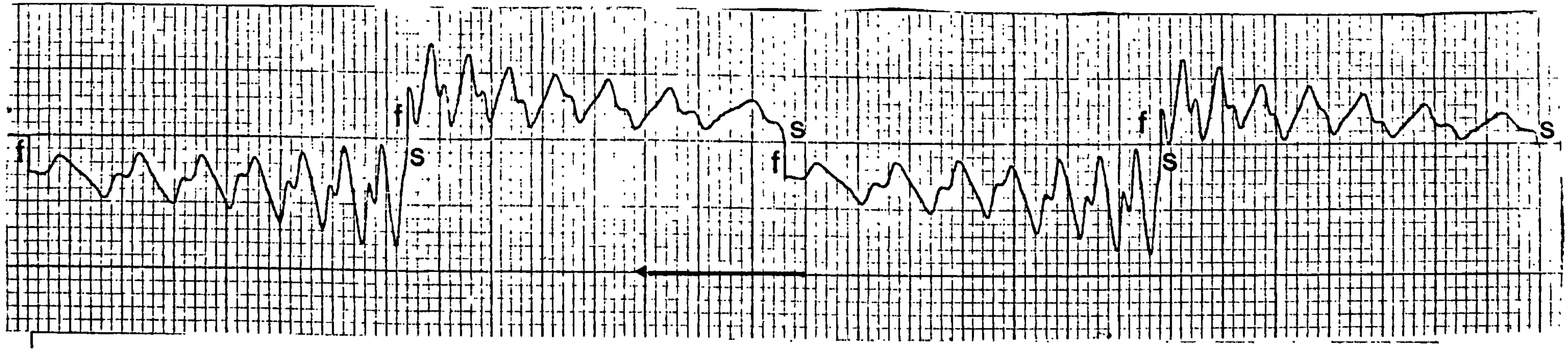
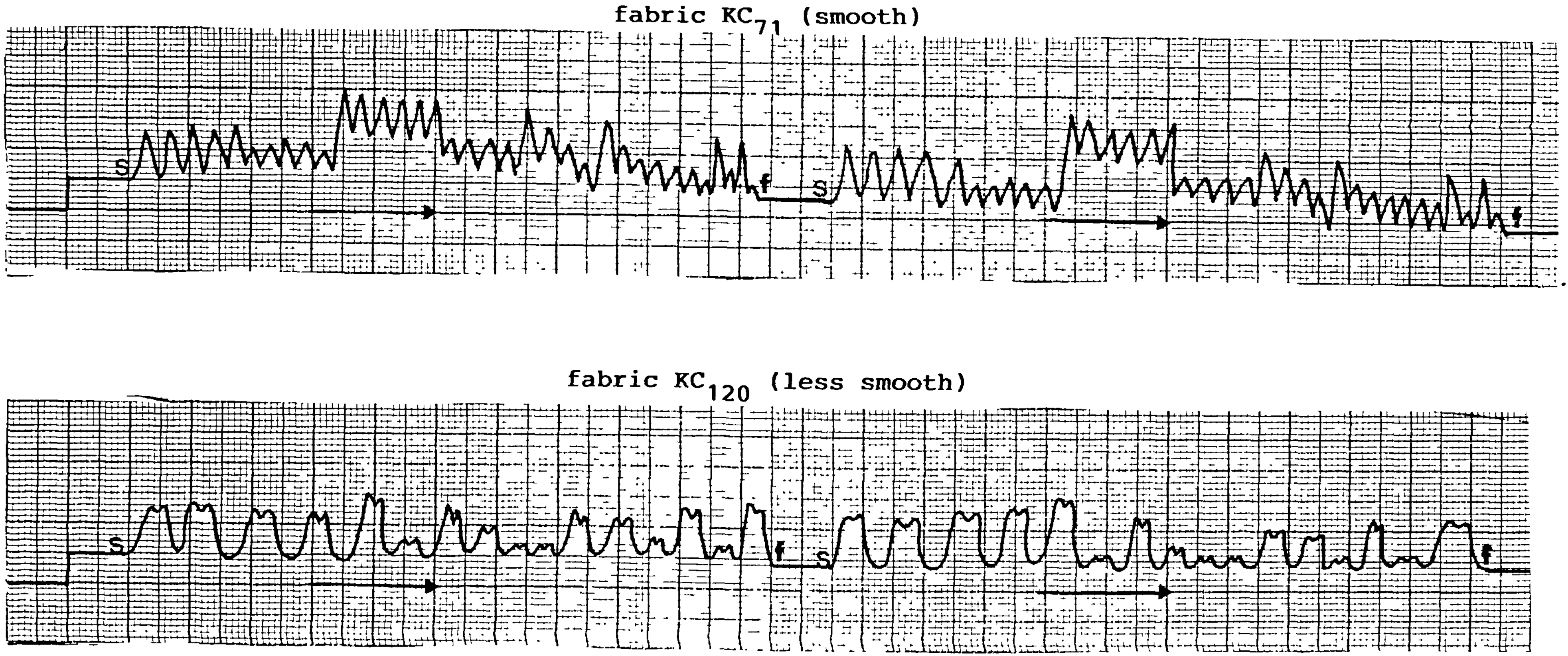


Figure 6.2(b)
Typical Roller traces of weft fabrics (Case 3)
Arrows indicate the direction of displacement of sample
s = starting point, f = finishing point


fabric KC$_{71}$ (smooth)

fabric KC$_{120}$ (less smooth)

Figure 6.3(a)

Typical stylus traces of knitted fabric (Case 4)

Arrows indicate the direction of displacement of specimen

s = starting point, f = finishing point

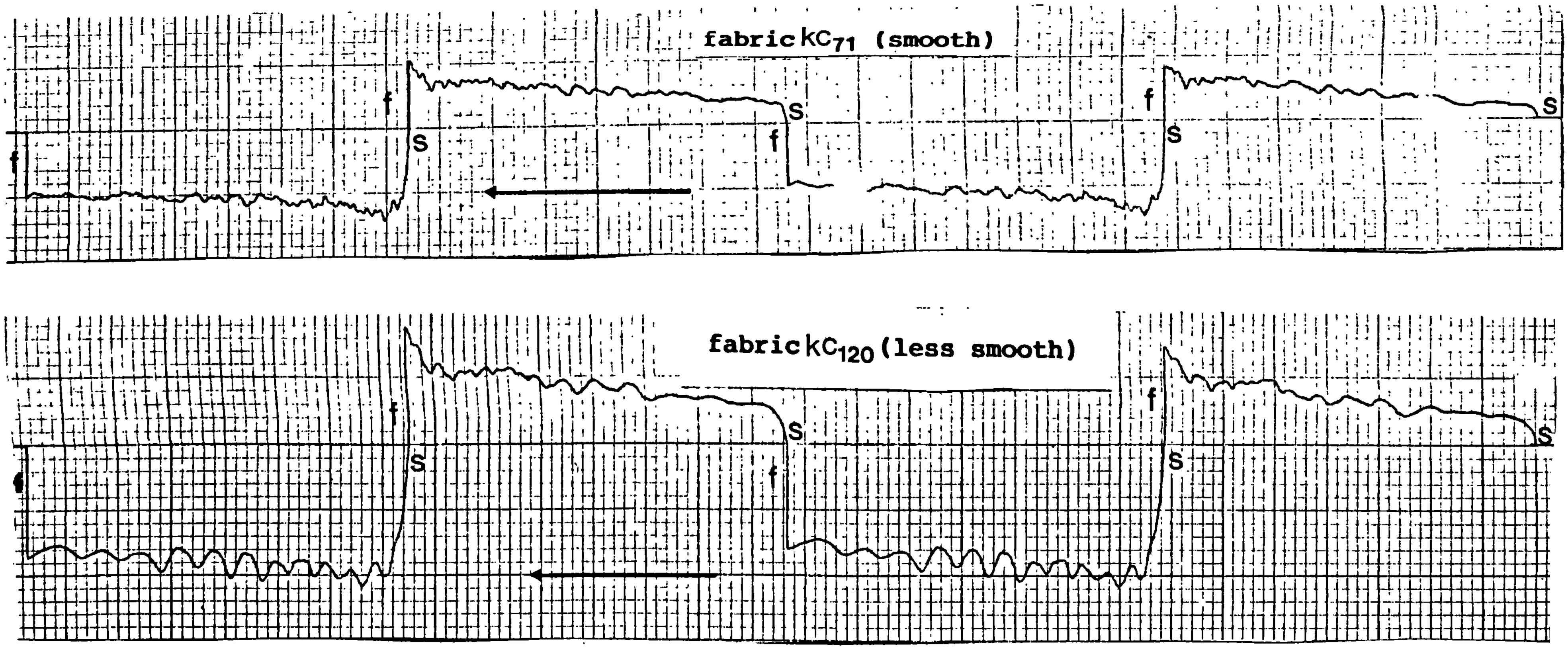


Figure 6.3(b)

Typical roller traces of knitted fabrics (Case 4)

Arrows indicate direction of displacement of sample

s = starting point, f = finishing point

fabrics (section 3.2.3). In spite of this, these traces represented a valid profile of fabric surfaces.

Two repeats of roller traces are also shown in Figures 6.1 - 6.3. In this case, a repeat consisted of one forward and one backward movement of the roller over the test surface. Thus a repeat corresponded to an upward and a downward movement of the crosshead as stated in Chapter 2. The start of a cycle also corresponded to the finish of the previous one.

A closer examination of the roller traces will show a slight inclination to the horizontal. This effect is associated with the geometry of the Instron linkage, i.e. point of attachment of the arm to the cross-head. An analysis of this is given in Appendix 2. Despite this angular function, it is considered that these traces represented a valid profile of fabric surfaces.

The surface contour of a fabric has been defined as the divergence of fabric surfaces from planeness(2,56). Quantitatively, surface irregularities may be expressed as the number of peaks, amplitude of pulses, and standard deviation of the pulses(56,73). These parameters were determined from the roller and stylus traces in the same manner as those of friction traces, and these are shown in Tables 6.1 - 6.3. From the consideration of Case 1, it was shown that frictional derivatives such as number of peaks, amplitude and resistance are readily identifiable with structural factors such as sett, cords and ribs.

It was therefore decided that a further consideration of Cases 2 - 4 inclusive would be useful. Cases 1 and 5 were omitted for reasons stated earlier.

6.2.1 CASE 2: PLAIN WEAVE FABRICS

The plain weave fabrics with alternate raised and sunk yarn profiles may be expected to cause the probes (roller and stylus) to be caught (raised) and released (lowered) appropriately. A glance at Table 6.1 will show an increase in the number of stylus pulses along the warp. The number of pulses along the weft remains approximately constant. These results are expected from the structural factors in which the density of weft sett was increased while the warp yarn sett was kept constant. These results also confirm earlier assumptions (section 3.3.2), namely: that motion of a sled along the warp direction indicated that the probe crossed the transverse weft threads.

In the case of the roller, a different result was obtained. The number of pulses diminished initially and then increased again as the density of weft sett increased. Perhaps the wider yarn spacing at lower sett, i.e. fabric C_6 allowed a better discrimination than at higher sett, but it is equally likely that more yarns lay under the roller as yarn sett increased.

