THE RELATIONSHIP BETWEEN THE LOOP LENGTH AND PROPERTIES OF SOME PLAIN WEFT-KNITTED FABRICS

By

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SUMMARY

The object of this work is to investigate the effect of loop length on the geometrical and more particularly on the physical and mechanical properties of the plain weft knitted fabrics.

Two sets of fabrics were produced from 2/26s worsted yarn using knitting machines different in type and gauge. The first set was knitted from single yarn and the second from two-ends with a wide range of loop length. Both sets were given three different relaxation treatments, dry, wet- and full-relaxation.

Dimensional measurements and geometrical parameters were determined and examined and the results show that for some fabrics there is some deviation from the results of other workers in this field.

The study also involved measurements and tests of certain yarn properties which provided useful background information about this yarn and which might help to explain certain properties of the knitted fabrics. The yarn properties measured and tested were, twist, friction, flexural rigidity, tensile and elastic properties.

Experimental results indicate that an increase in loop length leads to an increase in air permeability and percentage weight loss when the fabric subjected to abrasion. It is found that for two-end fabrics the percentage weight loss is non-linearly related to the

loop length and this reflects the yarn arrangement within the structural unit cell. While there is not always a direct relation between the loop length and the fabric thickness, there is however, a proportional relationship between the parameter t/L and the cover factor K.

In this investigation, the predicted tensile strength and extension at the point of break worked out on the geometrical basis when the fabric is extended in walewise and coursewise direction.

Once more the fabric made from two-ends behaved differently when it was subjected to tensile and to repeated cycles of extension. Fabrics made from two-ends are stronger at break but have lower recovery than the fabrics made from single yarn. While there is a relationship between the total elastic recovery and the loop length for the fabric made from one-end, it appeared that it is difficult to find a systematic relationship between the total elastic recovery and the loop length for fabrics made from two-ends in both the dry- and fully-relaxed state due to the involvement of the yarn arrangement within the structural unit cell of the fabric.

In addition to the pattern of yarn arrangement within the structural unit cell in the two-end fabric, there is relative yarn movement which may affect the dimensions of the cell.

CONTENTS

CHAPTER 1

INTRODUCTION

The technological developments in recent decades have made it possible to produce much more complex fabric constructions. However, the plain knitted construction still forms the largest proportion of all knitted fabrics. Although a great deal of work has been done on the dimensional and geometrical properties of plain knitted fabrics, very little work has been done on physical and mechanical properties.

The fact that the loop length is the major factor which determines the fabric properties is well established but there is a lack in experimental confirmation of the effect of this factor and the nature of this effect particularly on the physical and mechanical properties of the fabric. Some other factors which may affect the fabric properties such as doubling the yarn and the fabric treatment are also examined in the present work.

As in weaving, it is common practice in knitting to use more than one end to knit fabric. It appeared, as it will be seen in this work, that the number of ends which may be used have an important effect on the dimensional and mechanical properties of the knitted fabrics. The effect of yarn doubling differs from the effect of increasing yarn diameter in the sense that the doubling does not produce properties equivalent to those produced by a single yarn with a greater diameter in both geometrical and phsycial aspects.

For the present investigation, two sets of fabrics have been knitted in different types of knitting machines. The first fabric set has been knitted from single yarn and the second from two ends of yarn. Each of these sets were arranged in three sub-sets of fabrics; dry-relaxed, wet-relaxed and fully-relaxed. The results of measurements show that wet-relaxed fabrics lie between the dry-relaxed and the fully-relaxed fabrics and therefore they were excluded from the present investigation.

In order to provide a useful background in understanding the fabric properties, the most important properties of the yarn, which may have contributed to fabric properties have been investigated.

This research is concentrated mainly on the effect of loop length for both one-end and two-end fabrics on the dimensional, geometrical, physical and mechanical properties of the plain-weft knitted fabric in dry- and fully-relaxed state.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Properties of wool fibres:

Although the statistics show that the use of man-made fibre in knitting sector of textile industry has been expanding significantly in recent decades, wool for its resilience properties, is still an extremely important source of textile materials to this sector. Despite this change, the research efforts have not been affected significantly and they continue to be concentrated on wool as much as on any other textile material.

The chemical structure of wool is much more complicated than other protein fibres. Research was carried out to investigate the structure of wool by using electron microscope and X-ray diffraction techniques[1]. The important structural properties of wool were investigated by various authors[2-4].

The behaviour of wool fibres when they are subjected to the loading and unloading force has vital practical importance, as the fibres, during the manufacturing processes are subjected to stress cycles.

Physical properties of wool fibres, notably the tensile and elastic recovery properties were investigated in early works of Astbury[1] and Meredith[5]. Other contributors in this field were Chapman[6], Collins and Chaikin[7]. Many detailed researches on the effects of temperature, moisture, humidity and test conditions on the tensile and recovery properties have been carried out by several workers[8,9].

2.2 Physical and mechanical properties of the wool yarns:

2.2.1 Yarn diameter:

The yarn diameter is one of many important dimensions required in the study of fabric properties. Most workers assumed that the yarn has a circular cross-section. In practice, however, when the yarn is converted into fabric, it is distorted and it may be flattened during calendering.

Although Peirce[10] accepted the assumption of the yarn circularity, he noted at the same time that the yarn in the fabrics are flattened. However, the number of formulae derived to calculate the yarn diameter were based on the assumption of circularity[11].

2.2.2 Yarn twist:

Twist is the process in which a strand of fibres in a more or less parallel order is spun or rotated on its axis to form a yarn and the term "twist" is measured by the number of turns per unit length[11].

In Textile Terms and Definitions[12],twist is defined as the spiral disposition of the components of a yarn which is usually the result of relative rotation of the extremities of the yarns.

Twist in yarn could have either of two directions which indicated the use of the letter S or Z. While from the spinning point of view, it normally matters little which way the twist goes[11], it does matter when single yarns are plied. The direction and the amount of twist in ply yarns becomes more important because they influence the physical properties and the appearance of the finished fabrics. Ply yarns, for example, in which the ply twist is in the opposite direction to the single twist are very stable and can be made perfectly stable by using a suitable combination of twist[13]. By the use of twist, cohesion between the constituent fibres may be obtained and therefore sufficient strength of yarn to resist the stresses imposed during the processes of its preparation and fabric manufacture. The most important factor which can be used to describe the amount of twist in the yarn is the twist factor, which takes into account the yarn diameter as well as the twist in the form $T.F.=t.\sqrt{tex}$, where t is the turns per centimeter. Therefore the choice of twist factor will be related to the use to which the yarn is to be put; weft, warp, knitting, etc.

In knitting, the single twist is generally similar to that in weaving, but to prevent twist liveliness and hence spirality, the doubling twist for knitting is half the singles twist. Although an increase in twist will lead to an increase in strength, it does not necessarily give the strongest fabric since the strength depends on fabric geometry also[13].

Knapton[14] states, that an increase in yarn twist usually causes an increase in yarn strength and this leads to a decrease in fault rate during the knitting process but Feltaous [15] found difficulties involved in manufacturing knitted fabrics from high twist and unbalanced twist yarns. It is also true, however, that high twist will lead to an increase in curling the fabric, in the effect of the couples on the knitted loops of certain structures such as the purl structure[16] and will affect the dimensional properties, handling and appearance characteristics of the fabric.

2.2.3 Yarn friction

The frictional characteristics of yarn have been a matter of interest to numerous scientists[17-19], all of whom have described methods, and instruments used for measuring the coefficient of friction between running yarn and guides.

The coefficient of friction is defined as the ratio between the force required to produce sliding of one surface on another (the tangential force) and the force holding the pair of surfaces together (the normal force)[17].

Most investigations of friction in textiles were based on studying the friction of yarns against steel or any solid material. In textiles, yarns pass at various speeds over surfaces of steel, chromium, ceramic, plastic and or any other solid material. Researches have shown that the coefficient of friction is influenced not only by the speed and the type of material the yarns pass over, but by the angle of contact of the yarn on the cylinder, the temperature, area of contact and many other factors. Buckle[18] and Marvin[20] have noted that the coefficient of friction increases as the yarn speed increases. Baird and Mieszkis[21] observed a similar effect and also that with increase in twist, the coefficient of friction decreased, and they concluded that in almost all cases a lubricant is present and has a considerable effect on the coefficient of friction. Using the twist method originally suggested by Lindberg and Gralen [22], Knapton[23] measured the yarn/yarn friction and noted that poorer knitting performance of certain wool (chemically modified) may be attributed not to yarn/metal, but due to changes in yarn/yarn friction.

In another method of measurement of yarn-on-yarn friction which uses linked loops, the geometry of the yarns at the points of contact is similar to that in knitted facbrics. MacRoy and McNamara[24] have used this method to measure the coefficient of friction of cottonand wool yarns and similar results were obtained for both yarns ($\mu = 0.34$).

Feltaous[15] used the same method and the results showed that the frictional coefficient is influenced by the distance between two ends of the loop.

2.2.4 Tensile properties of yarn

When a force is applied to the yarn in the direction of its axis, the yarn will stretch until it breaks and a wide range of machines to measure the behaviour of the yarn under tension are in use. A study of the behaviour of yarns with various fibre configuration has been made by numerous workers. Stanbury and Byerley[25] have investigated the relation between the strength, count and twist and used theoretical formulaeto describe this relation. They also found that a minimum twist factor is required, whatever the count of the yarn, to produce the necessary cohesion of the fibres.

Holdsworth et al[26], investigated the strength-count relationship of single worsted yarn. From their experiments, various results have been set out and a relation between the count and strength has been drawn. Although the relation is not linear, it shows, as expected a decrease in strength as the yarn becomes finer.

In all experiments[25,26,11] on the relation between the yarn strength and the twist, there is evidence that not only is a minimum twist factor required to give the yarn a sufficient strength for the following process, but there is a maximum twist factor beyond which the yarn strength begins to decrease. This is possibly because, as a result of an increase in twist angle, a torsional forces is in play.

2.2.5 Loop strength of yarn:

If a fibre or a yarn is loaded longitudually in a bent state, it will break more easily than if it is straight. The loop test gives an indication of the effect of bending on the yarn strength and this effect is expressed by the ratio of loop strength to twice the single yarn tensile strength(27). Morton and Hearle(28) found that the reduction in strength was greatest in fibres with the lowest elongation at break.

2.2.6 Elastic recovery of yarn:

Elasticity may be defined as the property of a body by which it tends to recover its original size and shape after deformation(11).

Elastic recovery is a measure of the behaviour during a cyclic change of stress or strain in which the results do not fall on a single line, but after a few initial cycles, tend to fall on a loop(28). This form of behaviour is a consequence of loss in internal energy after repeated loading and unloading of the material.

The molecular structure of the material will be affected when that material is subjected to the stress or strain[28] and it is thought that recoverable or elastic deformation is due to a stretching of inter-atomic and inter-molecular bounds, and non-recoverable or plastic deformation results from a breaking of bonds and their re-forming in new positions or to the stabilization of new chain conformations.

A method of testing the materials, used by Meredith[29] was adopted by most workers in this field. A typical record shows the division into elastic and permanent extensions and from this record, the elastic recovery can be calculated. The results of Meredith's tests show that wool and hair recover 60% from an extension of 35% which is well above some other fibres such as cotton and bast fibres at much lower extension.

Farrow[30] observed in his experimental work that wetting may have a pronounced effect on recovery and wool and hair exhibit almost total recovery from extension when wet.

2.2.7 Flexural rigidity

Flexural rigidity is a measure of yarn resistance to bending. The importance of this property is that the yarn in the knitted fabric is bent in almost circular shape in one plane in addition to the considerable degree of bending in the other dimensions.

Doyle[31] suggested that flexural rigidity of the yarn is greatly influenced by changes in its diameter. By assumming that the yarn has a circular section and on the basis of the following expression:

$$G = B\,R = E\,I = \frac{\pi\, d^4 E}{64}$$

Where, G_ Flexural rigidity

I_ Moment of inertia

B_ Bending moment

R_ Radius of curvature of bending produced

E_ Young's modulus, and

d_ Yarn diameter

he stated that if the yarn diameter is doubled, the flexural rigidity would be increased by sixteen times. In contrast to this, the effect of such changes on strength in extension is much lower, it would be increased by four times.

Methods of measuring the flexural rigidity of the yarn are limited. The ring method originally suggested by Peirce[32] was preferred by Carlene[33], Owen[34] and Hunter[35] not only for its simplicity, reproducibility and applicability, but also it is often the only method available[34].

Hunter et al[35] tested worsted yarns with various linear density, twist factor and fibre diameter. Regression equations based on the logarithms of the results were obtained and they found that flexural rigidtv may be influenced by those three factors; linear density, twist factor and the fibre diameter.

Carlene[33] investigated the relationship between fibre and yarn flexural rigidity in continuous filament viscose yarn and he suggested that the relation between filament flexural rigidity and filament denier of viscose filaments can be expressed by the equation:

$$G = KD^n$$

where, G – Flexural rigidity

K – Constant

D – Filament denier and

n – Integer less than 2

This equation may be applied to continuous filament single yarns of very low twist (less than 4 t.p.i) by simple sum of the rigidities of the component filaments.

Peirce[32], realising the labour involved in computing the exact mathematical solution fitted a trigonometrical expression to the load-deflection relation, but Owen[34] employed modern computional methods which have made it convenient to use the exact solution. This solution is tabulated in a form suitable for the calculation of yarn flexural rigidity from the experimental load-deflection data. From this table, after obtaining the experimental value of d/L, a non-dimensional load Z is read off and flexural rigidity G calculated as PL^2/Z g.cm^2, where P is the load and L is the circumference of the loop.

2.3 The production and geometry of weft-knitted fabrics

2.3.1 Knitting operation and factor affecting the knitting quality

Even after the introduction of machinery to the knitting sector of the textile industry, for many centuries the quality of the knitted fabrics was based on the experience of the knitter to produce fabric of the required characteristics and dimensions. Only in recent decades, has a quantitive study of fabric geometry by many workers [36-40] led to positive methods of control. Since then it has been established that the amount of yarn in one repeated unit of fabric structure termed as "loop length" or "stitch length" or "structural unit cell length", is a major quality parameter of the knitted fabric. Other parameters such as regularity of the loops within the fabric structure are also important.

In the knitting operation, the quality parameters may be affected by several variables, some of which are related to the yarn, others related to the machine. The major variables which affect the knitting quality are:

1. Yarn variables: Yarn count, twist, friction and moisture content and package hardness. These variables are inter-related. Baird and Mieszkis [21] noted, for example, that with decrease of twist, the

coefficient of friction increases. Similarly, the harder the package, the greater the friction.

2. Machine variables: Machine variables could be; machine gauge, yarn tension, take-down tension, cam setting, dial height, needle timing, and sinker timing. The most important variables are:

(a) Machine gauge:

Machine gauge is a term specifying the needle spacing (the distance between two needles in the machine) and expressed as the number of needles per unit length. There are various gauging systems for various knitting machines listed in Textile Terms and Definitions [12]. Each type of machine may have different gauges and for one machine gauge, a limiting yarn count can be used. Although there is no general relation between the machine gauge and the yarn count, it is generally accepted that, for any given type of yarn and machine, optimum conditions giving useful range of loop lengths are obtained when:

$$\text{Gauge} = \frac{\text{constant}}{\sqrt{\text{tex}}} = \text{const.}\sqrt{N} \quad \text{,N-Yarn count}$$

In addition to the machine gauge, the needle size and type may also affect the range of yarns it is intended to knit.

(b) Yarn tension:

Yarn tension is the most important factor which may affect the loop length and the regularity of the fabric. To reduce the variation of yarn tension during the knitting process, tension devices have been attached to most weft knitting machines. Many attempts were made to produce constant yarn tension, but they were only partly successful. On circular knitting machines, the positive feed devices have been developed to feed each feeder a fixed length of yarn during each machine revolution. As a result of positive feed control on the fabric production, dimensional variation has been greatly reduced, and course length variation eliminated.

(c) Cam shape and setting

The size of the loops and consequently the dimensions of the fabrics are influenced by the movement of the needle which itself is controlled by the cam. For this reason, machines are provided with adjustable cams. The shape of knitting cams also affects the quality of knitted fabric. Many faults with distorted and irregular loop sizes may occur, when the cam is linear. With non-linear cams good quality fabric can be produced at much higher knitting speed[44].

(d) Dial height:

The gap between dial and machine cylinder through which the fabric passes should be adjusted when a new structure or a different yarn is used.

2.3.2 The geometry and dimenstional propeties of weft-knitted fabrics

An early attempt to analyse the geometry of knitted fabric was made by Tompkins[36], but his simple assumption scarcely amounted to a geometrical model.