Some changes occurred in the amplitude and standard deviation of the peaks which were not entirely consist-

Table 6.1

Surface contour parameters of the plain weave cotton fabrics (Case 2)

Fabric* Code	Stylus			Roller		
	1	2	3	1	2	3
C_6 P	45	2.3	2.5	30	2.8	0.8
T	38	2.0	3.2	30	1.9	0.5
C_7 P	56	2.0	1.2	23	2.5	0.5
T	37	2.1	1.2	30	2.1	0.4
C_8 P	59	0.8	1.3	19	3.2	1.4
T	38	0.9	1.2	29	2.6	0.6
C_9 P	66	0.6	1.2	18	3.1	1.0
T	37	0.5	0.9	31	1.9	0.7
C_{10} P	70	0.4	1.1	22	2.7	0.8
T	38	0.2	0.9	29	2.5	1.1

* Fabric details in Table 2.3

1 Number of peaks/5cm

2 Amplitude

3 Standard deviation

ent with changes in yarn crimp and linear density. A similar result was obtained for the amplitude of frictional resistance. Probably the differences in crown height (0.12 - 0.16mm for fabric C_6, and 0.05 - 0.06mm for fabric C_{10}) are not sufficiently great to produce any appreciable difference in amplitude. Thus the judgement of smoothness or roughness of these fabrics would be based on yarn sett (number of peaks) rather than the relative height (amplitude) of irregularities.

6.2.2 CASE 3: WEFT PILE FABRICS

Reference to Table 6.2 will show the surface contour (irregularity) parameters of a set of weft pile cotton fabrics (Case 3). The objective here was to demonstrate the relation between a systematic variation in surface characteristics such as cord height, width and spacing, and surface contour parameters.

As postulated, a reasonable agreement existed between the methods (stylus and roller) in terms of number of peaks. A comparison of these results with the number of stick-slip peaks in friction traces (section 4.3.2), and the number of cords estimated from the microscope shows a good agreement (Figure 6.4). The size of cords and their spacing must have enhanced accurate detection by all methods. In view of this excellent correlation, it may be concluded at this stage that the number of peaks is a useful indicator for structural characteris-

Table 6.2

Surface contour parameters of weft pile fabrics

Fabric Code*	Stylus			Roller		
	1	2	3	4	5	6
C_{12}	15	0.8	0.3	14	1.1	0.6
C_{13}	30	1.4	0.7	32	2.2	0.4
C_{14}	20	3.1	1.1	19	7.5	1.2
C_{15}	15	11.7	1.6	15	9.9	1.3
C_{16}	8	6.8	2.0	8	6.3	1.4

* Fabric details in Table 2.4

1 Number of peaks/5cm

2 Amplitude (gf)

3 Standard deviation of peaks

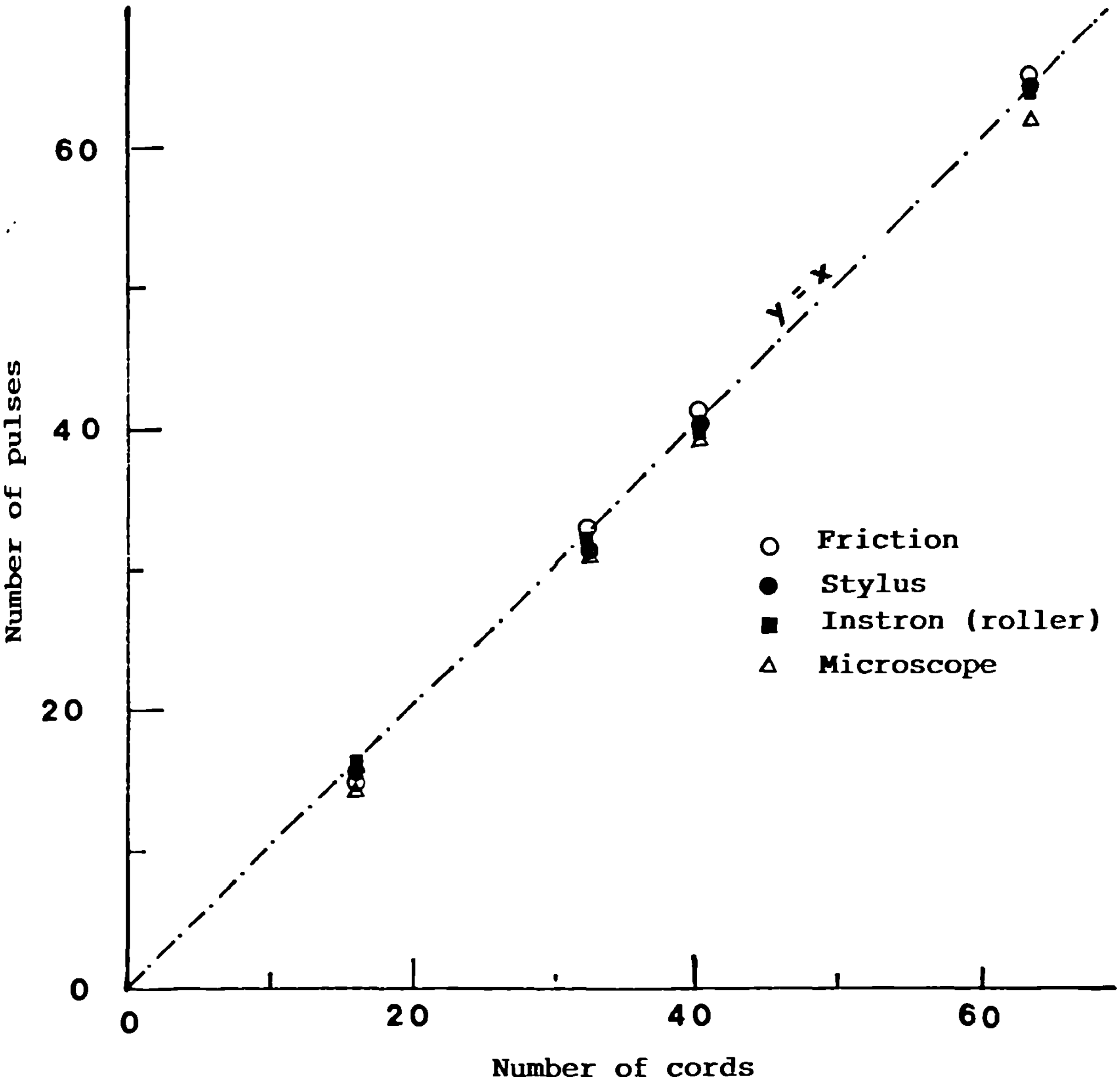


Fig. 6·4

Relationship between the number of "stick-slip" friction trace and number of cords detected by stylus, roller and projection microscope ation of fabrics.

Similarly, an increase in cord height and width caused a significant increase in the amplitude and pitch (i.e. the reciprocal of the number of peaks). The standard deviation of peaks also increased slightly.

If it is assumed for the moment that the deeper and larger the ridge (cord) the rougher the texture (this is demonstrated in section 6.5.2) then fabrics such as C_{13} which had the greatest number of peaks, but lower amplitude and standard deviation, should be considered smoother than fabric C_{16}. A similar result was obtained for frictional resistance, amplitude and the number of stick-slip peaks in frictional trace. A comparison of the previous friction traces in Figure 4.7, and those of the stylus and roller traces (Figures 6.2 (a) and (b)), will show a broad similarity.

On the basis of these results, the corduroys may be ranked from smoothest to roughest as follows: C_{13}, C_{14}, C_{15}, C_{16}. The plane face velveteen was omitted in this consideration as this did not fall within the category of ridginess, but felt smoother than any fabric within the group. These rankings agree broadly with the ranking of lateral air flow in Table 6.5, and the classification of surfaces by microscopic appearance.

6.2.3 CASE 4: KNITTED FABRICS

Three fabrics, namely cotton, wool and acrylic, knitted into plain and rib structures as stated earlier, were employed. The objective was to demonstrate the influence of fabric structure and fibre content on surface contour parameters measured by the roller and stylus.

Several problems were encountered with these knitted fabrics. The stylus tended to penetrate the relatively looser and softer structure especially the wools and acrylics, resulting in snagging and consequently higher amplitude and pitch and might be expected. Similarly the heavier mass of the roller produced compression and a "bow wave" effect which caused some assymetry during the forward and backward reciprocation of the roller.

In spite of these problems, the number of peaks in the series of plain knitted fabrics (KC_{71}, KW_{71} and KA_{71}) is significantly higher than those of the rib knitted structure (KC_{120}, KW_{120} and KA_{120}). A similar result was also found for friction measurements. Again, similar to the friction results the changes in amplitude and standard deviation of peaks of the roller and stylus traces were not very consistent with structural variations. As stated earlier, one possible reason for this is the effect of hairiness of these fabrics.

A comparison of Cases 2, 3 and 4 will reveal a broad agreement with the results of friction measurements. As far as Case 2 (C_6 - C_{10}) is concerned, the number of

Table 6.3

Surface contour parameters of knitted fabrics

Fabric Code*	Stylus			Roller		
	1	2	3	1	2	3
KC_{71}	35	4.0	1.1	24	3.1	0.8
KC_{120}	16	3.2	0.6	19	3.8	0.7
KW_{71}	33	2.1	0.8	20	2.9	0.5
KW_{120}	12	4.0	1.8	19	3.4	0.4
KA_{71}	35	1.4	1.2	25	2.5	0.9
KA_{120}	18	3.3	1.6	20	3.6	1.2

* Fabric details in Table 2.5

1 Number of peaks/5cm

2 Amplitude

3 Standard deviation of peaks

peaks, particularly along the warp direction, is deemed to be a common factor between the methods. The weft pile fabrics (C_{13} - C_{16}) Case 3 provided an interesting result in which the number of peaks, and amplitude of friction, roller and stylus show clear relationships with fabric structure. The inconsistencies in the results of the objective measurements of the knitted structures were probably due to some variations in fabric surfaces such as hairiness, loop size, etc., rather than any extraneous effect in the methods of measurements. It will be interesting to see whether other methods such as lateral air flow would give a more positive discrimination than the objective measurements considered in this section.

6.3 LATERAL AIR FLOW

The rate of air flowing laterally across the surface of a fabric specimen sandwiched between two flat plates depends upon the deflection of the latter by the surface irregularities on the fabric. The greater the rate of air flow, the more irregular and rougher the suface.