Chamberlain[38], in his investigation, used a simple two dimensional loop model and Peirce[37] a relatively more complex one, where the yarn takes a certain configuration in the structure at a particular tightness, the loops of adjacent courses and wales being in contact. On the basis of these assumptions derived from his model shown in Fig.1, Chamberlain suggested that the following relationships existed:

$$\text{Course spacing} = \frac{1}{C_{p.i.}} = \frac{\sqrt{3}}{2W_{p.i.}}$$

$$\text{Wale spacing} = \frac{1}{W_{p.i.}} = 4d$$

$$\frac{Cp.i.}{Wp.i.} = \frac{2}{\sqrt{3}} = 1.15 \quad \text{and}$$

$$\text{loop length} = \frac{3\pi + 2\sqrt{13}}{4W_{p.i.}}$$

Where $C_{p.i.}$ and $W_{p.i.}$ - Courses and wales per inch repsectively.

d - Yarn diameter

Peirce in his work on geometry of plain fabric attempted to give a more advanced description based on a three dimensional plain loop model and obtained the

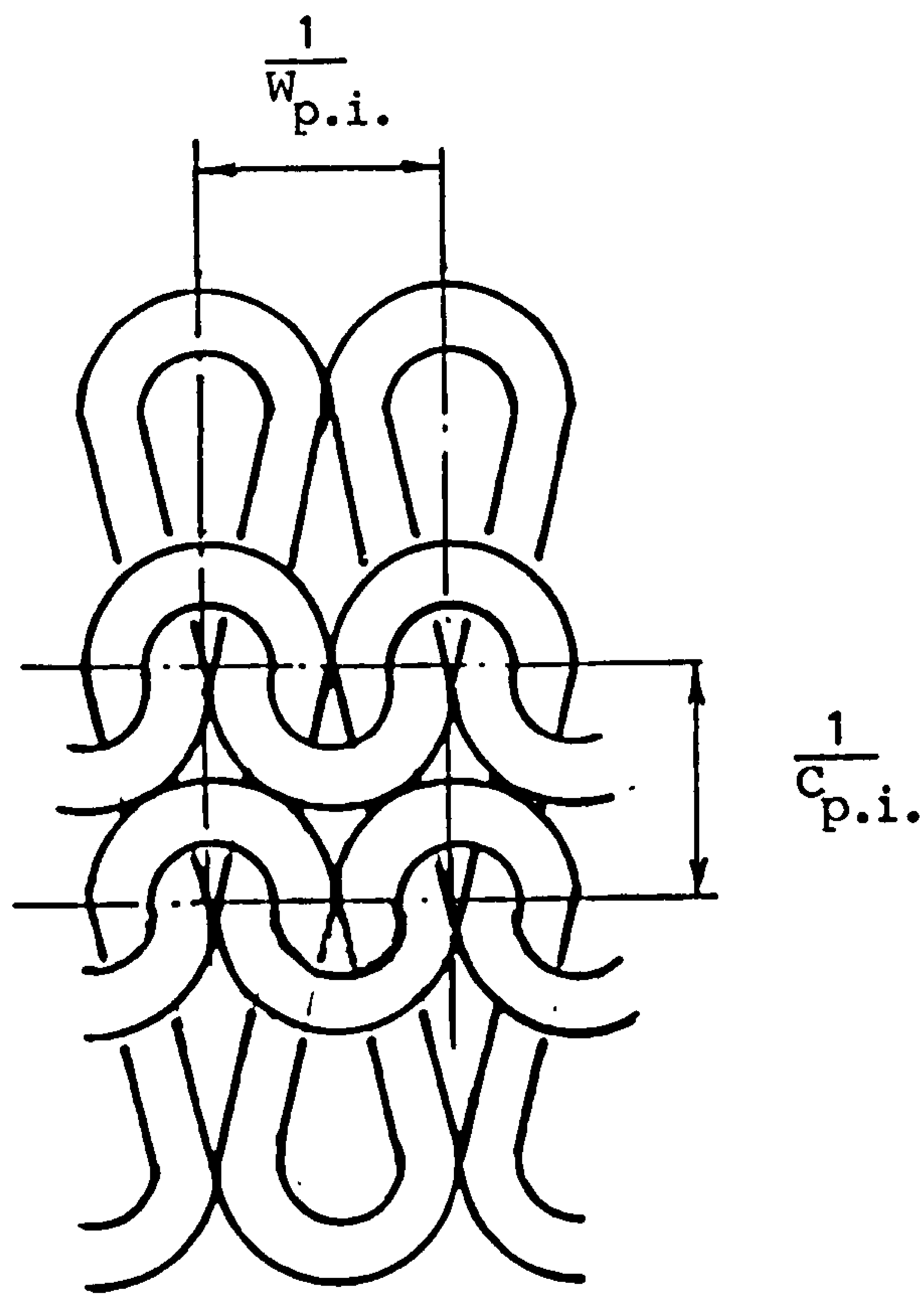

Fig.1:Chamberlain's two-dimensional model of plain loop.

following relationship:

$$L = 2p + w + 5.94\ d$$

where: p- Course spacing

w- Wale spacing

d- Yarn diameter.

In Munden's [40] view, neither Chamberlain's nor Peirce's model have given results sufficiently in accord with practical experience to justify their general acceptance.

Later investigation made by Doyle[39] showed, that for a range of knitted fabric, knitted from various hosiery yarns on various knitting machines and under different knitting conditions, the stitch density of the fabric in the dry-relaxed state was a function dependent primarily on the length of yarn per unit cell and it was independent of the yarn material, yarn structure and the system of knitting used to form the fabrics. Doyle expressed his statement as follows:

S = Cp.i.xWp.i. which is a function of the length of yarn per loop F(L).

where: S - Stitch density

Cp.i.- Number of courses per inch

Wp.i.- Number of stitches (wales) per inch.

He also stated that the ratio of courses to stitches per inch is closely dependent on the yarn properties and conditions of knitting as well as on the length of yarn per stitch and therefore it is not possible to generalise as broadly as for stitch density.

After Doyle's work, the idea that the loop length is a major parameter governing the dimensional proprties of the knitted fabric, has been accepted broadly.

Munden[40] used Doyle's[31] perspective views of plain knit fabric model in his theoretical investigation. He also made the further assumption, that the intermeshing of the adjacent courses always occurred at corresponding points, hence it followed that courses per inch and wales per inch, and loop length should be related to each other by constants. These relationships are:

$$K_c = C_{pi} \times L$$

$$K_w = W_{pi} \times L$$

$$K_s = S \times L^2$$

$$K_r = \frac{K_c}{K_w} = \frac{C_{pi}}{W_{pi}}$$

Where, K_c, K_w, K_s and K_r - constant values

C_{pi}, W_{pi} - courses and wales per inch respectively.

S - Stitch density

L - loop length

Munden obtained numerical values of the constants for fabrics knitted from various yarns. For K_s values this was done by calculating the slope of the graph of S against $1/L^2$ and in similar way, K_c and K_w values were obtained from the graphs of C_{pi} and W_{pi} respectively against $1/L$. He also identified two states of equilibrium for fabric. These two states are dependent on the type of treatment of the fabric after it has been knitted. He concluded that the natural configuration of the knitted loop is determined by conditions of minimum energy i.e. by the type of treatment and that this configuration is independent of yarn properties or loop length.

Dalidovich(43) in his study of the geometry of various knitted structures suggested a two-dimensional and a three-dimensional plain-stitch model(Fig.2). From his theoretical investigations, he obtained the following expressions:

a. loop length for two-dimensional model:

$$L = 1.57W + d + 2C$$

b. loop length for three-dimensional model:

$$L = \sqrt{(0.5W + d)^2 + d^2} + 2\sqrt{W^2 + 2d^2}$$

where; C and W- Course and wale spacing respectively

d - yarn diameter.

He also obtained from his model the following relationships:

a. For fabric where the yarns in the lower part of the loop are not in contact,

$$C = \frac{L - d}{4}$$

$$W = \frac{L - d}{\pi}$$

$$\frac{C}{W} = \frac{Wp.c.}{Cp.c.} = 0.785$$

b. For fabrics where the yarns in the lower part of the loop are in contact:

$$W = 4d$$

$$C = \sqrt{W^2 - (0.5W)^2} = W\frac{\sqrt{3}}{2} = 0.865W$$

$$\frac{C}{W} = \frac{Wp.c.}{Cp.c.} = 0.865$$

These two values of the ratio $\frac{C}{W}$ are close to those reported in works of several other investigaters[37,38,40].

Dalidovich stated that, the loop length could be obtained from the second expression only under certain

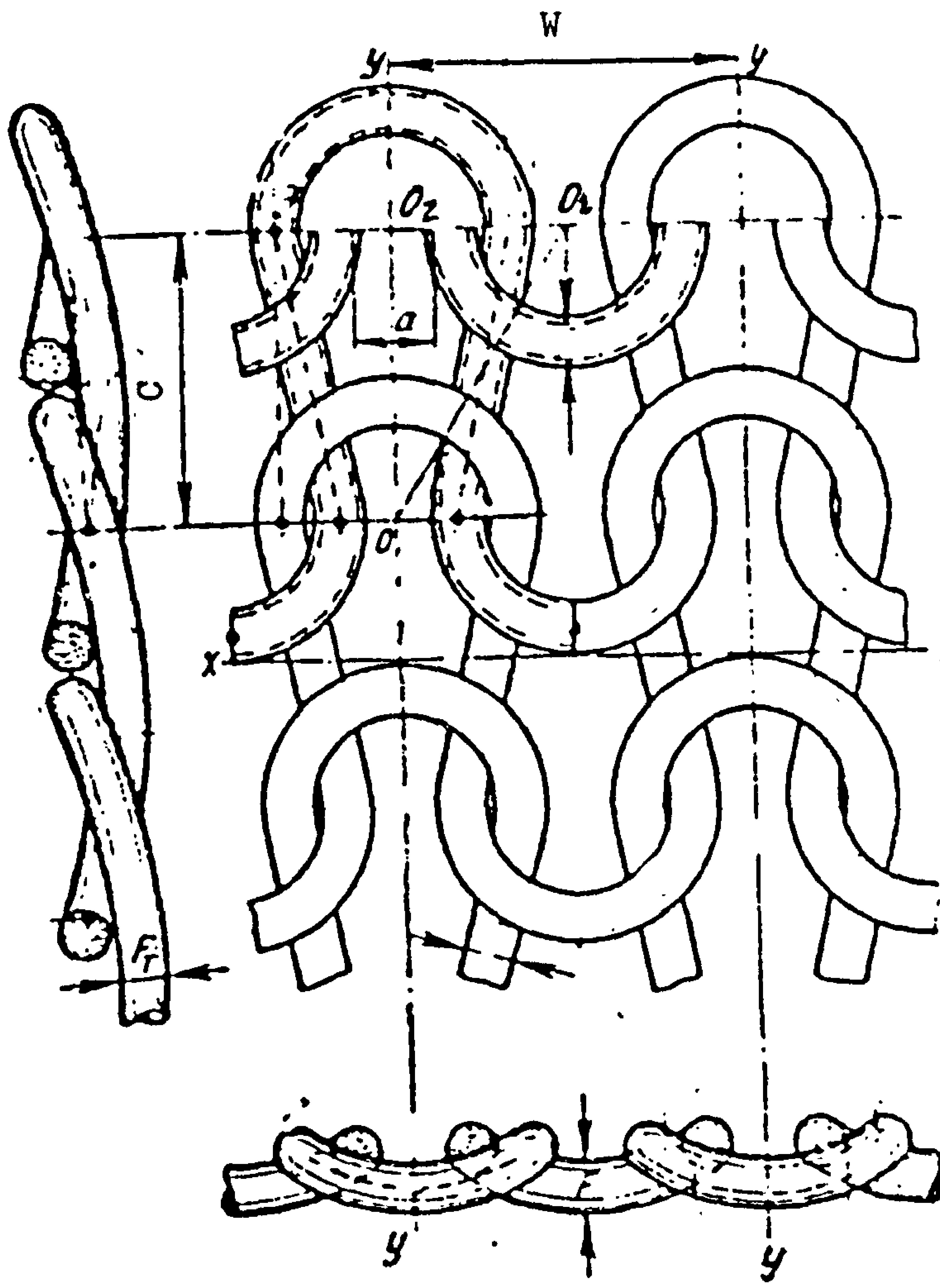

Fig 2: Dalidovich's model of plain loop.

conditions.He specified these conditions as follows: fabric after being treated should not be subjected to ironing or the fabric should be knitted from yarn with high elasticity.

On the basis of the flexural properties of the yarns,Leaf(44) proposed two models of the plain-knitted loop, the first one is a two dimensional and the second is a three dimensional one. The first model which is simpler than the second can be fitted to wet-relaxed fabric only, while the second model is more complicated, but appeared to provide a more complete picture of the plain knitted loop in both the wet relaxed and dry-relaxed states.

Postle and Munden[45] in their analysis of the dry-relaxed knitted loop configurations considered the loop to be a force determined structure, which therefore can be analysed as a function of the forces acting in the plane of the fabric at the points of loop interlocking. They stated, that two parameters may affect the plain-knit loop configuration. These are the loop angle α , which determines the actual shape of the loop and the interlocking angle β , which determines the points of the loop at which interlocking occurs, this is shown in Fig. 3. They concluded that the dimensional parameters, knitted-fabric cover $= \frac{\text{area of yarn}}{\text{area of fabric}}$ and the parameter L/d (the ratio of loop length to the effective diameter of the yarn at the interlocking points in the fabric), can be expressed as a function merely of α and β. They also found that the fabric slackness is related to the parameter L/d and for the practical range of plain-knit fabrics $16 \leqslant L/d \leqslant 20$. For any value of the parameter L/d in this range, the interlocking angle β is a function of the

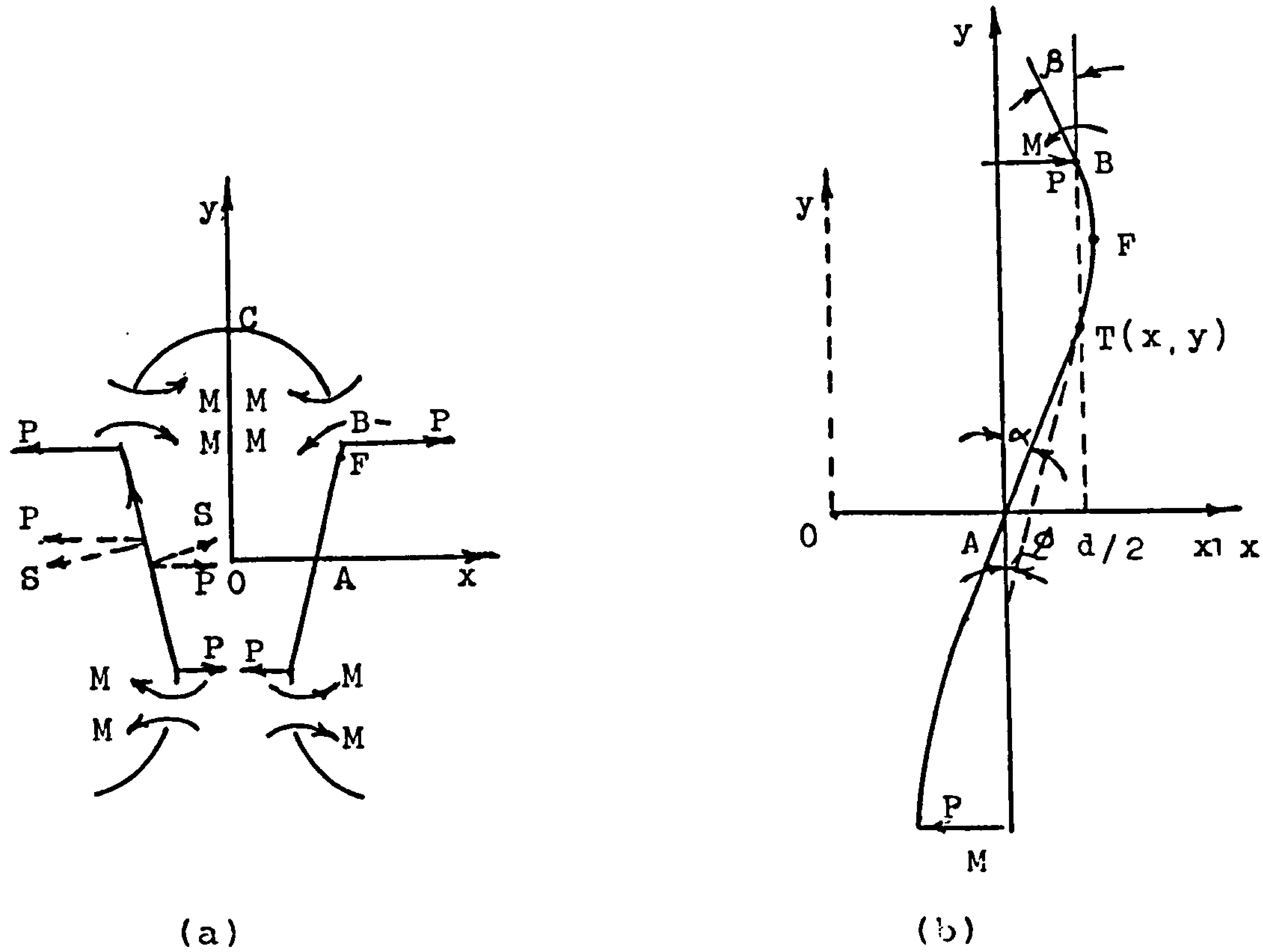

Fig 3: (a) Equilibrium of the loop segments and (b) Geometry of the loop segment AB.

coefficient of static yarn friction μ and the loop angle α can acquire any value that is compatible with the limitation of jamming. Knapton et al(45), in their investigation of the dimensional properties of knitteed wool fabric noted that, the individual values of K_c, K_w, K_s and $\frac{K_c}{K_w}$, while Munden's(40) observations suggest that these values are constant and independent of cover factor $(\frac{\sqrt{tex}}{L})$, which has a value between 13 and 15 for plain-knit worsted fabrics of average tightness of construction and they are also independent of the physical properties of the yarn. In their theoretical analysis of relaxed fabric, Shanahan and Postle(46) supported Munden's view, but they noted that, some deviations in K-values may exist.

2.4 Some physical and mechanical properties of plain knitted fabrics

2.4.1 Fabric thickness

Thickness is an important property for knitted fabrics produced for clothing in general and underwear garments in particular. Because thickness is closely related to weight per unit area, a wide range of samples from selected knitted fabrics were studied by Edwards[47]. He combined the thickness and the weight of the fabric in the form of index ($100 \frac{T}{W}$), to give sufficient information, so that the knitted fabrics can be constructed to any specification of weight and thickness by using the appropriate material and structure. Edwards noted that a large increase in this index occurred as the stitch construction developed. The 1 x 1 rib, half-cardigan, jacquard and tuck-stitch fabrics are definitely distinguished from the plain-knitted fabrics, while the purl-stitch gives the highest values of all. He also noted that compressibility at a given pressure, depends mainly on the fabric structure.

In later work, Edwards[48] studied the fabric thickness in relation to yarn twist and count. The results show that fabric thickness increases with yarn twist although the yarn diameter decreases and this could be attributed to spirality resulting from the twist. He also noted, that the fabric thickness may increase effectively due to the fact that loop is distorted sideways in the plane of the fabric and is also turned on its axis out of the fabric plane. Consequently the fabric produced from the finer yarn may be thicker than that produced from coarser yarn.

Smirfitt[49] used Leaf's[44] three dimensional model for plain-knitted loop and he obtained the following expression for fabric thickness:

$t = 0.09\,L + d$, or

$(t/d) = 0.09\,(L/d) + 1$

While Smirfitt suggests that fabric thickness increases with increases of the loop length, Postle[50] gives the opposite view, that is the fabric thickness increases with decreasing loop length. Peirce[37], on the other hand, found that fabric thickness is a little greater than 2d and he suggested that it may be taken as equal 2d under the slight compression "usually used in measurement".

The results of Knapton et al[45] investigation support Peirce's statement only when the fabric is in a fully-relaxed state, while thickness of dry-relaxed and wet-relaxed is dependent on loop length.

Postle[51] in his study of thickness of fully-relaxed fabrics, has different results. These show that, the "geometrical" thickness (t) increases as the loop length increases. In his work he distinguished the "geometrical" thickness and the "absolute" value of fabric thickness which has the following definition.

$$t_a = \sqrt{\frac{1.3}{g}} \cdot \sqrt{T} \cdot \frac{1}{a}$$

Where, g-Fibre specific gravity

T-Yarn linear density

a-Constant *

This expression appears to suggest, that fabric thickness is dependent on fibre specific gravity and yarn linear density and is independent of loop length but it must be remembered that loop length is also dependent on yarn diameter.

2.4.2 Fabric air permeability

Air permeability is an important property of the cloths because it influences the wind-resistance. It is also an important property of many industrial and technical fabrics[52].

An early work in this area of fabric properties is contributed by Clayton[53]. The work describes in detail the apparatus and the procedure used on testing the air permeability of various fabrics in relation to cloth structure and treatment.

Lord[54] in his work stated that air flow is proportional to pressure for close fabrics, but it is more nearly linearly related to the square root of pressure for open fabrics. Air flow is also proportional

* The constant(a)was missing in Postle's work.

to the area of the specimen within the limit studied. In Lord's view, the definition of air permeability as the flow in unit time through unit area at unit pressure drop across the specimen (cm^3/sec./cm^2.) is desirable. He defined two parameters, air permeability and air resistance and noted that the latter is useful when considering multilayers of fabrics such as clothing, since the air resistance of multiple layers are generally additive.

Oxtoby[55] studied the air permeability of a wide range of open fabrics by using layers of superimposed fabrics. The results have shown, that the relationship between the air flow and the number of layers plotted on a logarithmic scale fitted a straight line . He suggested, where fabrics that permit a high rate of air flow are to be measured for air permeability such as the knitted fabrics, the measurement should be made on multiple layers of fabric at a pressure difference of 10m m. head of water. An estimate of the rate of flow for single fabric layer may then be obtained by extrapolation from a logarithmic plot of the results.

2.4.3 Abrasion resistance

Abrasion is a process of wearing away any part of a material by rubbing that material against another surface[56].

Clegg[57] has shown that abrasion is not the only mechanism occurring in the wear of fabric and the breakdown of a large proportion of the fibres is caused by transverse cracking as the direct results of flexing and bending stresses suffered during wear. Fibres on the surface which are only lightly held suffer gentle abrasion, whilst only those fibres held firmly by packing pressure suffer intense abrasive action.

Backer and Tanenhaus[58] stated that relationship between the fabric geometry and durability exists. They noted that durability of a fabric can be significantly altered by modifying its structural design without change in the fibre used in its manufacture. On the basis of this, it is believed, that lower rate of attrition can be best obtained by increasing the geometric area of contact between fabric and abradant.

Several methods of assessing the extent of abrasion damage are used. The most important of these methods are:

1. The number of cycles required to produce a hole, broken yarn or broken strip.

2. Loss of weight.

3. Change in thickness due to the formation of pills.

4. Loss in strength.

5. Changes in air permeability, lustre and other properties.

Numerous testing machines, which are described as "abrasion testers" have been developed in recent decades. The one which is most suitable for testing the knitted fabric is the Martindale Abrasion Tester.

Tyrer[59] stated that the results of abrasion test can be useful when supplemented by other performance and quality tests not only in the investigation of defects, but in the comparison of fabric as well. On this basis, Hamburger[60] plotted an "energy coefficient" $(\frac{\%\ \text{elongation}}{\%\ \text{ultimate strength}})$ and "durability coefficient" $(\frac{\text{cycles}}{\%\ \text{loss}})$ for four yarns and the result was, that the four points lie on a straight line through the origin, therefore abrasion resistance can be predicted by the use of load-elongation diagram. Elder and Ferguson[61] support Tyrer's idea by noting, that abrasion resistance is closely related to tensile properties of the fibre, such as specific strength or energy of rupture per unit mass.

2.4.4 Tensile properties of knitted fabrics

There is little published work on tensile properties of knitted fabrics and it appears that there is no standard method for testing, but it has been suggested, that whenever possible, the testing procedures should follow the recommended methods of the British Standard Institution or some other authority[11]. Cook and Grosberg[62] studied theoretically and experimentally the load-extension properties of warp-knitted fabrics.

More theoretical analysis has been made by several authors[63-65] on the biaxial load-extension properties of plain-knitted fabrics. de Jong and Postle[66] studied theoretically the tensile properties for extension in two principal direction and they concluded that the major mechanism which governs the ability of a fabric to extend is the freedom of yarn movement within the structure. Hepworth's[67] work was also concentrated on theoretical analysis of the biaxial load-extension behaviour of plain-knitted fabric and found that the load-extension properties are highly depedent on the prevailing jamming conditions.

Numerous tensile testing machines have been developed to meet the variation in testing textile materials. The Denison and the Instron Tensile Testing Machines are more suitable for testing the materials because they are multipurpose testers and the switch from yarn testing to fabric is readily made[11].

2.4.5 Elastic recovery properties of knitted fabrics:

Dillon[68] noted that resilience (the ability of the material to recover from the deformation) is a much abused and poorly defined term and that much remains to be learned about its significance and the factors controlling it. In his work, a conclusion has been reached, that recovery is a general descriptive characteristic which is desirable in most textile materials.

For many end-uses of knitted fabrics, a high recovery is very desirable particularly in hosiery and underwear,even if the value of recovery is to be increased at the expense of tensile strength of the knitted garments.

The knitted fabrics whether they are weft knitted construction or warp knitted construction can be easily deformed. The deformation, taking the extension form in each of the wale direction or course direction, is usualy partially or fully recoverable and is more a function of the structure than of the yarn from which the structure is composed, the value of the extension and the recovery often being very different from those of the yarn[69].

There is also no standard method for elastic recovery tests and most investigators[15,69,70] kept to the principle of Meredith's method[29] although some of them such as Hamburger[71] and Hansen et al[72] used a different technique.

Fletcher and Roberts[73],in their work found that elastic recovery determined by applying loads manually was higher than the elastic recovery determined by the cyclic stress-strain curves, because the time of relaxation was less in the latter method. They also noted that the complete recovery of fabric depends upon the loop length, fabric structure and yarn friction. This view was supported by the results of several workers[15,70,74], which show that the values of recovery are different from one structure of the fabric to another and from one state of fabric relaxation and treatment to another.

CHAPTER 3

EXPERIMENTAL WORK

3.1 Material

A worsted 2/26s (34 x 2 tex) yarn was used to knit plain fabric. Owing to the absence of yarn history certain measurements were carried out to determine some of the yarn properties.

3.1.1 Measurement of the yarn diameter

After reconditioning the yarns, a screen-projection microscpe was used to measure the diameter of the yarns. The number of readings were 200 of both dry-and fully-relaxed yarns. The term dry-relaxed yarn refers to the non-treated yarn which is merely unwound from the cone and left for reconditioning when it is required. The term fully-relaxed yarn refers to the treated yarn. To give the yarn full relaxation treatment, the yarn unwound from the cone in a form of hank was tied in several places to prevent the yarn becoming loose during the operation which was similar to that described in section 3.3.1.2. After this operation, the hank was mounted on the surface of the drum of a tumble dryer machine, using Sellotape, and treated under conditions similar to those used for fabric (3.3.1.3.). Such treatment was given to yarns used for all other measurements.

The mean and the standard deviation of the measurements were calculated.

3.1.2 Measurement of the linear densty

To determine the linear density of both dry-and fully-relaxed yarns, the H.A.T.R.A. course length apparatus was used . Ten specimens were cut for each test, of approximately 1m. One of the specimens was placed in the upper clamp and a tension was applied to the specimen by hanging a mass of 0.5 g/tex. The yarn was allowed to hang freely for 2 minutes after which it was cut at 80cm. and the linear density in tex was calculated by weighing that length.

3.1.3 Measurement of yarn twist

The direct method, the number of specimens outlined by the British Standard Book[75] and manually operated twist meter was used to determine the twist of both dry- and fully-relaxed yarns. The number of readings in each case is 200. All specimens were conditioned at standard atmosphere prior to testing. The results were expressed in terms of turns per 1cm length.

3.1.4 Yarn friction

The method used in the present work for the measurement of yarn/yarn friction was as follows.

In this method, a length of yarn (5cm) was formed in a shape of loop by securing the ends of the yarn at (1cm) distance, using Sellotape as shown in Fig.4. The loop was clamped, in the upper jaw of an Instron Tensile Testing Machine. A length of the same yarn was passed through that loop, one end of the yarn was clamped to the lower jaw and the other end was attached to a known weight (T_1). Ten samples of the yarn were prepared and tested. The cross head speed was 5 in/min and chart speed was 10 in/min. On loading the cross head, the yarn was drawn over the looped yarn and a tension(T_2) was imposed in the fixed side of the yarn. The sum of T_1 and T_2 was recorded on the chart and the tension in the fixed side (T_2) was taken as the mean height of the peaks, above the value of (T_1). The typical trace of friction measurement is shown in appendix II.

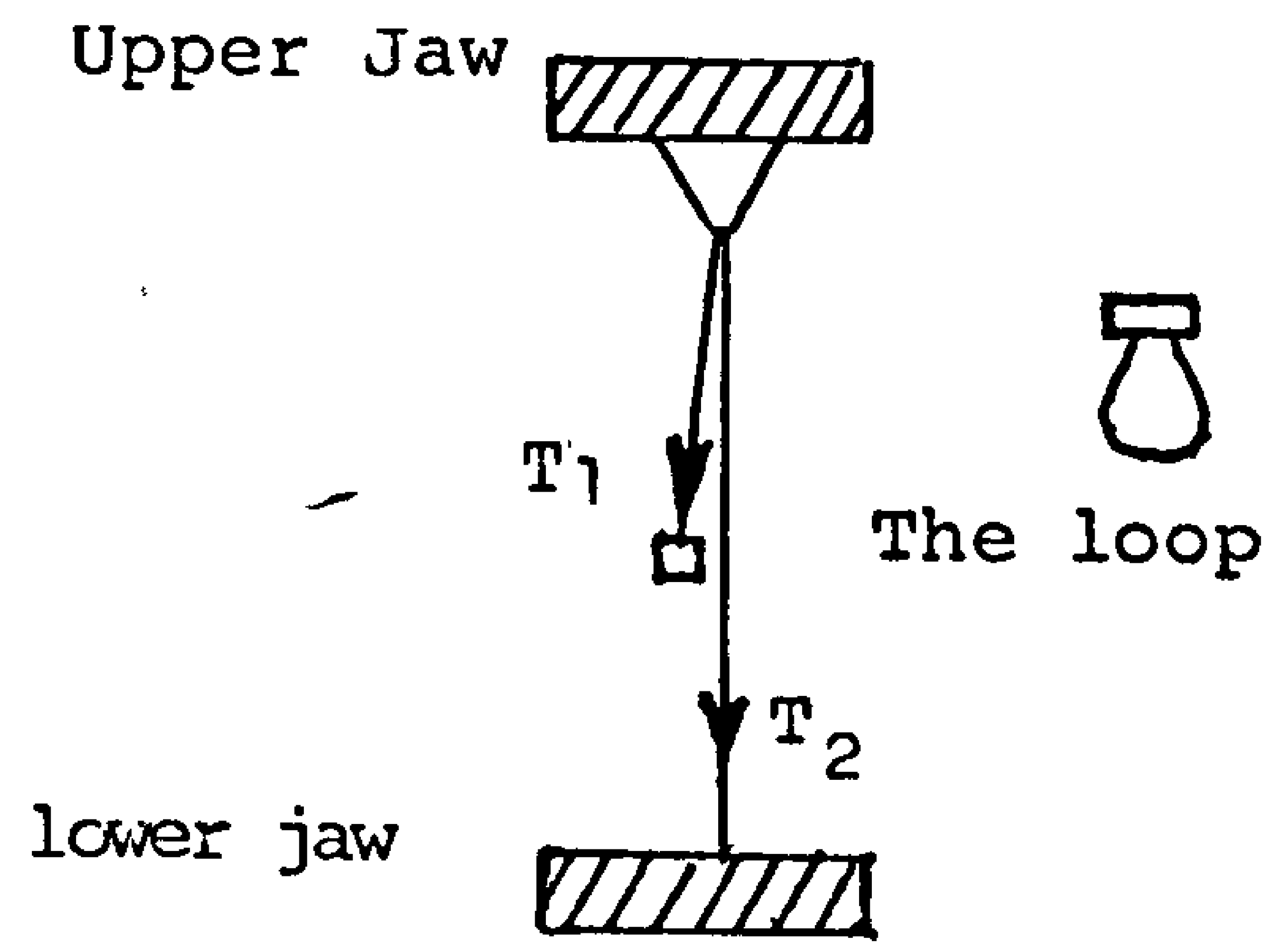

Fig.4: Schematic illustration of yarn friction measurement.

Determining T_2 and T_1, the coefficient of friction (μ) could be calculated from the following equation:

$$T_2 = T_1\, e^{\mu\alpha}$$

$$\log\left(\frac{T_2}{T_1}\right) = \mu\alpha \log e \qquad (\log e = 0.434,\ \alpha = \pi)$$

$$\mu = \frac{1}{\alpha\ 0.434} \log\left(\frac{T_2}{T_1}\right)$$

$$\mu = 0.732 \log\left(\frac{T_2}{T_1}\right)$$

3.1.5 Tensile properties of yarn

Yarns unwound from the cone and given dry-relaxed and fully-relaxed treatment were conditioned in a standard atmosphere for at least 24 hours before testing. The tensile tests were carried out on the Instron Tensile Testing Machine using a 10cm gauge length and rate of traverse of 5in/min. Jaw breaks were ignored. Some yarns extracted from knitted fabrics and also tested. Breaking load in gram force (gf.), extension in percentage (%), tenacity in gram force/tex ($gf.tex^{-1}$) were calculated from recorded extension curves. Twenty readings were recorded for each yarn. The standard deviation of these readings was also calculated.

3.1.6 Elastic recovery properties of yarn

The specimens for this test were prepared as those for tensile test. The yarns were tested on the Instron Tensile Testing Machine with a rate of extension of 5 in/min, using a 10cm. gauge length. Dry- and fully-relaxed samples were tested at different strain level from 2% to 10%. Five cycles of stress-strain recovery tests were carried out at each strain level. In each test, the yarn specimen was extended to the predetermined strain level and held for 30 seconds, then, returned to the original length and given one minute to recover before commencing the next cycle. For each increase in strain a fresh specimen was used.

3.1.7 Loop strength of yarn

To determine the effect of yarn bending on its strength a method described by British Standard Book[27], was used. In this method, the ends of 30cm length of yarn are brought togther, to form a loop, and clamped in the upper jaw of the Instron Tensile Testing Machine. The same length of yarn is threaded through the loop and the ends of this yarn are clamped in the lower jaw of the machine. The gauge length was 30cm, the cross head speed was 5in/min and the chart speed was 10in/min. From the recorded curves, a ratio of loop strength to twice yarn strength was calculated for each specimen.. The mean of ten tests and the standard deviation were determind.

3.1.8 Measurement of the flexural rigidity of yarn

To measure the flexural rigidity of the yarn, a ring loop method was used. Dry-relaxed yarn was conditioned and prepared in a ring form. The ring was formed by tying the yarn round a cylinder of 2.5cm.diameter and making a tight reef-knot. The loop was hung from one end in a groove in the brass rod and was loaded at its lowest point as shown in Fig.5. A chain hung at this point was used to form the load. It hung first with minimum length and the deflection of this point below its position for zero load was noted by using the travelling microscope. The load was applied in steps of 20m m. length of the chain to the maximum length possible and the deflection was noted at each step.

The load (P) was plotted against ($\tan\emptyset/\cos\emptyset$) and the flexural rigidity of the yarn was then calculated by using the following equation:

$$G = K\ P\ L^2\ (\cos\emptyset/\tan\emptyset)$$

where G is the flexural rigidity($g.cm^{-1}$), P is the load (g), L is the circumference of the loop (cm), $K=0.0047$, $\phi = 493\ d/L$ and d is the deflection.

The recovery of the ring loop was determined by noting the deflection at each step of unloading the ring. The deflection values were plotted against load (P) for this cycle of loading and unloading.