An examination of the data in Table 6.4 will reveal that a thinner, planer, and more even surface such as fabric C_2 offered a higher resistance (low rate of air flow) to the passage of air than a relatively thicker, hairier and more irregular fabric such as W_2. In the

Table 6.4

Lateral air flow of fabrics

Case 1		Case 2		Case 3		Case 4	
Code*	LAF**	Code*	LAF**	Code*	LAF**	Code*	LAF**
C_2	11	C_6	6	C_{12}	17	KC_{71}	10
C_3	16	C_7	7	C_{13}	27	KC_{120}	19
W_1	27	C_8	9	C_{14}	32	KW_{71}	25
W_2	76	C_9	11	C_{15}	36	KW_{120}	49
W_6	13	C_{10}	8	C_{16}	41	KA_{71}	34
C_{11}	19	-	-	-	-	KA_{120}	52

* Fabric Code see Chapter 2 (Section 2.2)

** LAF = lateral air flow (cm^3/s)

case of woven fabrics (Case 2), i.e. C_6 - C_{10}, the lateral air flow increased slightly then diminished as the density of yarn sett increased. The initial increase may be due to the systematic increase in yarn crimp, and as the surface became more even, i.e. fabric C_{10}, the lateral air flow declined. The weft pile cotton fabrics C_{12} - C_{13} (Case 3) show consistent increase in the rate of air flow as the height, spacing and width of cords increased. A similar result was obtained when the plain and rib knitted fabrics were compared. Accordingly, fabrics such as C_{13} with a lower rate of air flow may be regarded as smoother than fabrics such as C_{16} with higher rate of flow. Similarly the KC_{71}, KW_{71} and KA_{71} with relatively lower rates of air flow are smoother than their equivalent KC_{120}, KW_{120} and KA_{120} series, see Table 6.5.

Within the knitted fabric structure area, cotton fabrics gave relatively lower rates of flow than acrylic and wool fabrics. A glance at Table 6.4, and comparing like with like, i.e. plain with plain and rib with rib, will reveal that the wool fabrics were intermediate between cotton and acrylic fabrics. A similar frictional behaviour was also reported in Section 4.4. The fluffiness of the acrylic fabrics must be responsible for their higher rate of air flow. In spite of the higher rate of lateral air flow, and contrary to expectation, the acrylic fabrics actually felt smoother.

Finally, a comment about fabric W_2 (Table 6.4),

Table 6.5

Classification of fabric surfaces according to lateral air flow

Surface Characteristics	Smooth	LAF*	Rough	LAF*
Hairiness ($W_2 > C_2$)	C_2	lower	W_2	higher
Weave (C_3 = twill, W_1 = plain)	W_1	lower	C_3	higher
Sett ($C_{10} > C_6$)	C_{10}	higher	C_6	lower
Ridge (C_{12} = plane, C_{14} ridged)	C_{12}	lower	C_{14}	higher
Cord (C_{16} = deeper ridge than C_{13})	C_{13}	lower	C_{16}	higher
Rib (KC_{120} = greater size of rib than KC_{71})	KC_{71}	lower	KC120	higher
Fluffiness (KA > KC)	KA_{71}	higher	KC_{71}	lower
	KA_{120}		KC_{120}	
Flatness ($C_2 > C_{11}$)	C_2	lower	C_{11}	higher

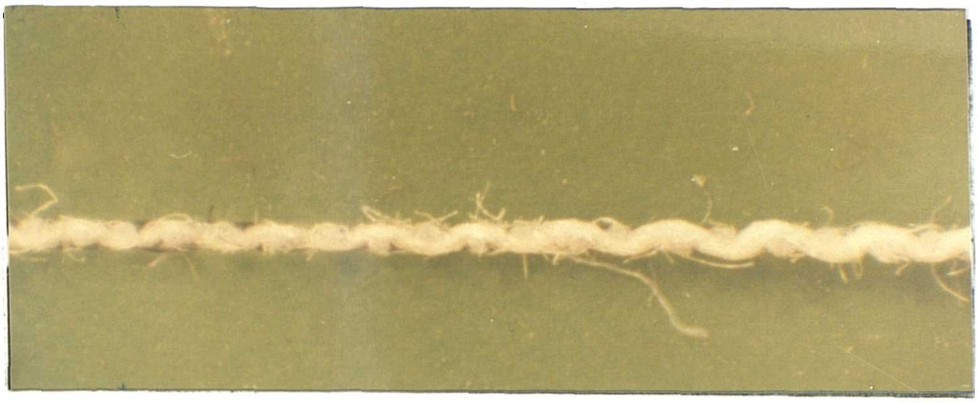
*LAF = lateral air flow

with the highest rate of air flow, this fabric was not necessarily the roughest. The surface hairiness coupled with a lower yarn sett (porosity), might have enhanced the lateral air flow. A classification of fabric texture (smooth or rough) on the basis of their air flow (Table 6.5) and on the handle (see rank order of subjective assessments in Table 6.12) is given in Table 6.5. It is apparent that thinner fabrics C_2, W_1, C_{12} and K_{71} series are respectively planer and smoother than thicker fabrics W_2 or C_{11}, C_3, C_{14}, C_{16} and K_{120} series.

6.4 MICROSCOPIC APPEARANCE

Apart from the use of this technique in the estimation of structural parameters such as crown height in plain weave fabrics, and cord height and width in weft pile fabrics, some qualitative information on surface characteristics of fabrics such as flatness, ridginess and hairiness could also be verified.

As shown in Plate 7 a cotton limbric fabric C_2 is thinner, planer, lighter and perhaps less hairy than a canvas (C_{11}). Tactually, the canvas was rougher and coarser than the limbric. Another example is given in Plate 8, whereby a velveteen (C_{12}) and a corduroy (C_{14}) were compared. It can be seen that although the base weaves of both fabrics were effectively concealed by the fibre pile, the corduroy felt more ridgy and hence rougher than the velveteen. Similarly, a comparison



(a) Smooth (limbric) fabric C_2

(b) Rough (canvas) fabric C_{11}

Plate 7

Examples of smooth (fabric C_2) and rough (fabric C_{11}) surfaces

(a) Smooth (velveteen)

(b) Less smooth (corduroy)

Plate 8

Examples of smooth (velveteen) and less smooth (ridged)(corduroy) surfaces

Shallower ridge (smooth)

Deeper ridge (less smooth)

Plate 9

Examples of shallower ridge (smooth)

and deeper ridge (less smooth)

between two corduroys as depicted in Plate 9 will also reveal some significant differences in the size, number and depth of cords. The size and depth are greater in fabric C_{15} and the texture was also rougher and coarser. This kind of roughness appeared to be associated with the ridginess of the corduroys. A further experimental scrutiny of this is given in Section 6.5.2.

Reference to the previous plates 4 and 5 will show that the surface boundaries of fabrics were altered by a systematic increase in the density of weft yarn sett. At higher sett Plates 4 (c) and 5 (c), the surface became planer, more even and smoother than at lower sett. As stated earlier, the differences in colour contrasts between the various plates were due to variations in film preparation and processing.

6.5 ASSESSMENT OF FABRIC HANDLE

6.5.1 PHYSICAL MEASUREMENTS

Apart from the objective measurements of surface properties discussed previously, other mechanical properties such as compression, compressibility, drape coefficient, flexural rigidity, coercive couple, bending length and air permeability are useful in the objective specification of fabric handle. Some of these properties are given in Tables 6.6 - 6.9 inclusive. Reference to Table 6.6 will show that the thicker, hairier fabric W_2

Legend to Tables 6.6 - 6.9

Co = Coercive couple

Go = Elastic flexural rigidity

Co/Go = Subjective liveliness

D.C = Drape coefficient

A.P = Air permeability

G = Flexural rigidity

C' = Bending length

Table 6.6

Physical properties of fabrics (Case 1)

	Compression		Compressibility		Flexion[1]							A.P[2]
Fabric Code	(mm) 1.9KPa	(mm) 19KPa	(%) 1.9KPa	(%) 19KPa	Co* (dyn.cm/cm) P	T	Go* (dyn.cm²/cm) P	T	Co/Go* (cm^{-1}) P	T	D.C[1] (%)	(cm³/cm²/s)
C_2	0.07	0.14	21	47	32	33	14	16	2.29	2.06	62	50
C_3	0.11	0.20	16	30	300	125	200	130	1.50	0.96	80	55
W_1	0.13	0.28	23	48	16	14	46	32	0.35	0.44	38	67
W_2	0.30	0.80	15	29	55	45	65	60	0.85	0.75	47	319
W_6	0.27	0.78	8	22	-	-	-	-	-	-	99	19
KC_2	0.10	0.26	10	28	41	7	85	11	0.48	0.64	25	-

See legend on page 176

1 = Drape coefficient (%)

2 = Air permeability cm³3cm²/s

Table 6.7

Physical properties of fabrics (Case 2)

	Compression		Compressibility		Flexion							A.P*
Fabric Code	(mm) 1.9KPa	(mm) 19KPa	(%) 1.9KPa	(%) 19KPa	Co* (dyn.cm/cm) P	T	Go* (dyn.cm^2/cm) P	T	Co/Go* (cm^{-1}) P	T	D.C* (%)	(cm^3/cm^2/s)
C_6	0.06	0.15	11	27	63	69	51	31	1.24	2.23	66	314
C_7	0.06	0.13	11	25	80	126	48	48	1.67	2.63	80	224
C_8	0.07	0.14	13	27	95	189	52	75	1.83	2.52	85	216
C_9	0.07	0.14	13	26	123	293	66	121	1.86	2.42	89	118
C_{10}	0.08	0.16	16	29	191	621	108	231	1.77	2.69	91	67

* See legend on page 176

Table 6.8

Physical properties of fabrics (Case 3)

Fabric Code	Compression		Compressibility		Flexion					A.P*
	(mm) 1.9KPa	(mm) 19KPa	(%) 1.9KPa	(%) 19KPa	G* (mg.cm)		C'* (cm)		D.C* (%)	(cm³/cm²/s)
					P	T	P	T		
C_{12}	0.08	0.19	6	15	69	107	1.3	1.5	46	8
C_{13}	0.17	0.37	18	40	311	64	2.4	1.4	66	8
C_{14}	0.20	0.46	18	40	165	46	1.9	1.2	52	23
C_{15}	0.19	0.40	16	34	803	239	2.9	1.9	81	-
C_{16}	0.28	0.59	17	37	702	142	2.6	1.6	71	11

* See legend on page 176

Table 6.9

Physical properties of fabrics (Case 4)

	Compression		Compressibility		Flexion				
Fabric Code	(mm) 1.9KPa	(mm) 19KPa	(%) 1.9KPa	(%) 19KPa	G* (mg.cm)		C'* (cm)		D.C* (%)
					W	C	W	C	
KC_{71}	0.21	0.54	16	40	106	58	1.52	1.2	35
KC_{120}	0.29	0.93	10	32	-	-	-	-	60
KW_{71}	0.32	0.71	22	50	105	59	1.5	1.2	36
KW_{120}	0.43	1.10	12	33	-	-	-	-	74
KA_{71}	0.30	0.77	19	49	51	25	1.4	1.1	36
KA_{120}	0.41	1.25	12	38	-	-	-	-	80

* See legend on page 176

is more compressible than a thinner, planer fabric C_2. Similarly, fabric W_6 is thicker and more compressible than fabric W_1. Elder et al(15) have shown that thicker fabrics are usually more compressible than thinner samples. According to these authors, if fabrics differ compressionally by 0.1mm or less, it is probable that their softness cannot be discriminated between. Similarly, a thinner fabric (W_1) is usually more flexible than a thicker fabric (C_3). As stated earlier, thinner samples are also usually more even and smoother.