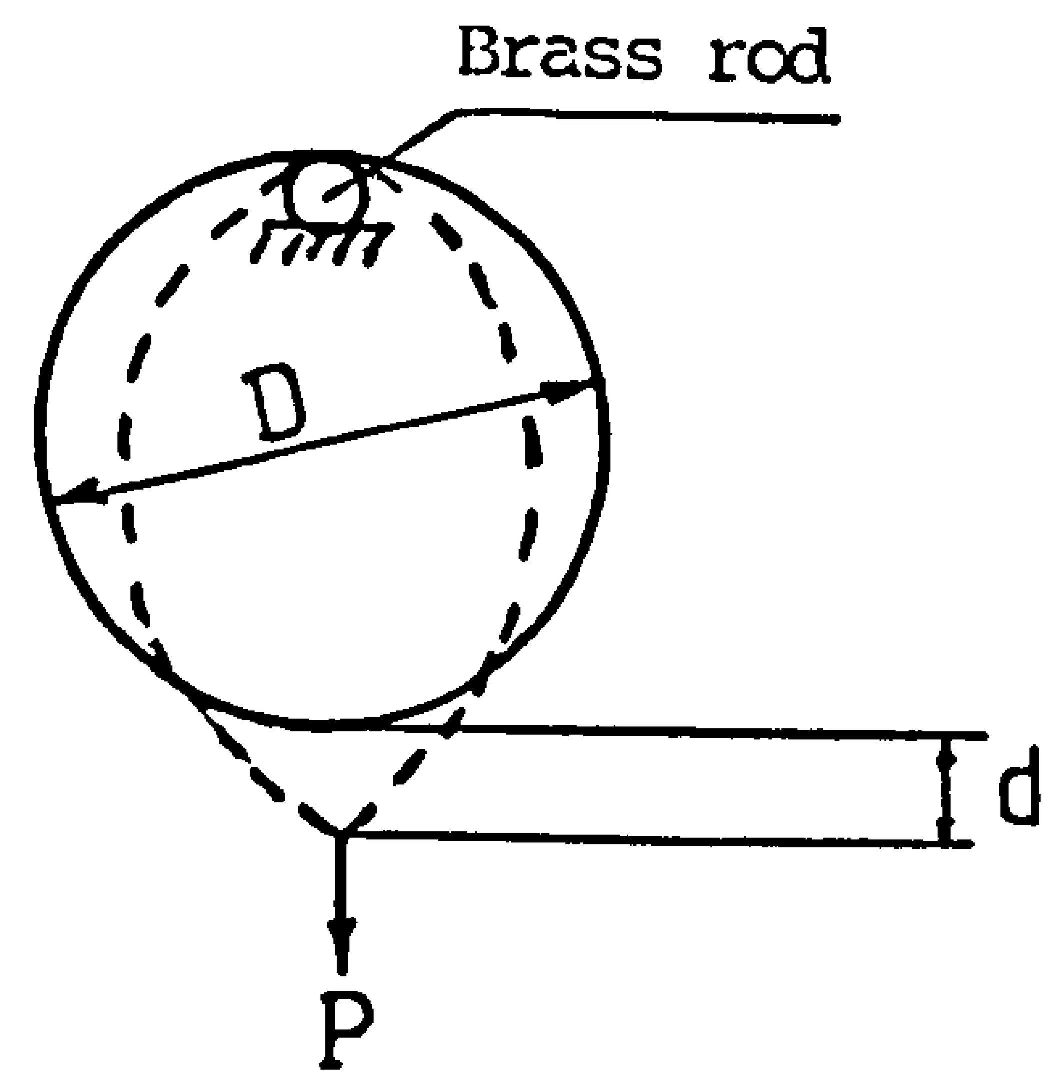

Fig.5: Schematic illustration of flexural rigidity test.

The test was carried out for fully relaxed yarn also but, it has been noted that because of the crimp resulting from the treatment and reconditioning, it was almost impossible to obtain from this yarn a circular loop perfectly suitable for test.

3.2 Knitting machines

To knit plain fabrics, six machines of three different types were used there being a coarse and fine gauge one of each type of machine. Each machine was used to produce as many samples as possible with different loop length. The types of the knitting machines and the details of knitting construction are illustrated in Table 1.

To reduce the variation in loop length of the samples produced in V-bed machines, the plain fabrics were produced by using a single bar only i.e. only the left and right stitch cams have to be adjusted. On the power circular purl

Table 1: Detail of knitting construction

Type of the knitting machine	Machine gauge	No. of feeders used	No. of ends per feeder	Yarn count (tex)	Fabric No.	Range of loop length L (cm)
1. Manual V-bed	5	1	2	34x2+34x2	1-5	0.93-1.39
2. Manual flat purl	5	1	2	34x2+34x2	16-20	0.98-1.51
3. Power circular purl	5	4	2	34x2+34x2	24-28	0.98-1.20
4. Manual V-bed	8	1	1	34x2	6-10	0.73-1.20
5. Manual V-bed	10	1	1	34x2	11-15	0.60-0.96
6. Power circular	11	4	1	34x2	21-23	0.48-0.53

machine, stitch cams of the four feeders were adjusted to the same height for each sample. Similarly in the power single cylinder circular machine, the sinker cams of the four feeders were also adjusted to the same height for each sample.

3.3 Experimental fabrics

All samples produced as outlined in 3.2 were divided into three sets for dry, wet and full-relaxation treatment.

3.3.1 Relaxation treatments

During the knitting process, the yarn is subjected to different deformations; tension, bending and torsion, resulting in stresses being set up in the structure. To remove or to reduce these stresses to the minimum, different relaxation treatments were applied to the samples.

3.3.1.1 Dry-relaxation treatment:

To achieve dry-relaxation, the fabrics were placed on a flat smooth surface in a standard atmosphere (20 $\pm$ 2°C and 65 $\pm$ 2% R.H.) for at least 24 hours.

3.3.1.2 Wet-relaxation treatment

To achieve wet-relaxation treatments, the fabrics were placed in water at 40°C containing one gram per litre of Teepol for 20 minutes and subjected to agitation. The machine used for this operation is a miniature paddle dyeing machine. The fabrics were briefly hydroextracted and then placed on a flat smooth surface in a standard atmosphere for at least 24 hours.

3.3.1.3 Full-relaxation treatment

Full-relaxation treatment was achieved by repeating the same operation described in section 3.3.1.2, but after the fabrics were briefly hydroextracted, they were left in a tumble dryer at 70°C for one hour and placed on a flat smooth surface in a standard atmosphere for at least 24 hours.

3.4 Geometry and dimensional properties of knitted fabrics

All fabrics were conditioned in the standard atmosphere of 20 $\pm$ 2°C and 65% $\pm$ 2% R.H. for at least 24 hours before any measurements were made.

3.4.1 Measurement of loop length:

The length of yarn in one structural unit cell is defined as the loop length. Thus the length of yarn in certain number of wales was measured on the H.A.T.R.A. course length tester in which a load of 10g was used to remove the knitting crimp. Ten readings from each fabric sample were recorded and the mean value of the loop length in centimeters was calculated.

3.4.2 Course and wales per unit length:

The number of courses and wales per ten centimeter length and width of the fabric were measured by using a counting glass. The reading for each direction was recorded and the mean value was obtained. Then the results were expressed in terms of courses and wales per centimeter.

3.4.3 Fabric weight:

Five samples 5cm. x 16cm. were cut from each fabric sample and weighed. The results were expressed in g/m^2.

3.4.4 Fabric thickness

Fabric thickness was determined by using a Shirley Thickness Tester. Three different pressures ($1.3g.cm^{-2}$, $2.2g.cm^{-2}$ and $4.4g.cm^{-2}$) were used. The measurements were carried out as specified by British Standard Institution.

3.5 Wear resistance of knitted fabrics:

The wear resistance of the fabrics was determined by testing specimens from each fabric samples on Martindale Abrasion Testing Machine.

The plain fabrics, unlike the woven fabrics and most of the knitted fabrics from other constructions, curls and buckles due to the internal forces and this causes great difficulties in carrying out the test. To prevent this,each specimen was backed with gummed paper.

The principle of end point determination by weight loss with intermediate weighings at 400 rubs, was used. The number of intervals used were five. The tests procedures and the specification of the standard abrasive surface used were as recommended by the British Standard Handbook[75].

3.6 Fabric air permeability

The Shirley Air Permeability Apparatus was used for the measurements of air permeability of the fabrics, as described by the British Standard Institution.

In many cases the fabrics were so open that it was not possible to operate the apparatus at a pressure difference, (P) of 10 m m. head of water. However, the alternative method stipulated in the British Standard Handbook[75] was not used because of the non-linear relationship between the mean flow and pressure difference.

Instead, the tested area was reduced from $3.93 cm^2$ to $0.785 cm^2$ to obtain the 10 m m. pressure drop (P). After being conditioned for 24 hours in standard atmosphere , five layers were tested twice, face and back, and the average value of the air flow in cm^3 per sec. at 1 cm. head of water was taken as a characteristic of the air flow value of the fabric.

3.7 Tensile properties of knitted fabrics

Specimens 16 cm. in length and 5 cm. in width were cut from each fabric sample in both walewise and coursewise directions. The specimens were clamped between the upper and lower jaws of an Instron Tensile Testing Machine at gauge length of 10cm, and the rate of traverse was 5in/min and they were not subjected to the pre-tensioning.

Five readings(in some very few cases three and four readings)were obtained, for each fabric in both walewise and coursewise directions. From the load-extension curves, the mean value of breaking load (gf.) and the extension [%] were recorded. The maximum extension of course spacing and wale spacing were also calculated from the load-extension curve. The test was carried out for samples in both the dry- and fully-relaxed states.

3.8 Elastic recovery properties of knitted fabrics

Specimens with size 16cm.in length and 5cm.in width were cut in both walewise and coursewise directions from fabric samples in both the dry- and fully-relaxed states. The gauge length in the Instron Tensile Testing Machine was set at 10cm and the cross head speed at 5in/min. Fabric pre-tension was not applied. The method used to determine the fabric recovery is as follows:

From Fig. 6, the specimen was extended to the predetermined strain level (OC) giving the load-extension curve (OM). The specimen was held at this level of strain 30 seconds, to permit stress relaxation to occur from (M) to (D). The stress on specimen was then removed and the immediate recovery (CB) which referred to as the

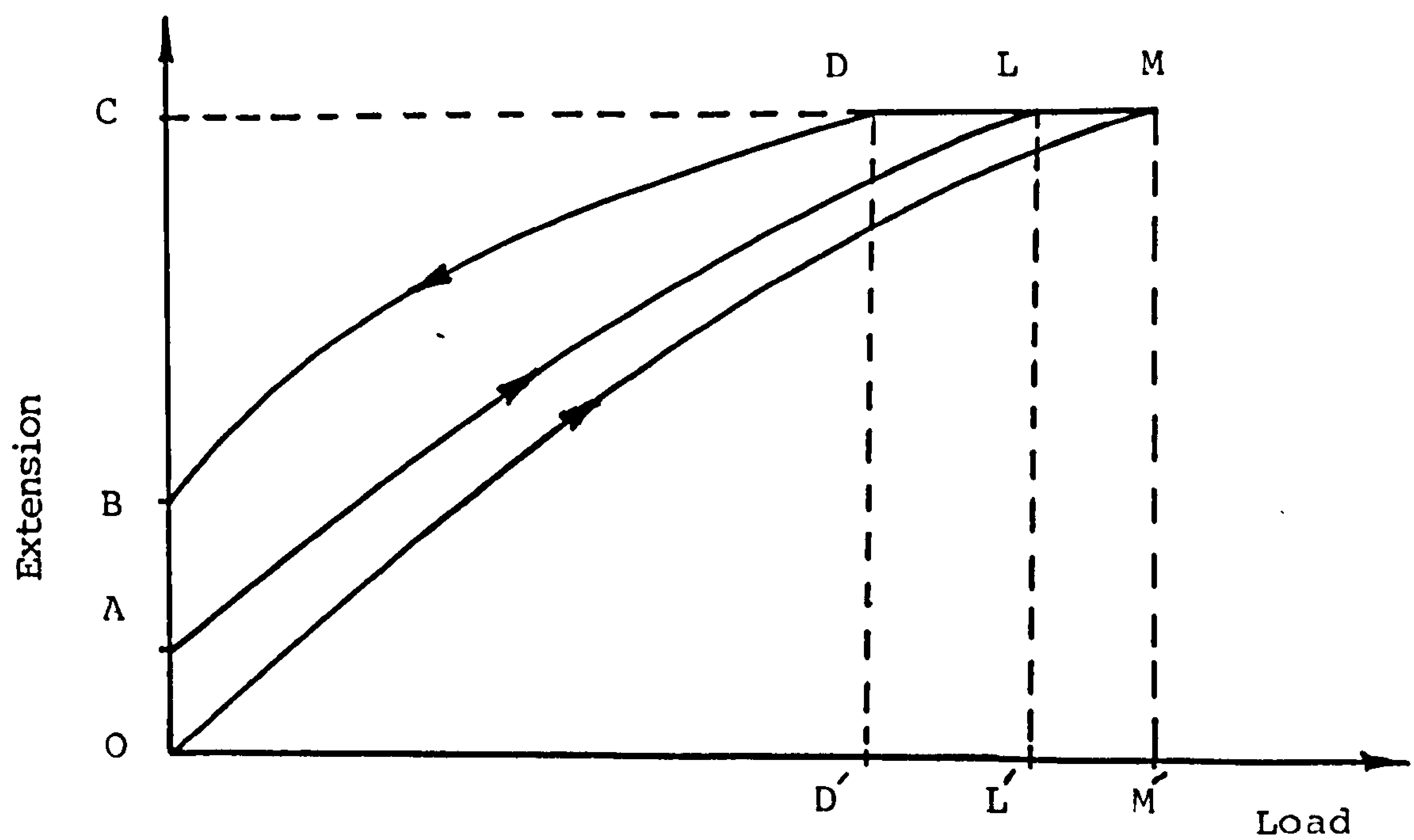

Fig. 6 : Typical diagram of cyclic elastic recovery measurement as obtained from Instron Tensile Testing Machine.

"Initial Elastic Recovery" was recorded. The specimen was then kept free of stress for one minute to allow for further recovery (BA) to occur before recording the curve (AL), of the next cycle. The recovery (CA) is referred to as the"Total Elastic Recovery"of the specimen from its original cycle.

Five cycles of loading and unloading the specimens at each strain level was recorded. From the curves obtained, the initial elastic recovery and total elastic recovery of the first and fourth cycles were determined by:

$$\text{Initial Elastic Recovery I.E.R.} = \frac{CB}{CO} \times 100\ (\%)$$

$$\text{Total Elastic Recovery T.E.R.} = \frac{CA}{CO} \times 100\ (\%)$$

A fresh specimen was used for each increase in strain level and the load was also determined.

CHAPTER 4

SOME PHYSICAL AND MECHANICAL PROPERTIES OF THE YARN

Although the properties of the knitted fabric are governed by the geometry, structure and finish, the properties of yarn from which the fabric is made may contribute to the ultimate properties of that fabric. In a knitted fabric the yarn is in a sense both the raw material and the finished product . It may be assumed that to assess the fabric properties, it is necessary to look at the appropriate yarn properties.

4.1 Yarn diameter:

The yarn diameter is an important dimension required in the study of fabric geometry. Different assumptions of cross-sectional shape of the yarn were suggested, but the general acceptable shape used was the circular shape [11] Whatever the cross-sectional shape may be assumed, it could be distorted when this yarn interlaced with other yarns and perhaps flattened during ironing and calendering. In this case the nominal diameter of the yarn may be calculated by the following formulae:

$$d = 0.0367 \sqrt{Tex \cdot V}$$

where V - is specific volume of the yarn,

The value of the specific volume, V of the worsted yarn is 1.32[76] then,

$$d = 0.041 \sqrt{Tex}$$

The general approach of deriving that formulae is in appendix II. The calculated and the measured diameter and the S.D. of the 200 diameter readings are shown in Table 2. The difference between the measured diameter of dry -relaxed yarn and fully-relaxed yarn shown in Table 2 is significant at 1% level. However the calculated

Table 2: Measured count(tex), measured diameter, S.D. and calculated nominal diameter of both the dry-and-fully-relaxed yarns.

Yarn	Measured count (tex)	Actual measured diameter (mm)	S.D.	Nominal calculated diameter (mm)
Dry-relaxed	66.6	0.398	0.068	0.335
Fully-relaxed	67.2	0.461	0.088	0.336

nominal diameter of dry-relaxed yarn is much closer to the measured diameter than the calculated nominal diameter of fully-relaxed yarn. This is probably due to the fact that the yarn becomes more bulky after full relaxation treatment and the contraction of yarn resulting from the treatment has little effect on the diameter. It can be noted from Table 2, that standard count measured in laboratory is lower than that given by the manufacturer. The count given by the manufacturer is 68.1 and the measured count is 66.6 tex.

4.2 Yarn twist

The effect of twist on the knitting performance has obtained little attention and most of the work is concentrated on the effect of twist upon the properties of knitted fabrics. This is probably because the twist has no or little effect on knitting performance.

From the spinning point of view the direction of twist in a single yarn generally is (Z) direction and in a doubled yarn is (S) direction, the twist factor in single yarn is higher than normal so that during doubling some of the singles twist will be removed and the result is that a normal amount of twist per unit length in the singles yarn will occur.

When the direction of twist in both single yarn and doubled yarn is similar,i.e.(S) direction or (Z) direction, the twist factor in the single should be lower than normal so that when singles are doubled in the same direction, the single twist will increase and reach the normal amount of twist per unit length of the singles yarn.

The yarn suppliers, very rarely, give full information for designation of the yarn structure. The necessary information for manufacturing and research works, is usually obtained experimentally.