A glance at Table 6.7 will show that there was no significant difference between the compressional properties of fabrics C_6 - C_{10}. However, a systematic increase in yarn sett also produced a systematic increase in the stiffness of these fabrics. The air permeability declined as the density of yarn sett increased and as the fabric became less open and more compact.

In the case of the weft pile fabrics (Table 6.8) the changes in the objective parameters of compression, flexion and air permeability are not necessarily consistent. Perhaps these properties are not directly related to structural and surface properties discussed earlier.

Considering the knitted fabrics in Table 6.9, the plain knitted fabrics are less compressible than their equivalent rib knitted structures. This is thought to be due to the relative thickness of the fabrics in which the thinner plain knitted fabrics are less compressible. Flexurally, the drape coefficients of the plain knitted fabrics are very similar and are significantly lower than the rib structures. If a lower value of drape coefficient represents a limp fabric, then a further examination of Table 6.9 will show that within the rib knitted structures the acrylic is stiffer than the cotton, and the wool sample is intermediate between the two structures. It would be seen from the foregoing that small variations in fabric structures produced large changes in some physical properties such as flexion and air permeability. The changes in compresssion are generally small in some fabrics C_6 - C_{10}, and inconsistent in fabrics C_{12} - C_{16}. In spite of these small and sometimes inconsistent changes, good correlations have been reported between fabric compression and softness(15,136), and fabric flexion and stiffness(16-18). This confirmed the statement made earlier.

6.5.2 SUBJECTIVE ASSESSMENTS (SMOOTHNESS)

The methods of subjective assessment are detailed in Chapter 2. The technique of scoring and calculation are exemplified in Appendix 3. The rank order of individual judges for fabrics in Cases 1 - 4 were broadly similar. Therefore in order not to introduce some unwieldy set of tables, only the results of weft pile fabrics are shown as examples to demonstrate the judges' response to changes in terminology. In Table 6.10, the pertinent question was "which fabric is rougher?" and in Table 6.11, the question was "which fabric is deeper ridge?" Clearly the rankings in both cases were the same but the agreements among judges were better in the latter case when the terminology was "deeper ridge".

The final composite rank order of all fabrics (Cases 1 - 4) and the coefficient of concordance, i.e. agreement among judges and the significant levels for both free and controlled handle trials are given in Table 6.12. This shows that there were no significant differences between the free and controlled handle trials, although judgements were fairly rapid and more accurate in the former.

Referring to Table 6.12, the composite rankings of fabric W_1 were lower than fabric W_2, as stated earlier, the hairiness of the latter must have influenced the roughness ascribed to its surface. In the case of woven fabrics C_6 - C_{10}, the free handle was influenced by the systematic increase in the density of yarn sett, and fabric C_{10} was ranked smoother than fabric C_6. Referring to the objective parameters of these fabrics in Table 6.7, a stiffer, more solid, impermeable and less compressible fabric such as C_{10} may be regarded as smoother than a limp, opener, more permeable fabric C_6.

Considering the weft pile fabrics (Table 6.12) the composite rank orders had perfect correlations regardless of the descriptive term used, and also there were statistically significant agreements among judges on both tests. It should be noted however that the level of agreement

Table 6.10

Rank order of judges (roughness test)

Fabric Code / Judges	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
1	1	3	2	5	4
2	1	2	3	5	4
3	1	2	3	4	5
4	1	2	4	5	3
5	1	2	3	4	5
6	1	2	3	4	5
7	1	2	3	5	4
8	1	2	3	4	5
9	1	2	5	4	3
10	1	2	3	5	4
	10 (1)	21 (2)	32 (3)	45 (5)	42 (4)

1 = smooth

5 = rough

Values in parenthesis is composite rank order

Table 6.11

Rank order of judges (deeper ridge test)

Judges \ Fabric Code	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
1	3	2	1	4	5
2	5	1	2	4	3
3	1	2	3	5	4
4	1	2	3	5	4
5	1	2	3	5	4
6	1	2	3	5	4
7	1	2	3	4	5
8	1	2	2	5	2
9	1	2	2	2	5
10	1	2	2	5	2
	16 (1)	22 (2)	27 (3)	45 (5)	40 (4)

1 = shallower ridge

5 = deeper ridge

Values in parenthesis is composite rank order

Table 6.12

Composite rank order of fabrics

Case Study	Composite rank order						W	P
*	C_2	C_3	W_1	W_2	W_6	KC_2		
1	(3)	(5)	(1)	(6)	(3)	(2)	0.82	0.01
	3	5	1	6	2	3	0.80	0.01
*	C_6	C_7	C_8	C_9	C_{10}	-		
2	(5)	(4)	(3)	(2)	(1)	-	0.72	0.05
	5	3	4	2	1	-	0.55	0.05
*	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	-		
	(1)	(2)	(3)	(4)	(5)	-	0.92	0.01
3	1	2	3	5	4	-	0.59	0.05
	$(1)^{++}$	(2)	(3)	(4)	(5)	-	0.98	0.01
	1^{++}	2	3	5	4	-	0.85	0.01
*	KC_{71}	KC_{120}	KW_{71}	KW_{120}	KA_{71}	KA_{120}		
4	(3)	(6)	(2)	(5)	(1)	(4)	0.66	0.05
	3	3	2	5	1	5	0.68	0.05

* See fabric details in Chapter 2

1 = smooth, 5 or 6 = rough

$^{++}$1 = shallow ridge 5 = deeper ridge

values in parenthesis = free handle (visual + tactual)

W = coefficient of concordance } See Appendix 3

P = significant level }

was not as good when the descriptive term "rough" was used All judges could differentiate between the pairs of fabrics and found them easily identifiable. This is confirmed by the fact that there were no tied ranks in Table 6.11. The same is not true in Table 6.10 where the descriptive term was "rough". Three of the judges found three of the fabrics indistinguishable on that dimension. This suggested that in subjective tests of surface feel the basic terms "rough" and "smooth" are likely to be inadequate as descriptive terms. As stated earlier, and a glance at Table 4.3 (in Chapter 4) will show that the number of peaks and amplitude of resistance are the best objective indicators of the surface characteristics. With this particular set of fabrics, the use of the terminology "deeper ridge" overcame some of the problems but was not totally successful as can be seen from the confusion of judgements on fabrics C_{15} and C_{16}. Referring to fabric details in Table 2.4, fabric C_{16} had a broader, flatter and double ridge, so that the judges were not in agreement on whether this fabric was broader and deeper or broader and flatter than fabric C_{15}. It may be concluded at this stage that there were no problems in subjectively distinguishing the differences between fabrics by touch but there were difficulties in finding a suitable descriptive label for these differences.

6.5.3 ADAPTED SIGNAL DETECTION TESTS FOR FINISHED FABRICS

In order to relate the magnitude of changes in frictional properties of finished fabrics to the changes in subjective assessment such as smoothness or roughness, the normal approximation to the binomial was used.

$$\text{Formula } z = \frac{(X \pm 0.5) - N'P}{\sqrt{N'PQ}}$$

where X = total correct answers

N' = number of paired samples

P = the probability that subjects are guessing (in this case 0.5)

Q = 1 - P

The correction factors of 0.5 were used, i.e.

$+0.5$ when $X<N'P$

-0.5 when $X>N'P$

Experimentally, the task was to determine whether judges could feel any surface changes between treated and untreated fabrics. The judges were presented with two samples, and were asked to declare whether these were the "same" or "different". Each judge had to give decisions on 50 pairs of samples. In 25 pairs, the fabrics were the same, i.e. untreated with untreated, and 25 pairs were untreated with treated. This was to counteract any tendency to declare "different" whether a difference was genuinely felt or not. A pillory box was used so that decisions were based on touch only. The procedure was similar to the paired comparison as given in Appendix 3.

By setting out the results in the form of a table as shown in Tables 6.13 and 6.14 , a check can be kept on the surface feel of the untreated fabric.

An examination of the results in Tables 6.13 and 6.14 show identical trends in which the figure in the "true difference" column is higher than others in most cases. If the composite figure in the box "false difference" had been unacceptably high, it would have indicated a poor quality control in the original fabric. At an individual level, a high total in this box would indicate a judge who was merely guessing.

A comparison of these results with the magnitude of changes in kinetic frictional resistance (Tables 6.13 and 6.14) shows that the levels of discrimination were higher in lubricated and roughened fabrics. The results show clearly discerned differences between treated and untreated surfaces. What is also shown and may surprise is the high level of discrimination between the scoured sample and the original state, and between the softened fabric and the original state when in fact the changes in frictional resistance were only about ±6%. It is likely that judges responded to other stimuli such as softness when the difference in smoothness between fabrics was not obvious.

Table 6.13

Adapted signal detection tests of finished woven fabric C_2

	Diff +	Same −		
(a) Scoured (Teepol)	230 N/S*	218 N/N	True	$\frac{448}{500}$ = 89.6%
	52 N/N	- N/S	False	

	Diff +	Same −		
(b) Mercerised (Caustic Soda)	186 N/S	205 N/N	True	$\frac{391}{500}$ = 78.2%
	63 N/S	46 N/S	False	

	Diff +	Same −		
(c) Softened (Softlan)	160 N/S	110 N/N	True	$\frac{270}{500}$ = 54%
	120 N/N	106 N/S	False	

	Diff +	Same −		
(d) Lubricated (PEG 1000)	368 N/S	110 N/N	True	$\frac{478}{500}$ = 95.6%
	20 N/N	2 N/S	False	

* N = untreated (original sample)

S = treated (finished sample)

Table 6.13 (contd)

	Diff +	Same −		
(e) Lubricated (PEG 4000)	250 N/S	145 N/N	True	$\frac{395}{500}$ = 79%
	65 N/N	40 N/S	False	

	Diff +	Same −		
(f) Lubricated (PEG 6000)	135 N/S	172 N/N	True	$\frac{307}{500}$ = 61.4%
	155 N/N	38 N/S	False	

	Diff +	Same −		
(g) Roughened (Syton)	410 N/S	43 N/N	True	$\frac{453}{500}$ = 90.6%
	29 N/N	18 N/S	False	

	Diff +	Same −		
* Roughened (Raising)	226 N/S	209 N/N	True	$\frac{435}{500}$ = 87.0%
	41 N/N	24 N/S	False	

* Fabric C_{11}

Table 6.14

Adapted signal detection tests of finished knitted cotton fabric (KC_2)

	Diff +	Same -		
(a) Scoured (Teepol)	176 N/S	228 N/N	True	$\frac{404}{500}$ = 80.8%
	74 N/N	22 N/S	False	

	Diff +	Same -		
(b) Mercerised (Caustic Soda)	125 N/S	287 N/N	True	$\frac{412}{500}$ = 82.4%
	76 N/N	12 N/S	False	

	Diff +	Same -		
(c) Softened (Soflan)	195 N/S	200 N/N	True	$\frac{395}{500}$ = 79%
	78 N/N	27 N/S	False	

	Diff +	Same -		
(d) Lubricated (PEG 1000)	421 N/S	70 N/N	True	$\frac{491}{500}$ = 98.2%
	9 N/N	- N/S	False	

Table 6.14 (contd)

	Diff +	Same −		
(e) Lubricated (PEG 4000)	286 N/S	174 N/N	True	$\frac{460}{500} = 92\%$
	− N/N	40 N/S	False	

	Diff +	Same −		
(f) Lubricated (PEG 6000)	144 N/S	155 N/N	True	$\frac{299}{500} = 59.8\%$
	159 N/N	42 N/S	False	

	Diff +	Same −		
(h) Roughened (Syton)	435 N/S	24 N/N	True	$\frac{459}{500} = 91.8\%$
	33 N/N	8 N/S	False	

Table 6.15

Comparisons of the magnitude of changes in frictional resistance and correct discrimination between the original and finished fabrics (C_2)

Finishing Treatments	% change[+] in kinetic frictional force			Significance Level	
		% Correct Decision	z*	0.05	0.01
Scoured	+6	89.6	17.7	✓	✓
Mercerised	+27	78.2	12.6	✓	✓
Softened	-6	54.0	1.7	✓	X
Lubricated					
(PEG 1000)	-35	95.6	20.3	✓	✓
(PEG 4000)	-25	79.0	12.9	✓	✓
(PEG 6000)	-10	61.4	5.1	✓	✓
Roughened					
(Syton)	+63	90.6	18.1	✓	✓
(Raising[++])	+61	87.0	16.5	✓	✓

[+] Changes in frictional property of finished fabric with respect to the original state

[++] Treated for 5 min.