The amount of twist, the direction of twist and the twist factor of single and doubled yarns in dry- and fully-relaxed state of relaxation are shown in Table 3.

Table 3: Twist and Twist factor of single and doubled yarns

Yarn type	Relaxed State	Linear Density (tex)	Twist (t/cm)		Twist factor (turns/m · tex $\frac{1}{2}$)	
			Doubled (S)	Single (Z)	Doubled (S)	Single (Z)
Worsted	Dry	33.3 x 2	2.17	3.56	17.7	20.5
2/26s	Fully	33.6 x 2	2.26	3.90	18.5	22.6

The twist factor has greater practical and mechanical importance than the twist. Yarns from high quality fibres normally do not require high twist factor and vice-versa.

For the knitting industry, the importance of doubling is that, it increases the regularity and reduces the rate of defects in the yarn . In knitting, it is general practice to use several separate ends of a fine yarn rather than to use a single mutli-folded yarn to knit bulky fabrics, and experiments show , that change in dimensional parameters(K) when more ends of yarn are used, is greater than any brought about by altering yarn twist or quality [49].

4.3 <u>Yarn flexural rigidity</u>

The yarn in the plane of knitted fabric is being bent regularly in almost circular shape of radius depending primarily on the course and wale relationship. Furthermore, the unit of knitted fabric is actually a three dimensional structure, and as can be seen from the Fig. 2, a considerable degree of bending can occur in all three principal planes and not only in one plane. Thus, an examination of yarn properties which describe its flexing or bending characteristics is of great importance.

The results of flexural rigidity test which are described in section 3.1.8, are shown in Table 4. From this table, the weight(P) values were plotted against tanØ/cosØ for both dry-and fully-relaxed yarns as shown in Fig.7. Thus, the slope of the curve gives the value of P x cosØ/tanØ and this value is used to calculate the flexural rigidity of both yarns. The calculation shows that the mean of the flexural rigidity of the eight steps are the same for both yarns(0.034), but the S.D. is somewhat different, for dry-relaxed yarn it is 0.006 and for fully-relaxed it is 0.01

As can be seen from Fig.7, the relation obtained is fairly linear for the dry-relaxed yarn, but a deviation from this relation is noted for fully-relaxed yarn. This probably occurred due to the unavoidable error; a distortion in the circular shape of the yarn after reconditioning it for 24 hours is observed and a relative reduction in the diameter of the circle may have occurred due to the relaxation treatment. Perhaps, the effect of these errors could be seen more clearly in Fig.8, where the deflection(d) was plotted against the weight(P)for both yarns for the whole cycles of loading and unloading. As can be seen from this Fig., the deflection(d)

Table 4: Results of flexural rigidity test of Dry and Fully-relaxed yarns

Step No.	Weight P (g)	Dry-relaxed yarn loading Height (cm)	Deflection d (cm)	$\emptyset = 493\, d/_L$	$\frac{\tan\emptyset}{\cos\emptyset}$	Dry-relaxed yarn unloading Height (cm)	Deflection d (cm)	Bending Recovery B_r %	Fully-relaxed yarn loading Height (cm)	Deflection d (cm)	$\emptyset = 493\, d/_L$	$\frac{\tan\emptyset}{\cos\emptyset}$	Fully-relaxed yarn unloading Height (cm)	Deflection d (cm)	Bending recovery B_r %
1	0.0569	3.078	0.552	34.3	0.826	3.247	0.721	69.1	3.189	0.663	41.2	1.164	3.310	0.784	70.0
2	0.1710	3.310	0.784	48.7	1.724	3.428	0.902	36.0	3.370	0.844	52.5	2.140	3.438	0.912	38.4
3	0.2850	3.413	0.887	55.1	2.505	3.495	0.969	23.8	3.443	0.917	57.0	2.824	3.495	0.969	24.3
4	0.3990	3.488	0.962	59.8	3.416	3.530	1.004	17.4	3.495	0.969	60.2	3.513	3.525	0.999	16.8
5	0.5130	3.538	1.012	62.9	4.285	3.550	1.024	13.7	2.535	1.009	62.7	4.220	3.548	1.022	11.1
6	0.6270	3.565	1.039	64.8	4.988	3.583	1.057	7.7	3.555	1.029	63.96	4.639	3.565	1.039	6.9
7	0.7402	3.595	1.069	66.4	5.723	3.600	1.074	4.5	3.570	1.044	64.9	5.035	3.585	1.059	2.0
8	0.8540	3.625	1.099	68.3	6.810	3.625	1.099	0.0	3.593	1.067	66.3	5.667	3.593	1.067	0.0

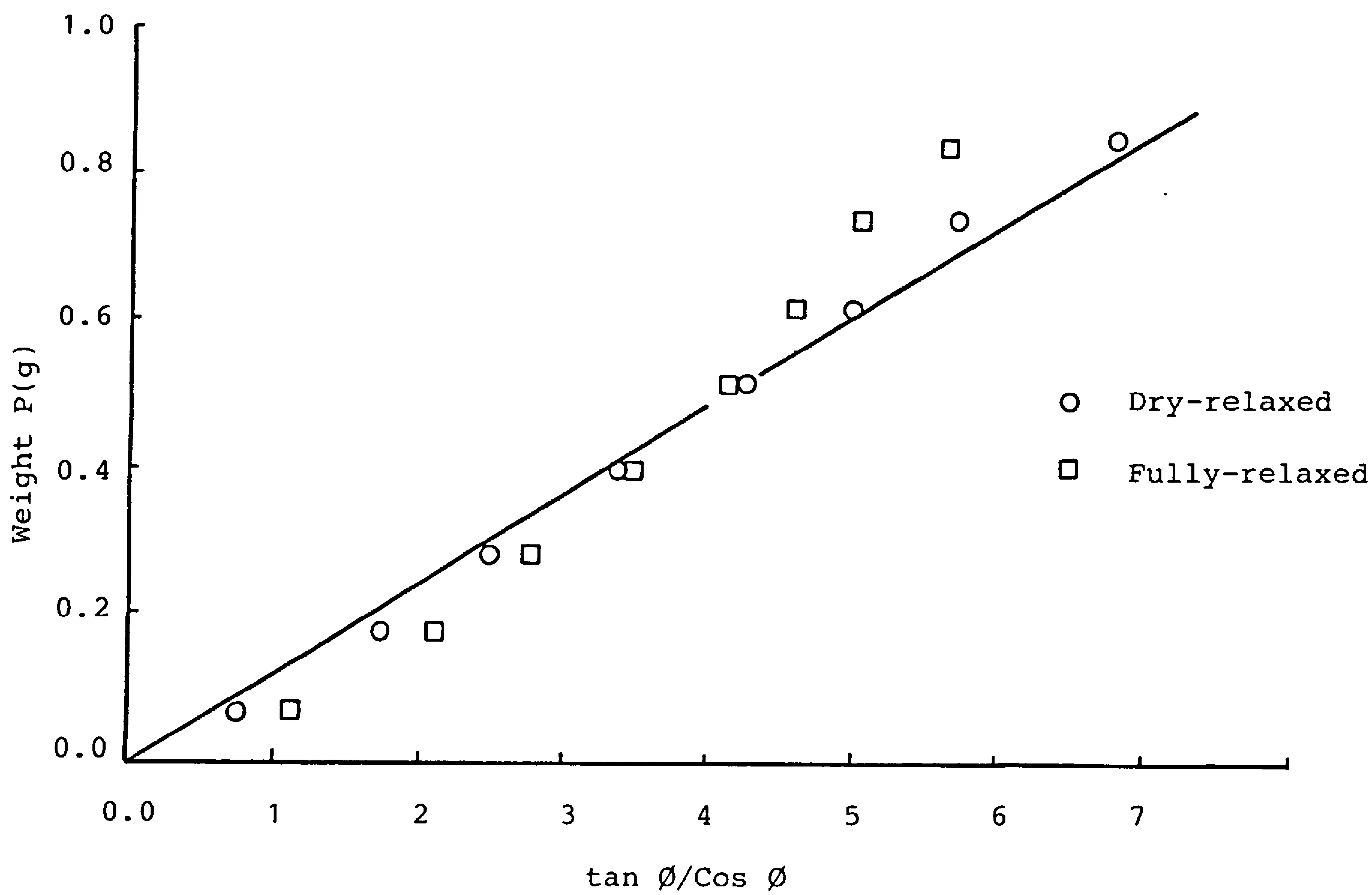

Fig. 7 : Plot weight P against tan Ø/Cos Ø

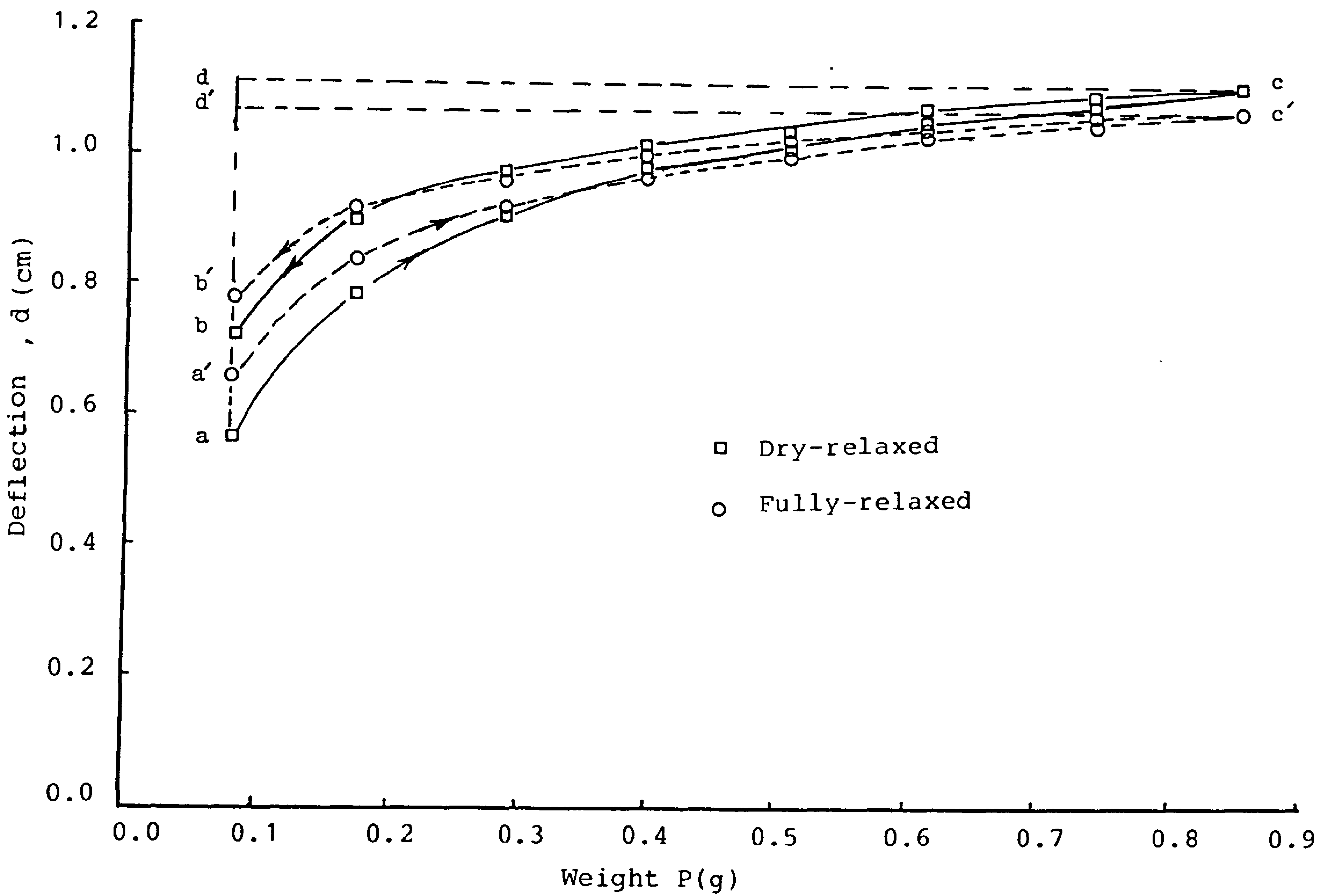

Fig. 8 : Deflection - Weight curves in loading and unloading cycle for dry- and fully-relaxed yarns

of fully-relaxed yarn initially, is greater than the deflection of dry-relaxed yarn, and then, as the loading proceeds, the deflection becomes lower. Apart from this, the load-deflection curves of both yarns are almost identical.

The values of bending recovery of each step represented in Table 4, was calculated by the following expression:

$$Br = \left(\frac{du - di}{du - d1}\right) \cdot 100$$

where, du - maximum deflection.

d_1 - deflection at first loading step.

di - deflection at particular unloading point.

It can be seen that the values of final bending recovery of both yarns are very close. Flexural rigidity was calculated by the folowing expression:

$G = K.P.L^2\ (Cos\emptyset/tan\emptyset)$ giving $G = 0.036\ gf.cm^2$.

Unfortunately, the value of flexural rigidity of the yarn used in this work cannot be compared with those used in the works of other researchers[33,35,70] because either the method of test employed or the type of yarn used is different. However, it is possible to compare the bending recovery of the yarn used in this work which was 69% with that used in Ugbolue's [70] work which was 84 %. The low value of bending recovery of present yarn could be attributed to the fact, that its structure is different, i.e. lower value of twist per meter and perhaps it has lower fibre quality.

It is worth noting, that the value of the flexural rigidity presented in Table 4 for each step, was found to be very close to the value obtained by using Owen's [34] exact solution method of calculation.

The curves of bending recovery presented in Fig.8, were used to calculate the work recovery of both dry- and fully-relaxed yarns. The work recovery $= \frac{S\ bcd}{S\ adc}$ where S, is the area under the curve . The calculation shows that the values of work recovery of both yarns are very close. They are 0.64 for dry-relaxed yarn and 0.65 for fully-relaxed yarn.

4.4 <u>Yarn friction</u>

Yarn friction may not only influence the knitting performance, but it also has importance in determining the relaxed state of knitted fabrics, particularly in the dry-relaxed state [31]. The yarn friction importance in the knitted construction is shown experimentally by the significant hysteresis effect observed in load cycling. Doyle [31] observed that in the looser plain construction in particular, the possibility of slippage in addition to rotation at the intersections of the loops adds to the hysteresis effect on release of the stretching forces. Similar observations were made by Cook and Grosberg [62] for load-extension properties of warp-knitted fabrics.

To remove or at least to reduce the effect of frictional forces on knitting performance to an acceptable level, yarn is often waxed or lubricated.

The coefficient of friction values and the S.D of the dry-and-fully relaxed yarns are shown in Table 5. By using the t-test, the difference between the value of dry-relaxed and the value of fully-relaxed is significant at 1% level.

It is clear, depending on the condition of test, that these values may be influenced by the length of the support loop[15]. This is simply because the area of contact

Table 5: Coefficient of friction and S.D of dry-and-fully-relaxed yarns.

Yarns	μ for T_1=100g	S.D.	μ for T_1=50g
Dry-relaxed	0.16	0.022	0.18
Fully-relaxed	0.26	0.036	-

between the yarns changes as these two factors change and this affects the value of yarn coefficient of friction. As can be seen from the Table 5, the coefficient of friction of fully-relaxed yarn is increased from 0.16 to 0.26. This increase is due to change in yarn diameter, hairness and possibly the removal of lubrication resulting from the treatment. This increase is significantly high in comparison to the increase in the yarn coefficient of friction from dry-relaxed state to wet-relaxed state in Feltaous's[15] work, which on average increased by only 14%.

It would also be seen from the table that, the change in T_1 at this level of about $1 g.tex^{-1}$ has little effect on the ratio $\frac{T_2}{T_1}$ and consequently on the coefficient of friction value. Such effect, with a certain limit of of T_2 values beyond which the ratio $\frac{T_2}{T_1}$ will remain constant, was reported by MacRory and MacNamara[77].

4.5 Tensile properties of yarn

The tensile properties of the dry-and fully-relaxed worsted yarns are shown in Table 6. As can be seen, the effect of full relaxation treatment on the results is great. The tenacity of fully-relaxed yarn is not very much lower than the tenacity of dry-relaxed yarn, but the initial modulus and the secant modulus are less than a half and the extension at break has been more than doubled.

As a result of the full relaxation treatment, the yarns become highly crimped and, apart from the effect of swelling and overall relaxation of tension in the low-twist yarns, the additional crimp due to axial shrinkage would appear to have affected both the extension at break and the initial modulus. During the tensile test, it was difficult to isolate the contribution of this induced crimp without stretching the yarns. Multiple ends of yarn were not tested because the values were expected to be very close to those of individual yarns and this was confirmed by Ugbolue[70].

The results of 50 tests of each yarn show that the S.D. of the readings is 42gf for dry-relaxed yarn and 37gf for fully relaxed yarn. The difference in the strength of the

Table 6. Tensile properties of dry- and fully-relaxed worsted yarns

Yarns	Tensile Properties				Elastic Recovery Properties						
	Tenacity (gf/tex)	Extension at break (%)	Initial Modulus gf/tex	Secant Modulus at break gf/tex	Strain level %	First Cycle load (g)	First Cycle I.E.R. (%)	First Cycle T.E.R. (%)	Fourth Cycle load (g)	Fourth Cycle I.E.R. (%)	Fourth Cycle T.E.R. (%)
Dry-relaxed					3	114	53.1	48.3	104	48.3	46.9
worsted					4	157	44.5	49.0	140	43.0	43.5
2/26s	6.3	10.9	122.5	56.9	5	274	43.2	48.4	212	41.6	43.6
(66.6 tex)					6	309	39.6	48.9	245	34.9	39.9
	(strength) (426gf.)				8	372	29.9	48.5	276	26.0	38.2
Fully-relaxed					6	125	26.7	40.0	86.6	20.0	30.0
worsted					8	146	26.6	36.1	88.0	21.0	27.9
2/26s	5.3	22.8	47.7	22.4	9	159	23.5	36.4	132.0	18.8	20.0
(67.2 tex)					10	212	19.9	33.7	136.0	18.9	24.1
	(strength) (357gf.)				11	250	19.0	40.9	140.0	16.1	32.3

two yarns is significant at 1% level.