✓ Significant

X Not significant

* Values above 1.65: Significant at 0.05 level

* Values above 2.33: Significant at 0.01 level

Table 6.16

Comparisons of the magnitude of changes in frictional resistance and correct discrimination between the original and finished fabrics (KC_2)

Finishing Treatments	(%) change+ in kinetic frictional force			Significance Level	
		% Correct Decision	z*	0.05	0.01
Scoured	+15	80.8	13.7	✓	✓
Mercerised	+55	82.4	14.5	✓	✓
Softened	+2	79.0	13.0	✓	✓
Lubricated					
(PEG 1000)	-45	98.2	21.5	✓	✓
(PEG 4000)	-42	92.0	11.7	✓	✓
(PEG 6000)	-31	59.8	4.3	✓	✓
Roughened					
(Syton)	+118	91.8	18.7	✓	✓

+ Change in frictional property of finished fabric with respect to the original state

✓ significant

* Values above 2.33: Significant at 0.01 level

6.5.4 SUBJECTIVE ASSESSMENT - OBJECTIVE MEASUREMENT

Subjectively, the judgement of fabric handle such as smoothness or roughness, according to Elder(14) and Stockbridge et al(119), was influenced by the sensations of irregularities caused when minute indentations were felt as the skin was pressed. It has been shown in the previous sections that these irregularities are readily identifiable with fabric structures such as yarn sett, cords or ribs, fibre content, i.e. cotton, wool, and acrylic, and the type of finishing treatments used in each case.

Objectively, these irregularities could be monitored by friction, roller and stylus probes. Similarly since the lateral air flow is regarded as an indicator of surface irregularities, in which an increase in the rate of flow usually indicates a roughening of fabric surface, and a decrease would imply a smoothing or laying down of the surface asperities(10). A correlation between objective and subjective assessment would be expected.

The composite rank order of judges for all fabrics is shown in Table 6.12. The rank order of objective measurements is shown in Tables 6.17 - 6.19 inclusive. Correlations were carried out using the Spearman's rank correlation coefficient as exemplified in Appendix 3.

$$\text{Formula } r_s = \frac{1 - 6\Sigma d^2}{N(N^2-1)}$$

where r_s = Spearman's rank correlation coefficient

d = difference between two ranks

N = Number of fabrics ranked.

The results are shown in Tables 6.20 and 6.21.

Reference to Table 6.20 will show that a good correlation existed between fabric smoothness and number of peaks as determined by friction, roller and stylus. This is positive in the case of friction and stylus, that is fabrics with fewer number of peaks are rougher, but negative in the case of the roller, that is fabrics with fewer number of peaks are smoother. As stated earlier, the latter results may be ascribed to the increase in the number of yarns that lay under the roller as sett was increased. Also, the frictional resistance and coefficient of friction are all negatively correlated with fabric smoothness. A poor and negative correlation was obtained between fabric smoothness and other frictional parameters such as F_A, F_S-F_K.

As shown in Table 6.21, a perfect negative correlation was found between the number of peaks and fabric smoothness. A perfect and positive correlation was found between fabric smoothness, amplitude of frictional resistance and lateral air flow, this result was expected. Surprisingly, there was no correlation at all between the coefficient of friction, frictional resistance, and fabric smoothness. Perhaps the reason was due to the confusion between surface characteristics and the descriptive term-

Legend to Table 6.17 - 6.21

μ_K = Kinetic coefficient of friction

F_K = Kinetic frictional resistance (gf)

F_N = Number of peaks/5cm in friction traces

F_A = Amplitude of frictional resistance

F_S-F_K = Difference between the static and kinetic frictional resistances

R_N = Number of peaks/5cm in roller trace

R_A = Amplitude of roller pulses

R_δ = Standard deviation of roller pulses

S_N = Number of peaks/5cm in stylus trace

S_δ = Standard deviation of stylus pulses

LAF = Lateral air flow

SS = Subjective smoothness

Table 6.17

Rank order of objective measurements of woven cotton fabrics (Case 2)

Fabric Code	μ_K	F_K	F_N	F_A	F_S-F_K	R_N	R_A	R_δ	S_N	S_A	S_δ	LAF
C_6	1	1	1	4	1	5	5	5	1	1	2	1
C_7	2	2	2	1	4	4	4	3	2	2	1	2
C_8	3	3	3	1	5	3	3	4	3	5	5	4
C_9	4	4	4	1	3	2	2	2	4	3	3	5
C_{10}	5	5	5	5	1	1	1	1	5	4	4	3

1 = lowest value

5 = highest value

Table 6.18

Rank order of objective measurements of weft pile cotton fabrics (Case 3)

Fabric Code	μ_K	F_K	F_N	F_A	F_S-F_K	R_N	R_A	R_δ	S_N	S_A	S_δ	LAF
C_{12}	5	5	5	1	1	2	1	2	2	1	1	1
C_{13}	1	1	4	2	2	5	2	1	5	2	2	2
C_{14}	2	2	3	3	3	4	4	3	4	3	3	3
C_{15}	3	3	2	4	3	3	5	4	2	5	4	4
C_{16}	4	4	1	5	5	1	3	5	1	4	5	5

1 = lowest value

5 = highest value

Table 6.19

Rank order of objective parameters of finished fabrics

Finishing* Treatments	Knitted fabric (KC_2)							Woven fabric (C_2)						
	μ_S	μ_K	F_S	F_K	F_A	F_S-F_K	LAF	μ_S	μ_K	F_S	F_K	F_A	F_S-F_K	LAF
Scoured	3	3	3	3	3	2	2	3	3	3	3	3	3	2
Mercerised	4	4	4	4	4	4	4	4	4	4	4	4	3	4
Softened**	2	2	2	2	2	3	4	2	2	2	2	2	2	4
Lubricated***	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Syton	5	5	5	5	5	5	2	5	5	5	5	5	5	2

* See details of finishing treatments in Section 2.4

** Softlan

*** Polyethylene glycol 1000

1 = lowest value

2 = highest value

Table 6.20

Correlations of objective with subjective properties (Woven fabric Case 2)

	μ_K	F_K	F_N	F_A	F_S-F_K	R_N	R_A	R_δ	S_N	S_A	S_δ	LAF	SS
μ_K*	-												
F_K	1.00	-											
F_N	1.00	1.00	-										
F_A	-0.15	-0.15	-0.15	-									
$F_{S-\ K}$	-0.25	-0.25	-0.25	1.70	-								
R_N	-1.00	-1.00	-1.00	0.55	-0.05	-							
R_A	-1.00	-1.00	-1.00	0.55	-0.05	1.00	-						
R_δ	-0.90	-0.90	-0.90	0.55	0.05	0.90	0.90	-					
S_N	1.00	1.00	1.00	0.15	-0.25	-1.00	-1.00	-0.40	-				
S_A	0.70	0.70	0.70	0.55	0.35	0.55	-0.20	-0.40	0.70	-			
S_δ	0.70	0.70	0.70	0.25	0.35	-0.60	-0.50	-0.20	0.60	0.90	-		
LAF	0.60	0.60	0.60	-0.95	0.35	-0.70	-0.70	0.50	0.70	0.70	0.60	-	
SS	-0.90	-0.90	-0.90	-0.15	-0.10	0.90	0.90	-0.50	-0.90	-0.20	-0.20	-0.50	-

* See legend on page **198**

Table 6.21

Correlations of objective with subjective properties (Weft pile cotton fabric Case 3)

	μ_K	F_K	F_N	F_A	F_S-F_K	R_N	R_A	R_δ	S_N	S_A	S_δ	LAF	SS
μ_K*	-												
F_K	1.00	-											
F_N	1.00	1.00	-										
F_A	1.00	1.00	-1.00	-									
F_S-F_K	-1.00	1.00	-0.85	0.95	-								
R_N	-1.00	1.00	0.40	-0.45	-0.35	-							
R_A	-0.30	0.30	-0.15	0.70	0.55	0.10	-						
R_δ	0.40	0.40	-0.90	0.90	0.85	-0.70	0.60	-					
S_N	-0.95	-0.95	0.45	-0.60	-0.40	0.95	-0.15	-0.85	-				
S_A	1.00	1.00	-0.90	0.90	0.75	-0.20	0.90	0.80	-0.55	-			
S_δ	1.00	1.00	-1.00	1.00	0.95	-0.05	0.70	0.90	-0.45	0.90	-		
LAF	1.00	1.00	1.00	1.00	0.95	-0.60	0.70	0.90	-0.45	0.90	1.00	-	
SS	0.00	0.00	-1.00	1.00	0.95	-0.60	0.70	0.90	-0.45	0.90	1.00	1.00	-

* See legend on page **198**

inology, but the inclusion of a plane face velveteen might have further complicated the situation.

From the results obtained so far, it is apparent that the number of peaks in the friction, roller and stylus traces is the best indicator of fabric smoothness or roughness. The number of peaks is usually but not always negatively correlated with the fabric smoothness.

6.6 CONCLUSIONS

1. The roller, stylus and friction traces of fabrics represent a valid profile of their surface characteristics. In weft pile fabrics, for example, where the cord profiles are distinct, an excellent agreement exists between the methods. This agreement is less perfect in woven fabrics particularly at higher sett, and is very poor in knitted fabrics.
2. The number of peaks is a better indicator of surface irregularity measurement. This quantity is negatively related to fabric smoothness. That is fabrics which yield more number of peaks in the friction, roller and stylus traces are usually smoother than those with fewer number of peaks.
3. The lateral air flow across the surface of fabrics may be used to classify their surface irregularities. Thin samples usually yield lower rates of flow than thicker fabrics, and the former are usually classified as smoother fabrics. The results agree broadly with the friction,

stylus and roller results.

4. Subjectively, there are no problems distinguishing the differences between fabrics by touch, and whether seen or unseen, but there were difficulties finding a suitable descriptive label for these differences.

5. A limit of discrimination is known to exist in certain subjective assessments such as softness. For example, when two fabrics differ compressionally by 0.05 - 0.1mm, judges are unlikely to discern between their softness.(15) If it is accepted for the moment, and until further evidence is available that the adapted signal detection paired comparison is a valid method of comparing the differences between finished fabrics, then if the difference between the frictional resistances (kinetic) of two fabrics is less than 10gf, or 6%, whichever is greater, it is unlikely that judges would be able to detect any difference in smoothness between them.

CHAPTER 7

CONCLUSIONS

The general conclusions reached in the present work are as follows.

1. The frictional properties of fabrics are sensitive to variations in fibre content, fabric structure and type of finishing treatments used in each case, as well as the experimental conditions.

A tenfold increase in normal pressure produces a decrease of between -50 to -80% in coefficient of friction and between -20 to -100% in the number of peaks. The increase in frictional resistance may be up to +500%. The amplitude may increase by +30 to +300%. Similarly, the influence of velocity of sled, number of traverses and nature of sled surface may be appreciable.

2. Under a constant experimental condition, a twofold increase in the weft yarn sett of a plain weave fabric is accompanied by a similar magnitude of change in yarn crimp, produces an increase of 65% in the trace peaks, a moderate increase in frictional resistance for example 15-37%, with little or no change in the amplitude of resistance.

3. The amplitude of frictional resistance and the numbers of peaks in the stick-slip motion are distinctly related to fabric structure, i.e. height and number of cords in pile fabrics respectively. The amplitude of resistance range between 1 - 37gf and is generally about ten times that of plain weave fabrics. The frictional resistance range between 66 - 160gf and is about two to

four times that of plain weave fabrics.

4. The frictional properties of knitted fabrics are related to those of their component yarns. The coefficient of friction of fabrics is about three times greater than those of their component yarns. Depending on the method of measurement, the coefficient of friction of yarns measured on the capstan (cylindrical surface) is almost twice those obtained on the linear friction meter (flat surface). Despite the very significant differences in fabric geometry, the friction traces of a woven and a knitted fabric may be remarkably similar.

5. Finishing treatments such as polyethylene glycol condensate which reduces frictional properties (frictional resistance, amplitude, and differences between statics and kinetic frictional forces) by about -40% also yield smoother handle. Conversely, deposits of silica particles on fibre substrates produce large increase +100% in frictional properties, accordingly the handle of the fabric is rougher.

6. In view of the diverse nature of fabric surfaces and finishing treatments, a wide range of frictional properties is obtained in the present work. For example, coefficient of friction 0.50 - 6.08, frictional resistance 30 - 160gf, amplitude 0 - 40gf, number of peaks 0 - 60 peaks/5 cm, and the difference between the static and kinetic frictional forces 0 - 30gf. Because of these variations, the use of a single valued function such as the coefficient of friction as the sole index of quality,

for example, degrees of smoothness or roughness is likely to be inadequate. This supports Dreby's(13) findings.

7. Apart from the conventional friction measurements, surface irregularity measurements by roller, stylus, lateral air flow and microscopic examination provide useful information on surface topography and fabric texture. Given the characteristic roller and stylus traces of woven, knitted and pile fabrics, a positive identification of fabrics is possible. For this reason the roller and stylus probes are considered more useful than the conventional friction measurements.

8. Subjectively, the frictional feel of fabrics may be readily identifiable as far as changes in fibre content, fabric structure and some finishing treatments are concerned. However, finding suitable descriptive labels for these differences remains a problem. For example, there are likely to be differences of opinion on whether a handle is smoother or more slippery, rougher or harsher.

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APPENDIX 1

GEOMETRICAL ANALYSIS OF A PLAIN WEAVE FABRIC STRUCTURE

(a) CROWN HEIGHT

The models of fabric-on-fabric (woven) contact for warp-over-warp and weft-over-weft motion are shown in Figures 1(a) and (b) respectively. A tangent to the weft yarn crown (XX^1) was taken as an arbitrary plane of the fabric. The protrusion of the yarn crown (warp) from the plane of the fabric is depicted by the hatched portion (see Figures 1 (a) and (b)).

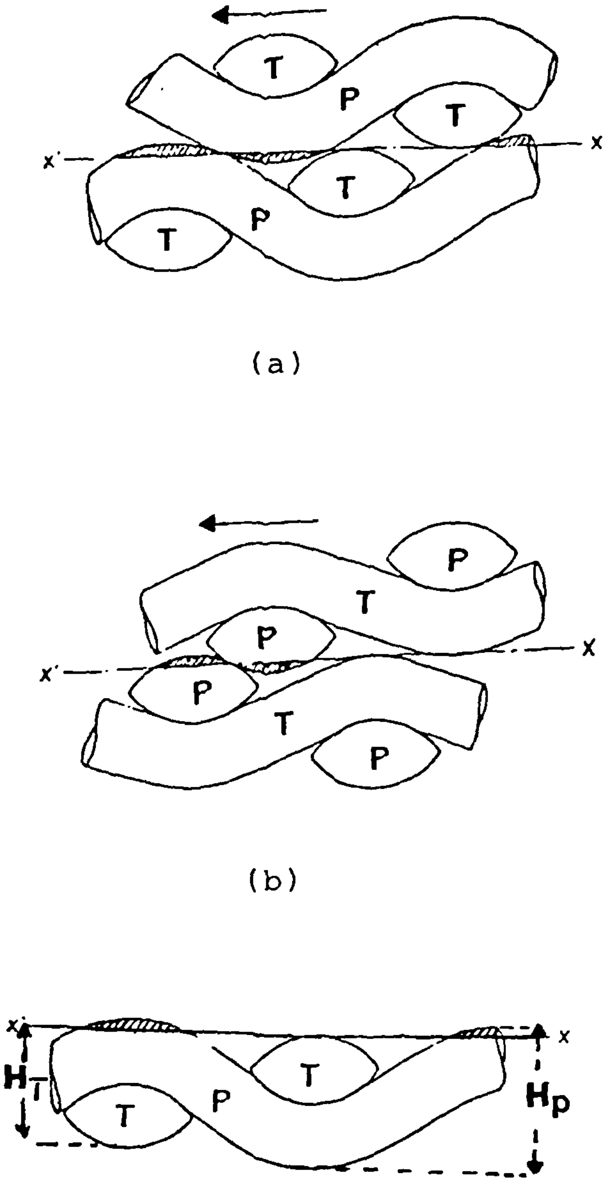
Following a similar procedure by Ohsawa and Namiki(93), Ohsawa et al(94), and Zurek et al(137), the relative height of the protrusion of yarn crown is calculable from the geometrical configuration.

According to Pierce(102,103), the relationship between the yarn crimp (C), spacing (P) (i.e. threads per cm) and the crimp amplitude (h) is given by the following equation:

$$\frac{h_P}{P_T} = \frac{4\sqrt{C_P}}{3} \qquad 1$$

where the subscripts P and T refer to warp and weft yarns respectively.

The distances between the planes tangent to the warp and weft yarn crowns (Figure 1(c)) are correspondingly given by:



(a)

(b)

(c).

Figure 1

Model of fabric on fabric contact

(a) warp on warp motion

(b) weft on weft motion

(c) a unit cell of a woven fabric.

XX^1 = arbitrary plane of fabric surface

P = warp yarn, T = weft yarn

arrow indicates the direction of sliding

$$H_P = h_P + b_P \qquad 2$$

$$H_T = h_T + b_T \qquad 3$$

where H = distance between the planes tangent to the yarn crown,

b = minor diameter of the flattened yarns

subscripts P and T refer to warp and weft yarns respectively.

In a balanced yarn system, where the warp and weft sett, and linear density are similar, it is evident that

$$h_P + h_T = b_P + b_T \qquad 4$$

Suppose the linear densities of the component yarns are different, and assuming the ratio of the minor diameter of warp to weft yarns is denoted by (δ), where

$$\delta = \frac{b_P}{b_T} \qquad 5$$

and substitution of this relation into equation 4 yields:

$$h_H + h_T = (1 + \delta)b_T = (b_P + b_T) \qquad 6$$

$$b_P = \frac{\delta}{(1 + \delta)}(h_P + h_T) \qquad 7$$

$$b_T = \frac{\delta}{(1 + \delta)}(h_P + h_T) \qquad 8$$

From equations 2 and 3

$$H_P = h_P + \frac{\delta}{(1 + \delta)}(h_P + h_T) \qquad 9$$

$$H_T = h_T + \frac{\delta}{(1 + \delta)}(h_P + h_T) \qquad 10$$

Therefore the relative height of yarn crown (H_C) may be written as

$$H_C = \frac{1}{2}(H_P - H_T) \qquad 11$$

$$H_C = \frac{1}{2}\{(h_P - h_T) - (h_P + h_T)(\delta - 1/\delta + 1)\} \qquad 12$$

The factor of ($\frac{1}{2}$) represents the protrusion of warp yarn crown from the plane of weft yarns on only one side, i.e. face. The magnitude of H_C may be positive or negative. A positive value would indicate a warp projection, otherwise a weft projection is obtained.

(b) FABRIC BALANCE

Generally, fabric balance is defined as the ratio of the cover factors of warp and weft$^{(32,94)}$.

However, the amount of crimp in yarns is not taken into consideration in this definition. Yarn crimp may not be ignored in considering fabric balance in which the surface boundary of the fabric is a major factor.

The ratio of the surface area made by warp and weft within a unit cell (Figure 1) is expressible by the following equation:

$$\beta\lambda = \frac{l_T . d_T}{l_P . d_P} = \frac{l_T . K_T \sqrt{T_T}}{l_P . K_P \sqrt{T_P}} \approx \frac{l_T \sqrt{T}}{l_P \sqrt{T}} . \qquad 13$$

where l = modular length of yarn

d = diameter of yarn (circular section assumed)

K^1 = diameter factor (yarn porosity, which may be assumed equal in this case)

T = yarn linear density (Tex)

subscripts P and T refer to warp and weft yarns respectively.

Assuming the crimp in the yarns is denoted by C, then according to Pierce(102,103),

$$C_P = \frac{l_P}{P_P - 1} \qquad 14$$

$$C_T = \frac{l_T}{P_T - 1} \qquad 15$$

Accordingly,

$$\beta\lambda = \frac{l_T\sqrt{T_T}}{l_P\sqrt{T_P}} = \frac{P_P(1 + C_T)\sqrt{T_T}}{P_T(1 + C_P)\sqrt{T_P}} \qquad 16$$

$\beta\lambda$ = fabric balance

This equation takes into account the ratio of the surface area of the crown part (protruded part) of the yarn making up the surface of a fabric.

APPENDIX 2

GEOMETRIC EFFECT OF ROLLER LINKAGE

Figure 2 shows the balance of forces in the Instron linkage, whereby the reaction of the roller sled and the thrust exerted on the cross-head by the brass metal arm are represented by P_1 and P_2 respectively. The arm of mass W inclined to the horizontal (i.e. fabric surface) at an angle of Φ.