4.6 Elastic recovery properties

The results of elastic recovery measurements given in Table 6, show unexpectedly poor properties of this wool yarn in comparison with the results obtained previously [15,70]. This is probably due to what was stated before, that is because the yarn has lower twist per unit length and possibly the poor quality of the fibre from which the yarn was made.

It can be noted from those results that, for the same value of strain, the load required for dry-relaxed yarn is often over twice the value required for fully-relaxed yarns. This again is the effect of the full relaxation treatment which results in an overall reduction in the magnitude of the yarn internal forces and stresses imparted to the yarn during the manufacturing process.

It can also be noted from the results in Table 6, that in a cyclic test, the load required to maintain the yarn at a specific strain is less in the fourth cycle than in the first cycle. Deformation due to cycling is not recovered completely at the end of each cycle, part of it becomes permanent, which is characterised as plastic deformation, and the accumulated residual strain in the sample will reduce the load required to maintain it at that specific strain. Here again, the rate of reduction in load to maintain a specific strain in cyclic test of fully-relaxed yarns is greater than in cyclic test of dry-relaxed yarn.

At higher strain levels, the plastic deformation of both dry- and fully-relaxed yarns becomes greater. Consequently, the values of elastic recovery deteriorate. This may be due to plastic flow of fibres and slippage within and between fibres from which that yarn is made.

4.7 Loop strength of yarn

If a filament or yarn is looped, it will break more easily than when it is straight. This happens when a yarn is bent to a small radius of curvature as in knitting. The reduction in strength is due to the initiation of breakage by the high extension of the outside layers.

There is very little work in assessing the bending effect on the yarn strength. Bohringer et al[78] tested various fibres and found a loop strength which was 85% of the normal tensile strength: the reduction in strength was greatest in fibres with the lowest elongation at break.

The loop strength value as a mean of 20 results of each dry-and-fully-relaxed yarns, was 816gf for dry-relaxed yarn and 662gf for fully-relaxed one. The bending effect, therefore, will be; for dry-relaxed $\frac{816}{2 \times 426} = 0.96$ and for fully-relaxed $\frac{662}{2 \times 357} = 0.93$. These results show that the bending effect on the yarn strength is not very great, but the difference between these two results is significant at 1% level.

CHAPTER 5

GEOMETRY, AIR-PERMEABILITY AND ABRASION RESISTANCE OF PLAIN-KNITTED FABRICS

5.1 Fabric geometry and dimensional properties

To determine the numerical values of Kc, Kw, Ks and then the shape factor Kc/Kw, it is usual practice for most research workers in this field to plot numbers of courses per inch $C_{p.i.}$ against $1/L$, number of wales per inch $W_{p.i.}$ against $1/L$ and number of stitches per unit area or stitch density S against $1/L^2$. The gradient of these plots represents the above K-values.

In the present work, the same technique has been used, but the centimetre has been used instead of the inch as the standard length. In addition to this technique, a numerical regression equation of these linear relation has also been employed.

The dimensions and the calculated parameters of dry- and fully-relaxed fabrics made from one end of yarn are presented in Table 7 and 8 and those of fabrics made from two ends of yarn are presented in Table 9 and 10. It should be noted that the fabrics have been arranged in each of these tables in orders of loop length and therefore they do not appear in the same sequence in each table.*

The statistical analysis of the measured courses per unit length of each fabric presented in above tables show (see Appendix III) that C.V. and the standard error are satisfactorily low.

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* This arrangement will be used in all subsequent tables.

Table 7 : Dimensions and Parameters of One-end Dry-relaxed Fabrics.

Fabric No.	loop length L (cm.)	1/L	$1/L^2$	Course Spacing C_s (cm.)	Wale Spacing W_s (cm.)	Course per cm $C_{p.c.}$	Wales per cm $W_{p.c.}$	Density per cm^2 S	Individual values Kc	Kw	Ks	$\frac{Kc}{Kw}$	Cover Factor, K $tex^{\frac{1}{2}}.cm^{-1}$
21	0.48	2.09	4.30	0.099	0.132	10.1	7.6	76.8	4.8	3.6	17.3	1.33	17.0
22	0.52	1.92	3.69	0.112	0.137	8.9	7.3	65.0	4.6	3.8	17.5	1.21	15.7
23	0.53	1.89	3.56	0.114	0.143	8.8	7.0	61.6	4.7	3.7	17.4	1.27	15.4
11	0.60	1.67	2.79	0.120	0.169	8.3	5.9	49.0	5.0	3.5	17.7	1.43	13.6
12	0.68	1.47	2.16	0.141	0.185	7.1	5.4	38.3	4.8	3.7	17.6	1.30	12.0
6	0.73	1.37	1.87	0.154	0.200	6.5	5.0	32.5	4.7	3.7	17.4	1.27	11.2
7	0.77	1.30	1.66	0.156	0.222	6.4	4.5	28.8	4.9	3.5	17.0	1.40	10.6
13	0.80	1.25	1.56	0.164	0.233	6.1	4.3	26.2	4.9	3.4	16.9	1.44	10.2
8	0.88	1.14	1.30	0.189	0.250	5.3	4.0	21.2	4.7	3.5	16.5	1.34	9.3
14	0.90	1.11	1.23	0.192	0.270	5.2	3.7	19.2	4.7	3.3	15.7	1.42	9.1
15	0.95	1.05	1.10	0.200	0.286	5.0	3.5	17.5	4.8	3.3	15.8	1.46	8.6
9	0.98	1.02	1.05	0.204	0.303	4.9	3.3	16.2	4.8	3.2	15.5	1.50	8.3
10	1.21	0.83	0.70	0.238	0.370	4.2	2.7	11.3	5.1	3.3	16.7	1.55	6.7

Table 8 : Dimensions and Parameters of One-end Fully-relaxed Fabrics

Fabric No.	loop length L (cm.)	1/L	$1/L^2$	Course Spacing C_s (cm.)	Wale Spacing W_s (cm.)	Course per cm $C_{p.c.}$	Wales per cm $W_{p.c.}$	Density per cm^2 S	Individual values Kc	Kw	Ks	$\frac{Kc}{Kw}$	Cover Factor, K $tex^{\frac{1}{2}}.cm^{-1}$
21	0.47	2.13	4.50	0.093	0.114	10.8	8.7	95.0	5.1	4.1	20.9	1.24	17.4
22	0.50	2.00	4.00	0.101	0.125	9.9	8.0	79.2	5.0	4.0	20.0	1.25	16.4
23	0.52	1.92	3.61	0.104	0.128	9.6	7.8	74.9	5.0	4.1	20.5	1.22	15.7
11	0.57	1.75	3.06	0.109	0.137	9.2	7.3	67.2	5.2	4.2	21.8	1.24	14.4
6	0.63	1.59	2.50	0.120	0.159	8.3	6.3	52.3	5.2	4.0	20.8	1.30	13.0
12	0.67	1.49	2.22	0.123	0.164	8.1	6.1	49.4	5.4	4.1	22.1	1.32	12.2
7	0.74	1.35	1.82	0.133	0.189	7.5	5.3	39.8	5.6	3.9	21.8	1.44	11.1
13	0.76	1.32	1.74	0.141	0.192	7.1	5.2	36.9	5.4	4.0	21.6	1.35	10.7
8	0.81	1.24	1.51	0.154	0.213	6.5	4.7	30.6	5.3	3.8	20.1	1.40	10.1
14	0.84	1.19	1.42	0.156	0.213	6.4	4.7	30.1	5.4	4.0	21.6	1.35	9.8
15	0.87	1.15	1.32	0.159	0.227	6.3	4.4	27.7	5.5	3.8	20.9	1.45	9.4
9	0.93	1.08	1.14	0.167	0.250	6.0	4.0	24.0	5.6	3.7	20.7	1.51	8.8
10	1.04	0.96	0.92	0.189	0.270	5.3	3.7	19.6	5.5	3.9	21.5	1.41	7.9

Table 9: Dimensions and Parameters of Two-end Dry-relaxed Fabrics.

Fabric No.	loop length L (cm.)	$1/L$	$1/L^2$	Course Spacing C_s (cm.)	Wale Spacing W_s (cm.)	Course per cm $C_{p.c.}$	Wales per cm $W_{p.c.}$	Density per cm^2 S	Individual values Kc	Kw	Ks	$\frac{Kc}{Kw}$	Cover Factor, K $tex^{\frac{1}{2}}.cm^{-1}$
1	0.92	1.09	1.19	0.192	0.263	5.3	3.8	20.1	4.8	3.5	16.7	1.37	12.5
24	0.97	1.03	1.06	0.189	0.294	5.2	3.4	18.0	5.1	3.3	16.8	1.55	11.8
25	0.98	1.02	1.04	0.208	0.303	4.8	3.3	15.8	4.7	3.2	15.1	1.47	11.7
2	1.07	0.94	0.88	0.213	0.303	4.7	3.3	15.5	5.0	3.5	17.5	1.43	10.8
26	1.08	0.93	0.85	0.233	0.313	4.3	3.2	14.8	4.6	3.5	16.1	1.31	10.6
3	1.14	0.88	0.77	0.238	0.333	4.2	3.0	12.6	4.8	3.4	16.3	1.41	10.1
27	1.18	0.85	0.72	0.255	0.345	3.9	2.9	11.3	4.5	3.4	15.6	1.53	9.7
28	1.20	0.83	0.69	0.278	0.345	3.6	2.9	10.4	4.3	3.5	15.1	1.23	9.6
18	1.21	0.82	0.67	0.276	0.375	3.6	2.7	9.7	4.4	3.3	14.5	1.33	9.5
4	1.27	0.79	0.62	0.270	0.370	3.6	2.7	10.0	4.7	3.4	16.0	1.38	9.1
5	1.38	0.72	0.52	0.313	0.385	3.2	2.6	9.6	4.5	3.6	16.2	1.25	8.3
19	1.40	0.71	0.50	0.303	0.417	3.3	2.4	7.9	4.6	3.7	16.0	1.35	8.2
20	1.51	0.66	0.44	0.313	0.435	3.2	2.3	7.4	4.8	3.5	16.8	1.37	7.6

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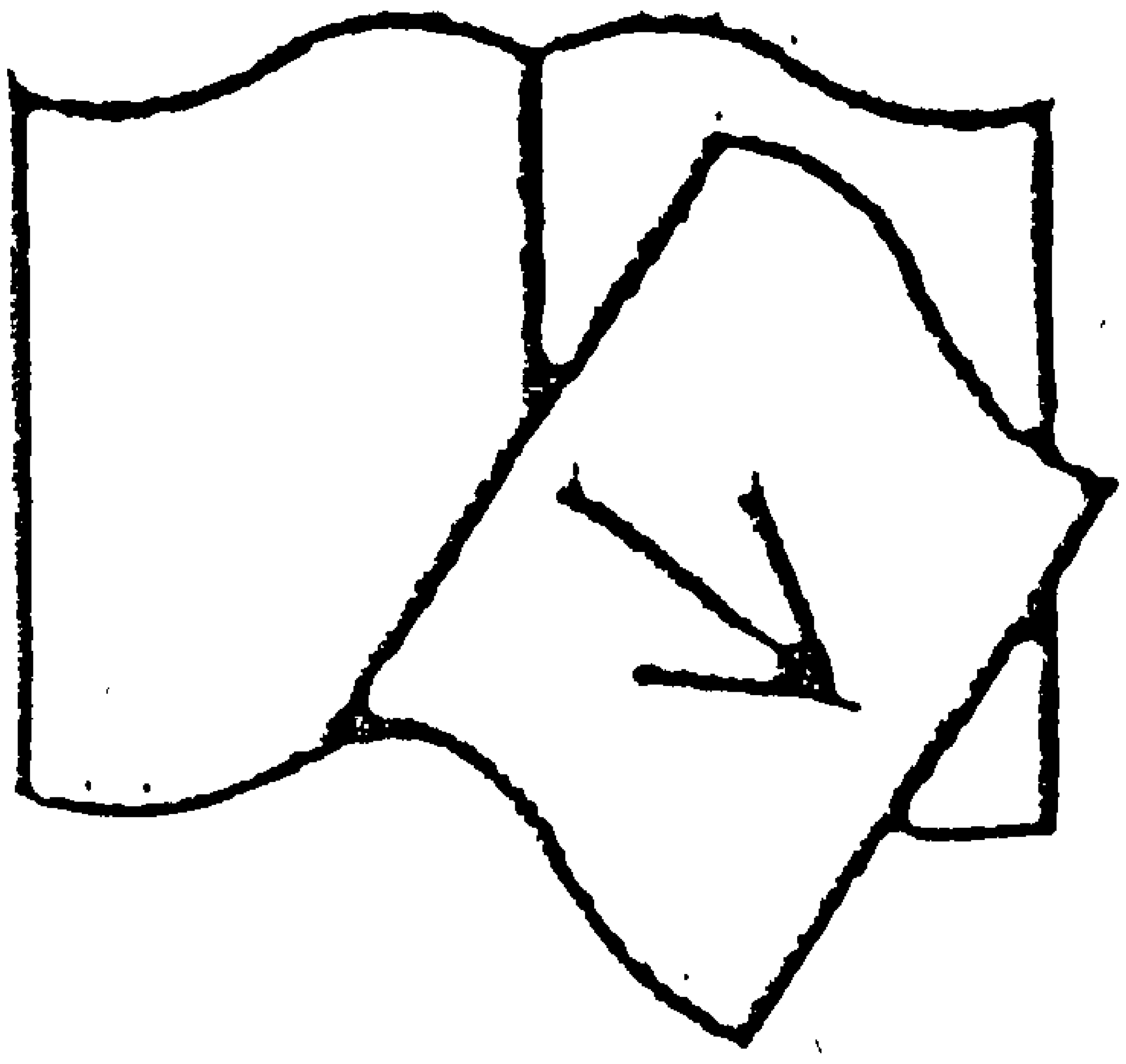

The mean of the individual Kc, Kw and Ks values are given with those obtained by Munden [40] and Knapton and Fong [79] in Table 11. These mean values represent the slopes of the best straight lines through the individual points and the origin. It can be seen from this table, that K-values differ somewhat from one state of relaxation to another and in the present work, they also change in going from one-end to two-end structure, which may suggest that not only does the type of treatment have an effect on the loop dimensions and geometry, but so also does the number of ends used. This is in agreement with the results

Table11: K-values of wool plain knitted fabrics in different states of relaxation.

Yarns used in present work	Kc	Kw	Ks	Kc/Kw
Single yarn:				
Dry-relaxed	4.8	3.5	16.8	1.37
Fully-relaxed	5.3	4.0	21.2	1.30
Two-end yarn:				
Dry-relaxed	4.7	3.5	16.5	1.30
Fully-relaxed	5.6	3.8	21.3	1.40
Munden's values of :				
Dry-relaxed	5.0	3.8	19.0	1.30
Wet-relaxed	5.3	4.1	21.6	1.30
Knapton's and Fong's values of Completely relaxed	5.5	4.2	23.4	1.31

obtained by Smirfitt [49] in his work on worsted rib 1 x 1 fabric, which show that the K-values change as the number of ends increases and this change is far greater than any brought about by altering yarn twist or quality.

The K-values obtained in this work are comparable with Munden's[40] and Knapton's and Fong's [79] values and the slight differences between them may be attributed to those factors suggested by Smirfitt [49] and Knapton et al[45], e.g. yarn diameter, number of ends, twist.

The measured values of $C_{p.c.}$ and $W_{p.c.}$ presented in the above tables were plotted against 1/L and S against $1/L^2$ for all fabrics in both dry-and fully-relaxed state, as shown in Fig. 9-14. A regression analysis of the relationship between $C_{p.c.}$, $W_{p.c.}$ and 1/L and between S and $1/L^2$ has been carried out and the results are shown in Table 12. By using the regression equation in Table 12, the best fit lines of these relationships are shown in Figs.9-14. As can be seen from the above tables and Figs., obvious definite intercepts on the ordinate exist. However, most of these intercepts are not significant and for practical purposes may be ignored, and only a few of these intercepts are significant which is difficult to explain. Feltaous[15] interpreted the intercepts to be the results of change in proccessing variables during

Table 12: The results of regression analysis of the relationship between Cp.c., Wp.c. and 1/L and between S and $1/L^2$. The form of the regression equations are: Cp.c= $\frac{a}{L}$ +b, Wp.c.= $\frac{a}{L}$ +b and S= $\frac{a}{L^2}$+b

Fabric made from:	Regression between:	Dry-relaxed			Fully-relaxed		
		Slope	Intercept	Corre. coefft.	Slope	Intercept	Corre. coefft.
One-end	Cp.c. 1/L	4.7 ± 0.13	$0.15\pm0.19^{**}$	0.995	4.6 ± 0.13	$0.98\pm0.20^{*}$	0.995
	Wp.c. 1/L	4.0 ± 0.10	$-0.75\pm0.15^{*}$	0.995	4.3 ± 0.10	$-0.79\pm0.15^{*}$	0.998
	S $1/L^2$	18.1 ± 0.20	$-1.48\pm0.44^{*}$	0.999	20.5 ± 0.48	$1.27\pm1.22^{**}$	0.997
Two-ends	Cp.c 1/L	5.7 ± 0.40	$-0.88\pm0.32^{***}$	0.981	5.8 ± 0.29	$-0.26\pm0.35^{**}$	0.991
	Wp.c. 1/L	3.5 ± 0.22	$-0.06\pm0.18^{**}$	0.981	4.4 ± 0.23	$-0.61\pm0.19^{*}$	0.993
	S $1/L^2$	17.1 ± 1.20	$-0.59\pm0.85^{**}$	0.982	21.5 ± 0.44	$-0.33\pm0.38^{**}$	0.997

The significicnce of intercepts:

* Significant at 1% level.

** Not significant at 1% and 5% levels

*** Not significant at 1% level, but significant at 5%.

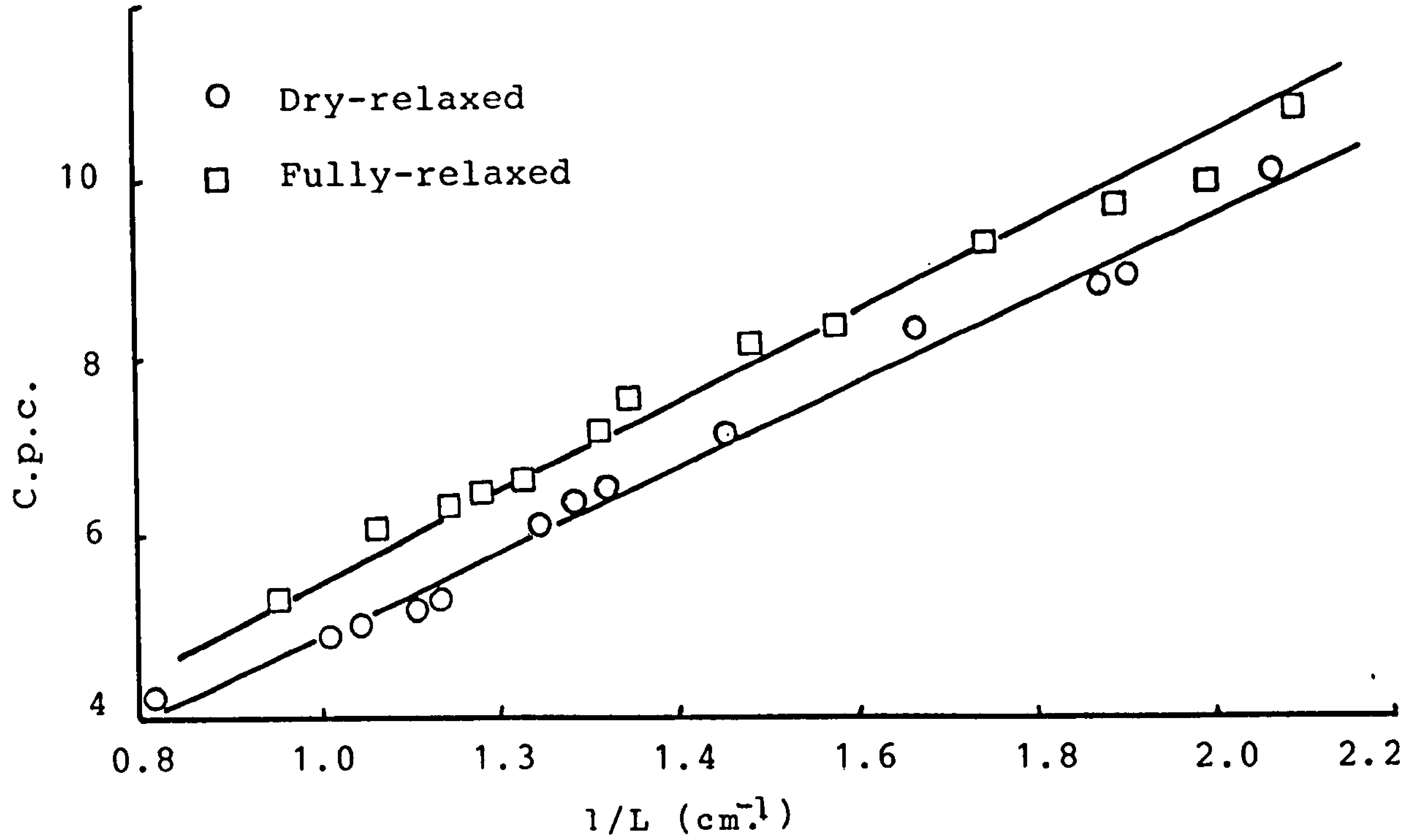

Fig 9 : Plot of Cp.c. against 1/L for dry and fully relaxed one-end fabrics.

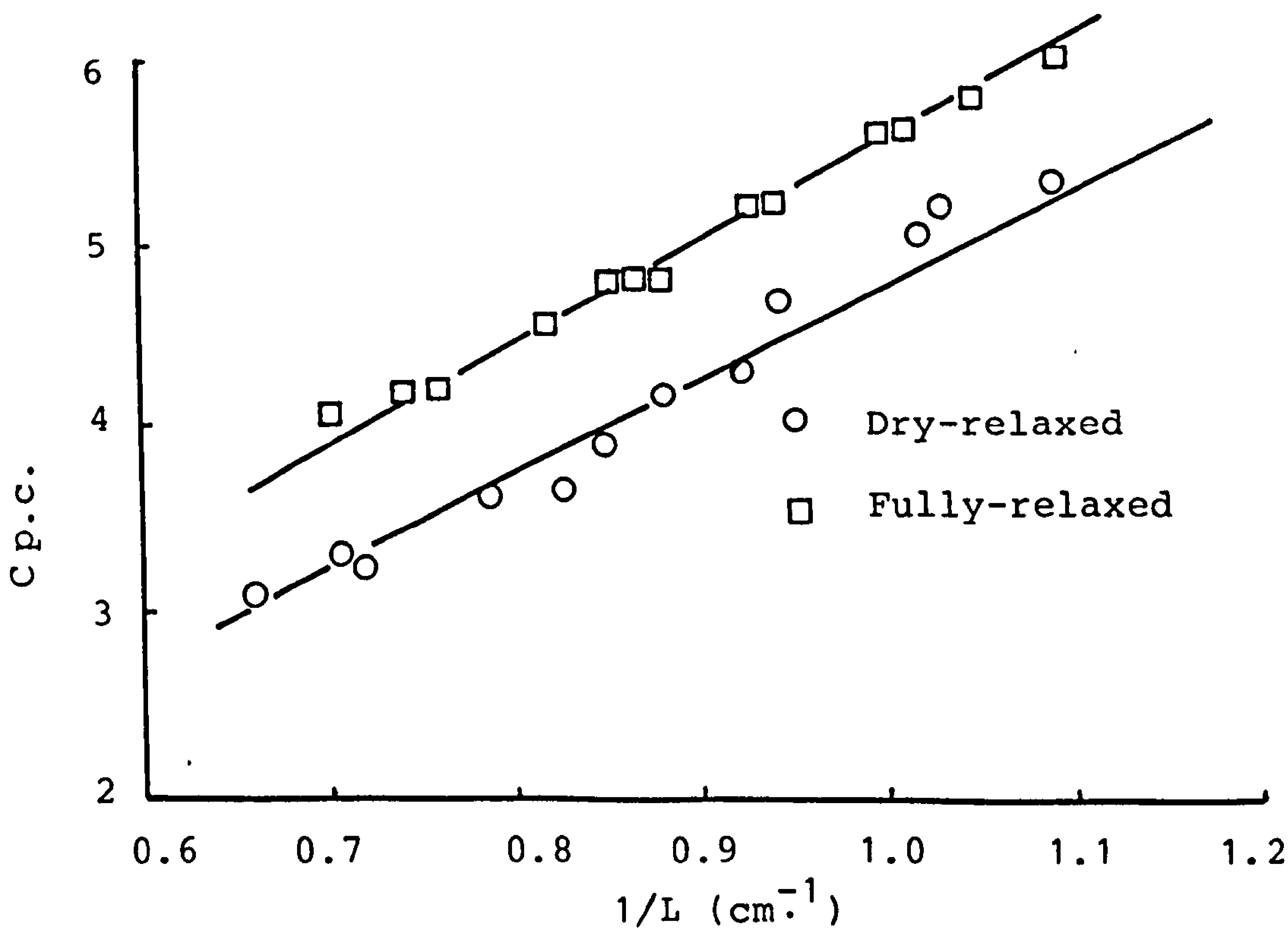

Fig 10 : Plot Cp.c. against 1/L for dry- and fully-relaxed two-end fabrics.

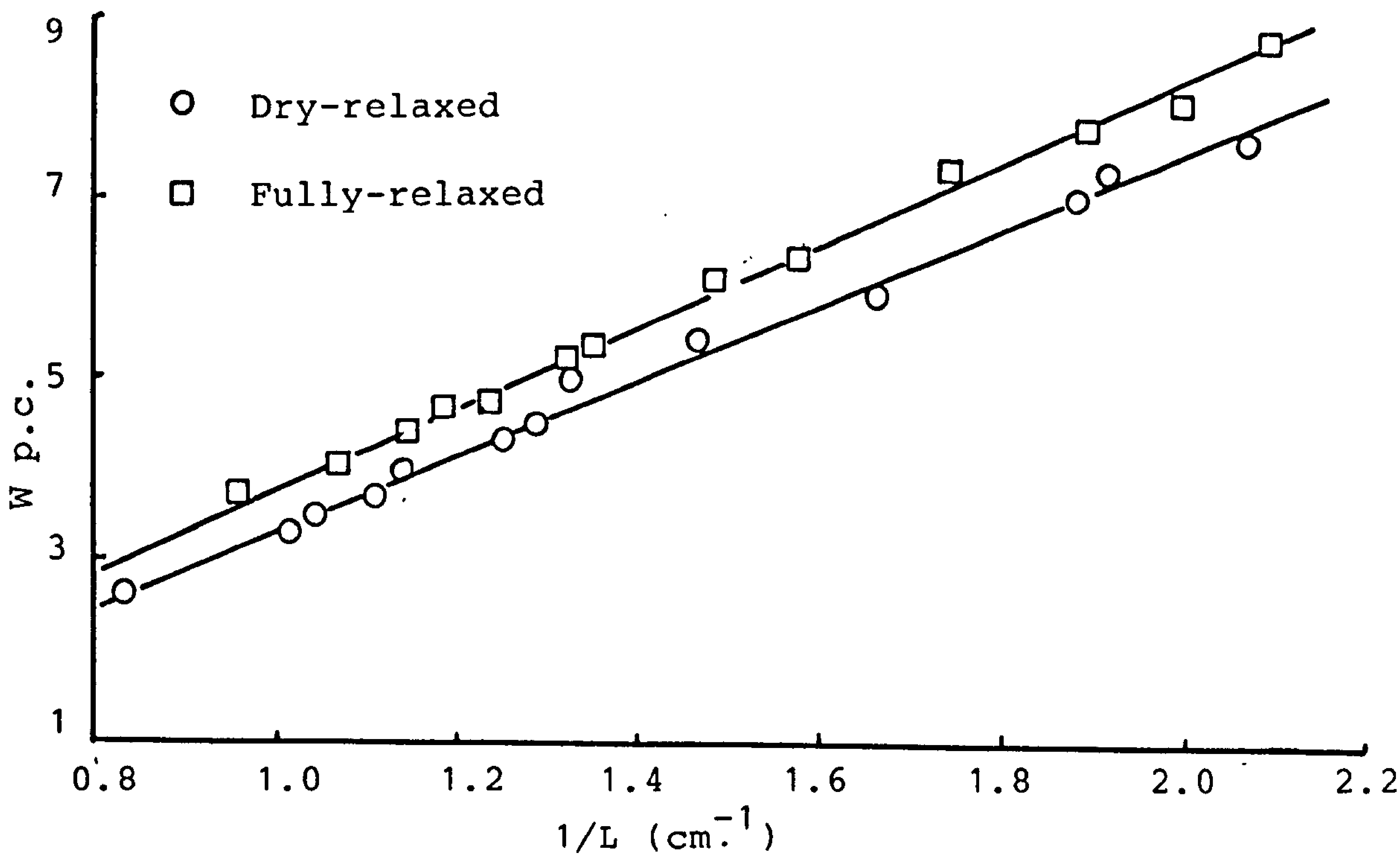

Fig 11 : Plot Wp.c. against 1/L for dry and fully relaxed one-end fabrics

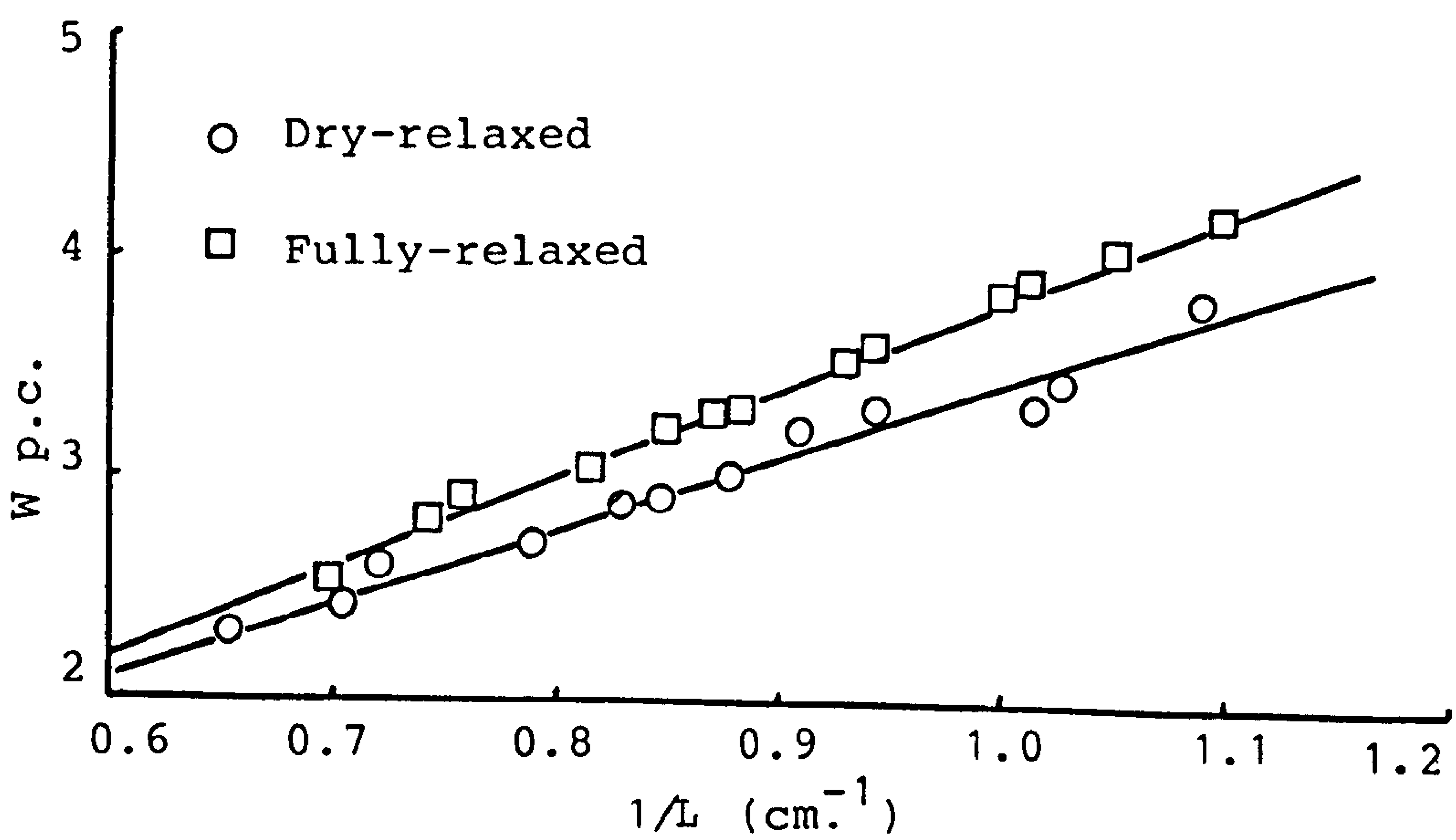

Fig 12 : Plot Wp.c. against 1/L for dry and fully-relaxed two-end fabrics.