As the cross-head moved upward, the roller was drawn along the fabric surface. The frictional resistance between the fabric and the roller (F) was counterbalanced by the horizontal component of P_2, i.e. the restraint in the link (F^1).

Therefore the equilibrium forces at any moment would be given by:

$$P_1 = W-P_2 \qquad 17$$

Taking moment about P_1

$$P_2.L\mathrm{Cos}\Phi = W.L_1\mathrm{Cos}\Phi + F^1\mathrm{Sin}\Phi \qquad 18$$

At the limiting value of frictional resistance

$$F = F^1 \qquad 19$$

Dividing both sides of equation 18 by $L.\mathrm{Cos}\Phi$, and since $F = F^1$

$$P_2 = W.L_1/L + F.\mathrm{Tan}\Phi \qquad 20$$

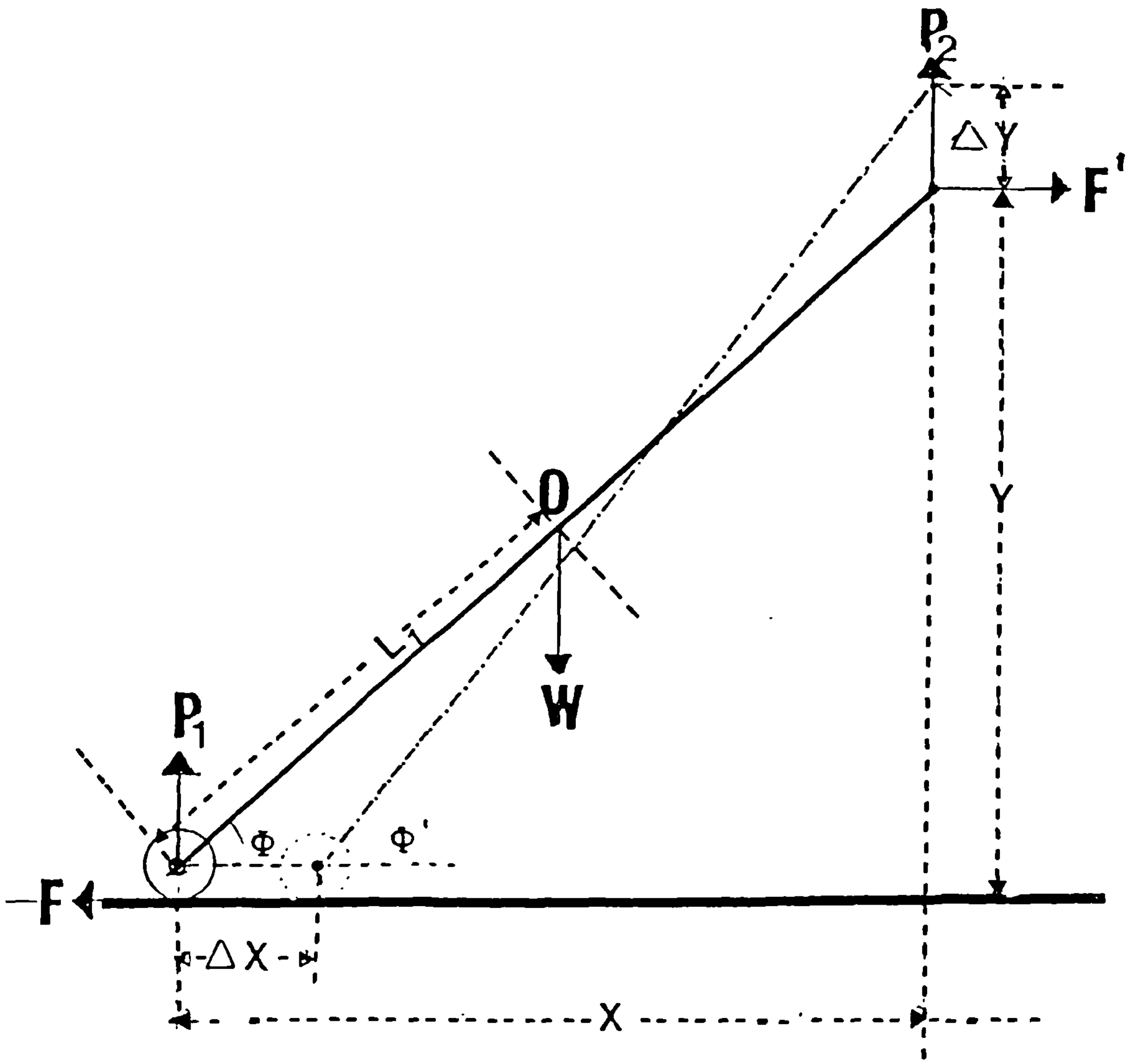


Fig 2

Geometrical analysis of the roller probe

F = frictional resistance between fabric and roller

F^1 = restraint in the cross-head and arm linkage

W = mass of the brass metal arm

P_1 = reaction of the roller

P_2 = force recorded by the Instron

Φ = angle of the inclination of the arm to the fabric surface (horizontal)

From the geometry of the system, the value of TanΦ can be determined, i.e.

$$\mathrm{Tan}\Phi = \frac{\sqrt{L^2 - (x-\Delta x)^2}}{x-\Delta x} \qquad 21$$

Equation 20 becomes

$$P_2 = \frac{W.L_1}{L} + \frac{F\sqrt{L^2 - (x- x)^2}}{x- x} \qquad 22$$

where L = Length of arm

L_1 = Distance between centre of roller and centre of gravity of the arm

Δx = Small displacement of roller

x = Fixed distance between roller and cross-head (98mm)

P_2 = Force exerted on the cross-head.

Since Δx is time dependent, i.e. increases as the cross-head traverses upward, and the value of F is constant for a particular surface, and $W.L_1/L$ is also constant (i.e. 87.3g), the value of P_2 in equation 20 would be dependent on TanΦ which in turn depends on Δx.

Therefore any increase in the value of tan Φ as the cross-head moves upward causes a systematic increase in the value of P_2, as shown in Figure 3. This in turn causes a systematic increase in the roller trace. This effect represented an error of about 7% per 5cm displacement of the roller. Despite this angular function, it was considered that the results represented a valid profile of fabric surface.

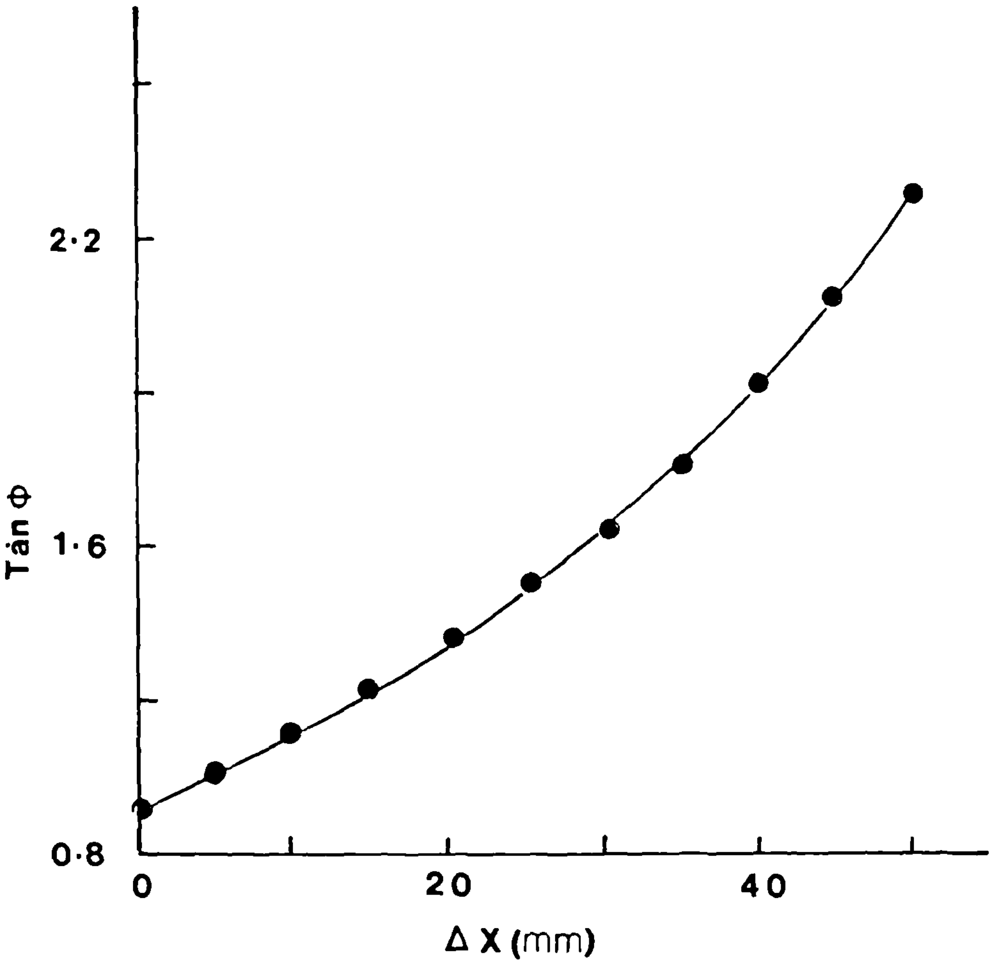


Fig 3

Relationship between roller displacement
(ΔX) and TanΦ

APPENDIX 3

PAIRED COMPARISONS OF FABRICS

SCOPE

To rank various fabrics for subjective properties, such as handle, dye regularity, colour difference, etc, by the paired comparison technique, comparisons of more than six fabrics are not recommended because of increasing fatigue of operator assessors. This technique can be used to obtain a one-dimensional ranking only.

DEFINITION

Paired comparison technique: A ranking technique by which each specimen is compared with each other specimen separately and in isolation. It is preferable to a simple ranking in that (i) it can be carried out 'blindfold'; (ii) it affords the possibility of checking the consistency of each assessor in his decisions, the agreement between assessors, and the significance of differences between rankings.

PRINCIPLE

Each fabric is compared in turn with each other fabric and at each comparison the assessor is asked to answer a pertinent question. The summed results from a series of assessors are analysed in order to rank the fabrics in order for the relevant property. Assessment of the significance of the ranking can be made, where necessary, using a computer programme.

APPARATUS

Pillory box (where necessary). This is a screen, with armholes, which prevents the assessor seeing the fabrics he is judging by touch.

CONDITIONING AND TESTING ATMOSPHERE

No special conditions are necessary unless the fabrics being assessed are likely to be affected by changes in ambient conditions. In the latter case all specimens are conditioned and all assessments carried out in the standard atmosphere for testing, i.e. a relative humidity of 65±2% and a temperature of 20±2°C.

TEST SPECIMENS AND ASSESSORS

Specimens need not be in any special form, but should be uniform.

The larger the number of assessors, the more representative will be the final ranking of general opinion. A minimum of six assessors is realistic. Each assessor will be required to make $\frac{1}{2}k(k-1)$ paired comparisons, where k is the number of specimens to be ranked. Each assessor should complete his "set" of assessments; any uncompleted set should be discarded, not finished by another assessor.

PROCEDURE

Establish with the job author the question to be asked to each assessor. Examples of useful questions are:-

Which fabric is softer?

Which fabric is bulkier?

Which is the least synthetic?

Which appears most irregular?

The question should relate as far as possible to only one aspect of the fabric.

Questions such as -

Which fabric do you prefer?

Which fabric has the best handle?

involve judgement of several aspects, which different assessors may rank differently. Such questions should preferably be avoided, but if necessary to give a general impression, should be asked of a large number of assessors (20) so that individual idiosyncrasies will not unduly affect the impression gained.

Give the specimens alphabetical references and mark these along the sides of a standard chart (see page 231). Mark the chart with the assessor's name.

Seat the assessor at the pillory box.

Select two of the specimens at random and present them to the assessor. Ask the agreed question, and record the answer in the upper triangle on the chart. If, for example, specimens B and D are being compared, and D is chosen as best answering the requirements of the question, record a '1' in the box in column D, row B. If B is chosen, record a '0' in this box. If no choice is given, record a '$\frac{1}{2}$' in this box (Figure 1 gives an example for seven specimens).

Repeat for all other pairs of specimens, selecting each pair randomly.

Repeat the same procedure for the remaining assessors.

CALCULATION AND EXPRESSION OF RESULTS

Complete the lower triangle of the chart. In the example where D was chosen rather than B, a '1' was recorded in the box in column D, row B, consequently a '0' should be recorded in the box in column B, row D (see page 232.).

Sum the (k-1) entries in each column.

Repeat the chart for each assessor.

Sum the totals on the charts for each specimen to give the overall ranking. The specimen with the highest score then ranks as the softest, bulkiest, etc. and that with the lowest score the least soft, least bulky, etc.

RECORD SHEET FOR PAIRED COMPARISONS

	A	B	C	D	E	F	G	H	
A									A
B									B
C									C
D									D
E									E
F									F
G									G
H									H
TOTAL									TOTAL

Assessor's Name: ....

Sex: ....

Age: ....

Enter results in upper triangle only.

Enter '1' if column ranked higher.

Enter '0' if row ranked higher.

Complete lower triangle later in accordance with instructions in "Paired Comparison with Fabrics".

	A	B	C	D	E	F	G	H	
A		1	1	½	1	1	1		A
B	0		0	1	1	1	1		B
C	0	1		0	1	1	1		C
D	½	0	1		1	1	1		D
E	0	0	0			0	1		E
F	0	0	0	0	1		0		F
G	0	0	0	0	0	1			G
H									H
TOTAL	½	2	2	1½	5	5	5		TOTAL

Job: MP/10/73

Assessor: A Smith

Enter results in upper triangle only

Enter '1' if column ranked higher

Enter '0' if row ranked higher

Figure 1(b)

STATISTICS FOR PAIRED COMPARISON RESULTS

From the final ranking of the scores SPEARMAN RANK CORRELATION COEFFICIENT r_s can be used to compare, for example, subjective judgements of handle with an individual objective measurement.

FORMULA: $$r_s = 1 - \frac{6\Sigma d^2}{N(N^2-1)} \qquad 23$$

where N is the number of fabrics ranked and d is the difference between the two ranks.

METHOD: make a list of the fabrics and under each fabric enter the ranks for the two measurements being compared. Calculate the difference (d) between the two ranks, square each difference (d^2) and add together these squared differences (Σd^2). Then enter this value and the value order of N (i.e. the number of fabrics) into the formula and calculate.

EXAMPLE: For a set of seven fabrics subjective ranks have been obtained and these are to be compared with the rank order of an objective measurement of these seven fabrics.

Fabrics	A	B	C	D	E	F	G
Subj. Ranks	2	6	5	1	3	4	7
Obj. Ranks	3	4	2	1	6	5	7
Difference (d)	-1	2	3	0	-3	-1	0
d^2	1	4	9	0	9	1	0

Sum of the d^2 (Σd^2) = 24

$$r_s = 1 - \frac{6d^2}{N(N^2 - 1)}$$

$$= 1 - \frac{6(24)}{7(7^2 - 1)}$$

$$= 1 - 0.429$$

$$= 0.571$$

For these seven fabrics the correlation between the subjective and the objective ranks is $r_s = 0.571$. To test for the SIGNIFICANCE of this result, it is customary to test what is called the NULL HYPOTHESIS. This means that we consider the 2 sets of ranks are NOT associated and that the obtained value of r_s differs from zero only by chance.

To determine this for small samples $(N<10)$ use Table A attached. If the calculated value of r_s equals or exceeds the value from the tables then the NULL HYPOTHESIS is rejected and it is accepted that the calculated value is significant at the level indicated, either 0.05 or 0.01. This means that there is a less than 5% or 1% probability that the results were obtained by chance.

EXAMPLE: From the data where $N = 7$ and $r_s = 0.571$ Table A shows that r_s would have to be greater than or equal to (>) 0.714 to be significant and that therefore the NULL HYPOTHESIS is accepted, meaning that the 2 sets of ranks are NOT associated.

For larger samples $N>10$ the null hypothesis may be tested by the formula

$$t = r_s \sqrt{\frac{N - 2}{1 - r_s^2}} \qquad 24$$

Calculate the t value from this formula. Refer to Table B, (df=N-2). Again the calculated value for 't' has to be greater than or equal to the tabled value for 't' before the null hypothesis can be rejected and it can be concluded that there is association between the 2 rank orders.

To compare more than 2 sets of ranking KENDALL COEFFICIENT OF CONCORDANCE W, would be appropriate. This is a measure of the relationship between several rankings and therefore may be used to express the degree of association among the rankings of fabrics obtained by several test methods or by several judges.

FORMULA:

$$W = \frac{s}{1/12\ k^{1}(N^{3}-N)} \qquad 25$$

where N is the number of fabric ranked

k is the number of tests or judges

s is the sum of squares of the difference between the total of the ranks for each fabric and the mean of these totals, i.e.

$$s = \Sigma(Rj - \frac{\Sigma Rj}{N})^{2} \qquad 26$$

METHOD: Make a list of the fabrics and under each fabric enter the ranks obtained for the tests or from the judges. Sum the ranks (Rj) for each fabric. Then sum the Rj and divide by N (the number of fabrics) to obtain the mean value of Rj. Subtract this mean from the total rank (rj) for each fabric and square the numbers thus obtained. Add the squared number derived from each fabric. This is the 's' value.

EXAMPLE: A set of six fabrics has been ranked by 3 judges.

JUDGES	FABRICS					
	A	B	C	D	E	F
1	1	6	3	2	5	4
2	1	5	6	4	2	3
3	6	3	2	5	4	1
Rj (sum of ranks)	8	14	11	11	11	8
$Rj - \frac{Rj}{N}$ (sum of Ranks - Mean	8-10.5 = -2.5	14-10.5 = 3.5	11-10.5 = 0.5	11-10.5 = 0.5	11-10.5 = 0.5	8-10.5 = -2.5
$(Rj-\frac{Rj}{N})^2$	6.25	12.25	0.25	0.25	0.25	6.25

$Rj = 63$ (Sum of Rj)

$\frac{\Sigma Rj}{N} = 10.5$ (Mean of Rj)

$$\Sigma(Rj - \frac{\Sigma Rj}{N})^2 = 25$$

(Sum of squared deviations from the mean)

i.e. $s = 25.5$

$$w = \frac{s}{1/12k^2(N^3-N)}$$

$$= \frac{25.5}{\frac{1}{12}(3)^2(6^3-6)}$$

$$= 0.16$$

w = 16 expresses the degree of agreement among the judges.

To test the significance of W consult Table C attached. This is applicable for k (number of tests or judges) from 3 to 20 and for N (number of fabrics) from 3 to 7. The tabled result is to be compared with the s values (N.B. - not the W value) and to be significant the s value has to be greater than or equal to the tabled value.

For examples where s = 25.5, k = 3, N = 6 Table C shows that for the agreement among judges to be significant at the 0.05 level, s would have had to be >103.9. Therefore the NULL HYPOTHESIS is accepted. That is, the judges' rankings are NOT associated other than by chance.

To test the significance of larger samples (i.e. when N is more than 7) chi square tables can be used, after converting the data by using the formula

$$\chi^2 = k(N-1)W \qquad 27$$

Refer to Table D, with df = N-1. For the obtained W to be significant the χ^2 value has to be greater than or equal to the value obtained from the table.

INTERPRETATION OF SIGNIFICANCE OF W

A significant value of W may be interpreted as meaning that the judges are applying essentially the same standard in ranking the N fabrics under study.

COMPUTER PROGRAMME

There is a programme on KENDAL COEFFICIENT ON CONCORDANCE W on the ICL 1900 which can be assessed from the terminal in the Fibre Science Unit.

Table C: Table of critical values of % in the KENDALL COEFFICIENT OF CONCORDANCE*

k	N					Additional values for N = 3	
	3#	4	5	6	7	k	%
Values at the .05 level of significance							
3			64.4	103.9	157.3	9	54.0
4		49.5	88.4	143.3	217.0	12	71.9
5		62.6	112.3	182.3	276.2	14	83.8
6		75.7	136.1	221.4	335.2	16	95.8
8	48.1	101.7	183.7	299.0	453.1	18	107.7
10	60.0	127.8	231.2	376.7	571.0		
15	89.8	192.9	349.8	570.5	864.9		
20	119.7	258.0	468.5	764.4	1,158.7		
Values at the .01 level of significance							
3			75.6	122.8	185.6	9	75.9
4		61.4	109.3	176.2	265.0	12	103.5
5		80.5	142.8	229.4	343.8	14	121.9
6		99.5	176.1	282.4	422.6	16	140.2
8	66.8	137.4	242.7	388.3	579.9	18	158.6
10	85.1	175.3	309.1	494.0	737.0		
15	131.0	269.8	475.2	758.2	1,129.5		
20	177.0	364.2	641.2	1,022.2	1,521.9		

* Adapted from Friedman, M. 1940. A comparison of alternative tests of significance for the problem of m rankings. Ann.Math.Statist.,11,86-92, with the kind permission of the author and the publisher.

\# Notice that additional critical values of % for N=3 are given in the right-hand column of this table.

Table A: Table of critical values of r_s,

THE SPEARMAN RANK CORRELATION COEFFICIENT*

N	Significance level (one-tailed test)	
4	1.000	1.000
5	.900	.943
6	.829	.893
7	.714	.893
8	.643	.833
9	.600	.783
10	.564	.746
12	.506	.712
14	.456	.645
16	.425	.601
18	.399	.564
20	.377	.534
22	.359	.508
24	.343	.485
26	.329	.465
28	.317	.448
30	.306	.432

* Adapted from Olds, E.G. 1938. Distributions of sums of squares of rank differences for small numbers of individuals. Ann.Math.Statist.,9,133-148, and from Olds,E.G. 1949. The 5% significance levels for sums of squares of rank differences and a correction. Ann.Math. Statist.,20,117-118, with the kind permission of the author and the publisher.