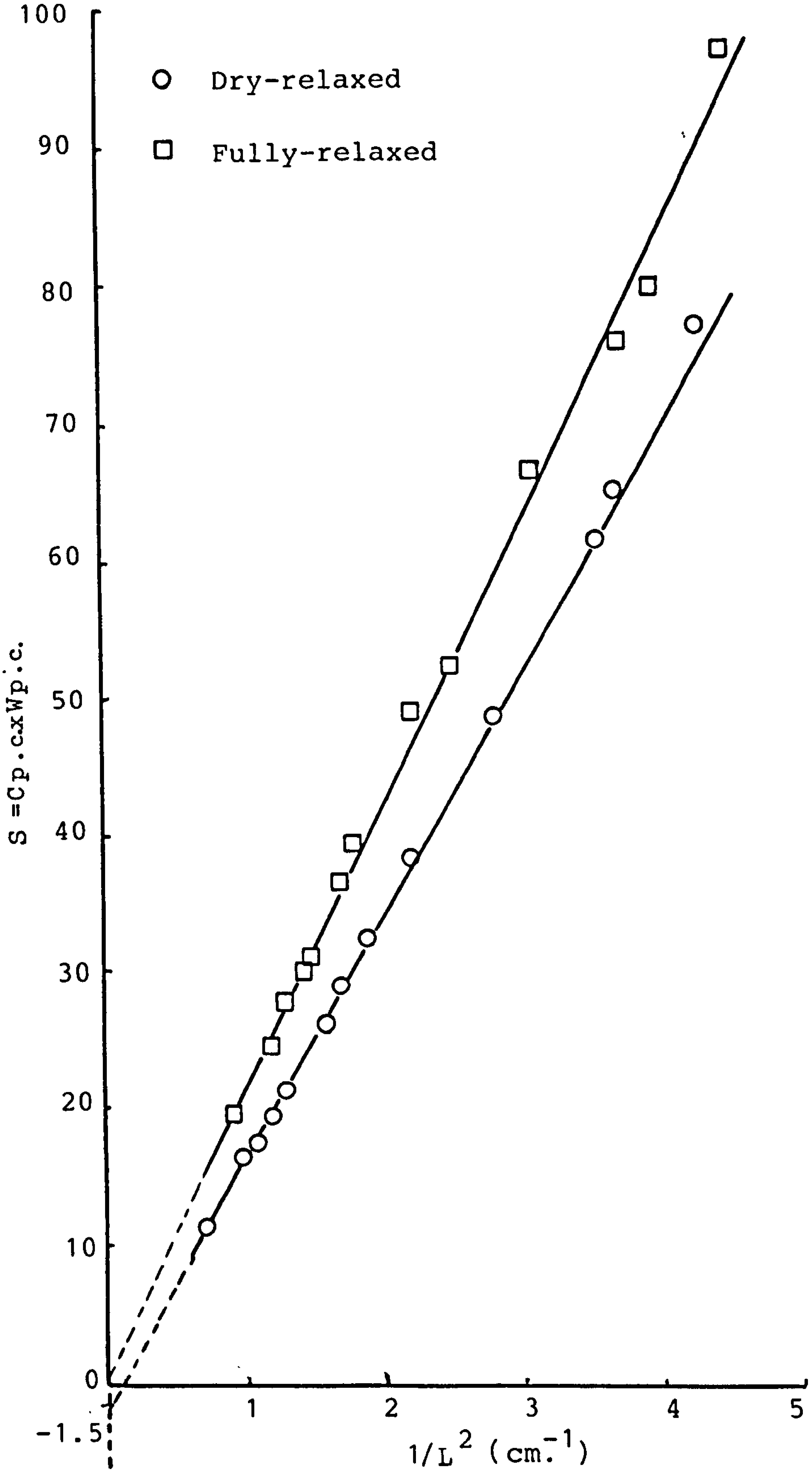

Fig 13: Plot stitch density(S) against $1/L^2$ for dry- and fully-relaxed one-end fabrics.

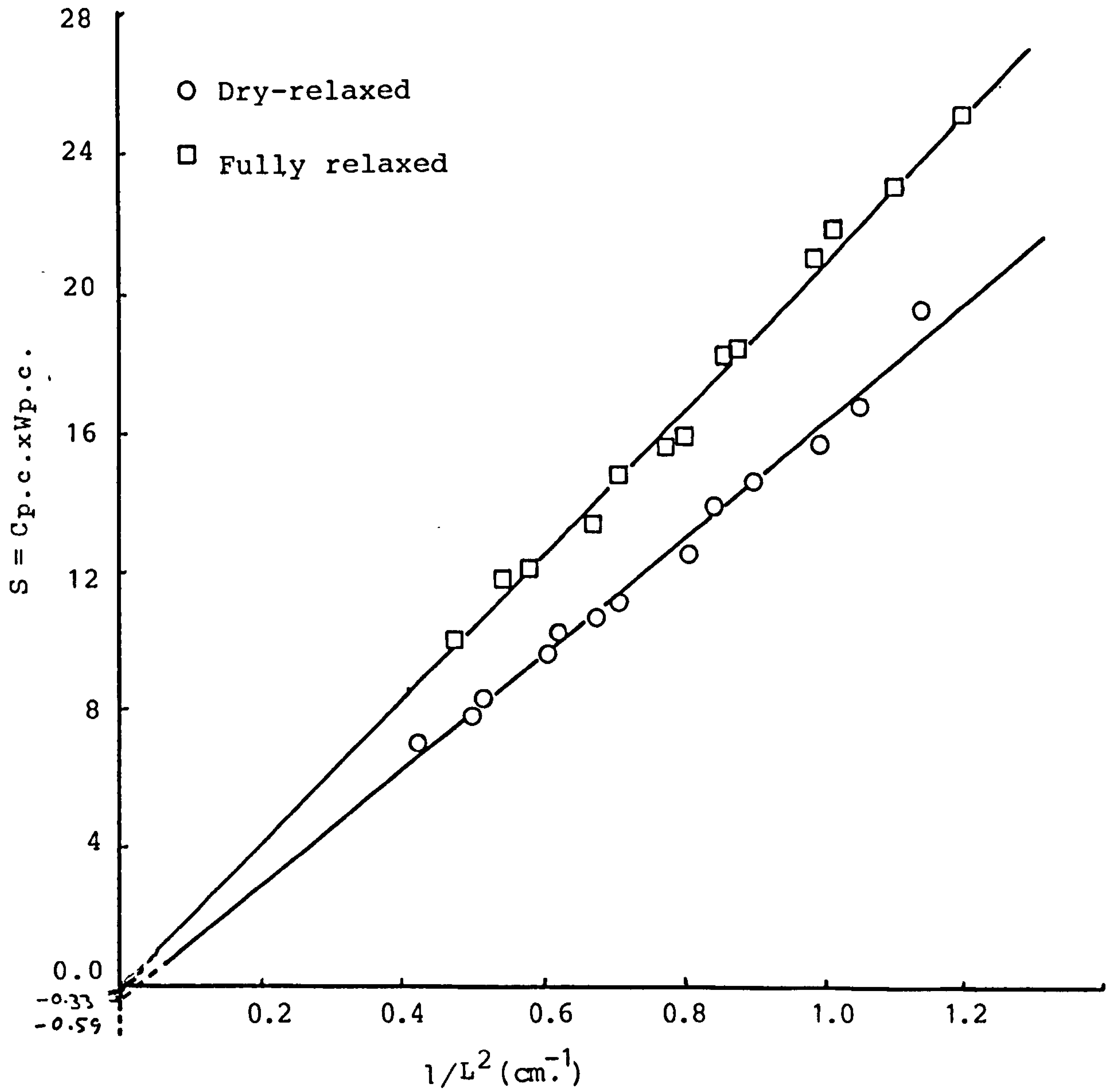

Fig 14 : Plot Stitch density (S) against $1/L^2$ for dry- and fully relaxed two-end fabrics.

the knitting, while Knapton and Fong[79] in their analysis of plain-knitted fabric made from two different yarn counts, suggested that Kc and Kw values may be critically affected by d, L and d/L in the dry-and wet-relaxed states, but Smirfitt[49] stated that there is no satisfactory explanation for these intercepts.

While the intercepts of the regression between S' and $1/L^2$ decrease as the treatment progresses, they do not, in one case, disappear entirely (see Table 12 and Fig. 14 for fully-relaxed two-end fabrics) as suggested by Knapton et al[45]. This might be due to the different condition of the treatment. However, perhaps the best interpretation of the intercepts is to question the validity of the extrapolation to infinite stitch length.

The linear correlation coefficient of the two fabric sets in both dry-relaxed and fully-relaxed states are, as shown in Table 12, highly significant, the only marked difference being between the correlation coefficient of the two-end fabrics in the fully-relaxed state and in the dry-relaxed state. This is because the fabric, given the full relaxation treatment, reaches the state of minimum energy and the loop configuration takes its final shape. Thus, the points round the lines in Figs. 9-14 are spreading less for the fully-relaxed fabrics than for dry-relaxed fabrics. This confirms the original work of Munden[40].

A t-test of the significance between the K-values of one-end fabrics and the K-values of two-end fabrics obtained by the regression analysis shows that only Kc-values differ significantly at 5% level, but not at 1% level in either state of relaxation. Kw and Ks-values do not differ significantly. This would suggest that the number of ends had no significant effect on the K-values.

Since there are significant intercepts in plotting $C_{p.c.}$ and $W_{p.c.}$ against 1/L an alternative way of relating the Cs and Ws against L may prove to be desirable. The results of regression analysis of these plots are shown in Table 13. The most marked aspect of these results is that none of the intercepts is significant at 1% level and only three of the intercepts are significant at 5% level. This would provide clearer physical meaning of these relationships. Thus the regression lines of the above plots shown in Figs.15-18 may well be drawn through the origin.

It can be seen from Table 13,that the correlation coefficients are also highly significant, but again with a marked difference between the coefficients of the two-end fabrics in the fully-and in the dry-relaxed state.

In both forms of the regression equation in Table 12 and 13 the intercepts of the plots S against $1/L^2$ and 1/S against L is small and therefore Ks may be rgarded the most useful K-value.

The individual values of Kc, Kw and Kc/Kw in both

Table 13: The results of regression analysis of the relationship between Cs, Ws and L and between 1/S and L^2. The form of the regression equations are: $Cs=aL+b$, $Ws=aL+b$ and $\frac{1}{S}=aL^2+b$

Fabric made from	Regression between:		Dry-relaxed			Fully-relaxed		
			Slope	Intercept	Corre. coefft.	Slope	Intercept	Corre. coefft.
One-end	Cs	L	0.199±0.007	0.0086±0.006*	0.993	0.164±0.0070	0.0195±0.009*	0.996
	Ws	L	0.339±0.036	-0.0086±0.041*	0.997	0.282±0.0050	-0.0290±0.010**	0.997
	1/S	L^2	0.064±0.004	-0.0018±0.003*	0.998	0.047±0.0009	0.0002±0.001*	0.998
Two-ends	Cs	L	0.238±0.019	-0.0270±0.022*	0.964	0.162±0.0250	0.0195±0.008**	0.980
	Ws	L	0.276±0.018	0.0197±0.021*	0.978	0.293±0.0099	-0.0290±0.011**	0.990
	1/S	L^2	0.056±0.013	0.0025±0.019*	0.966	0.047±0.0060	0.0009±0.008*	0.995

The significance of intercepts:

* Not significant at 1% and 5% levels

** Not significant at 1% level, but significant at 5% level.

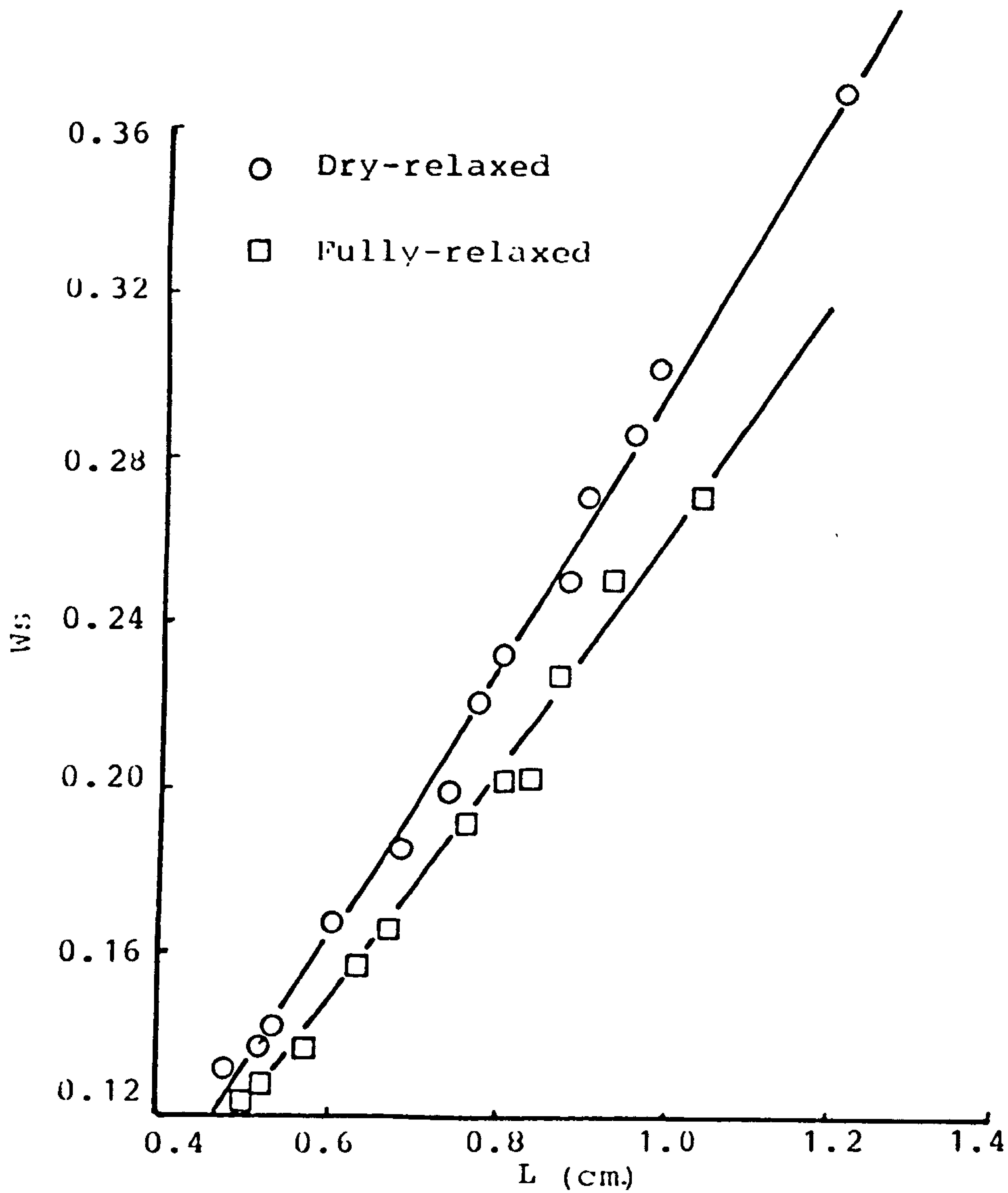

Fig 15: Plot wale spacing Ws against loop length L for one-end fabrics in both dry- and fully-relaxed state.

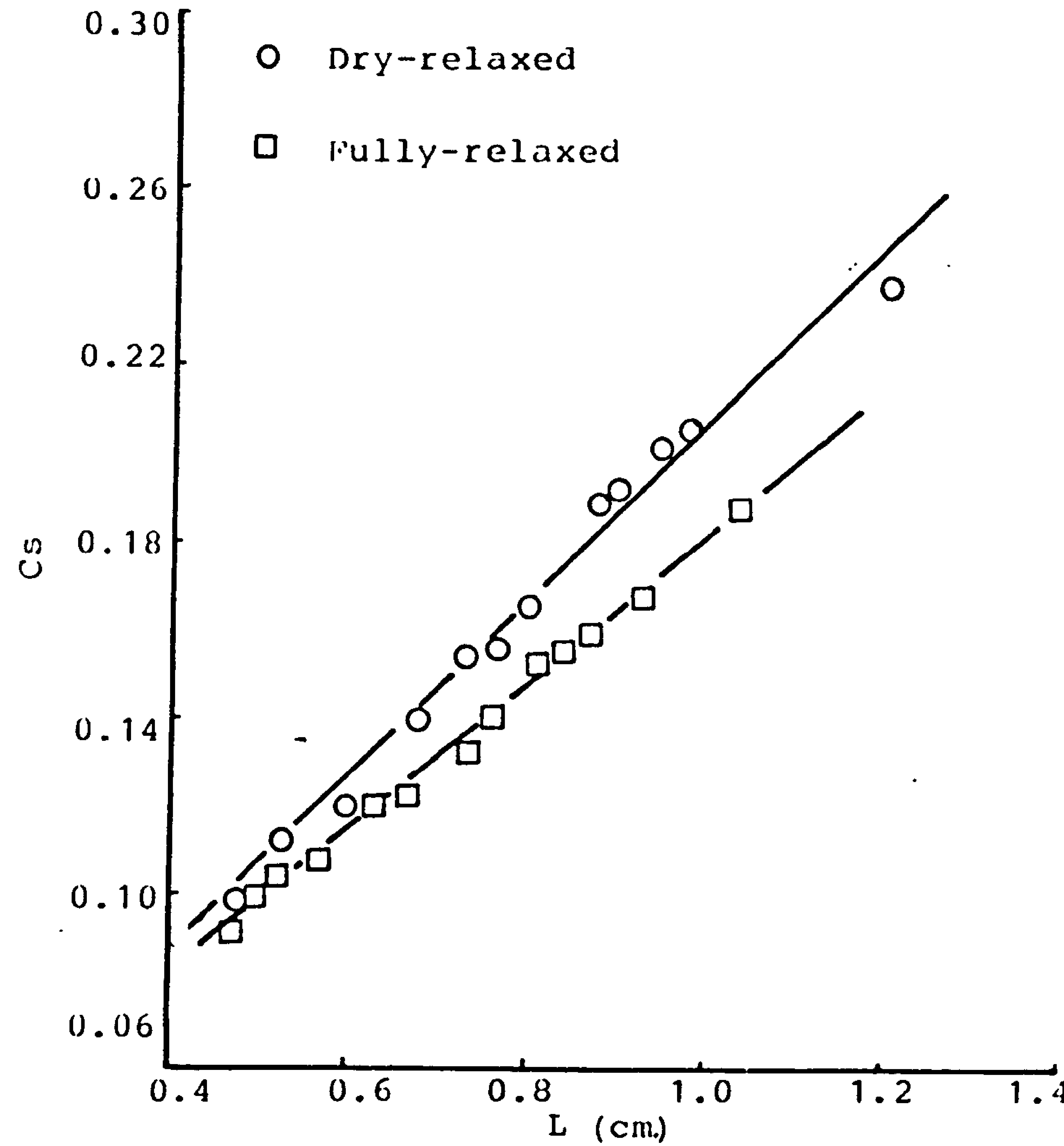

Fig 16: Plot Course spacing, Cs against loop length L for one-end fabrics in both dry- and fully-relaxed state.

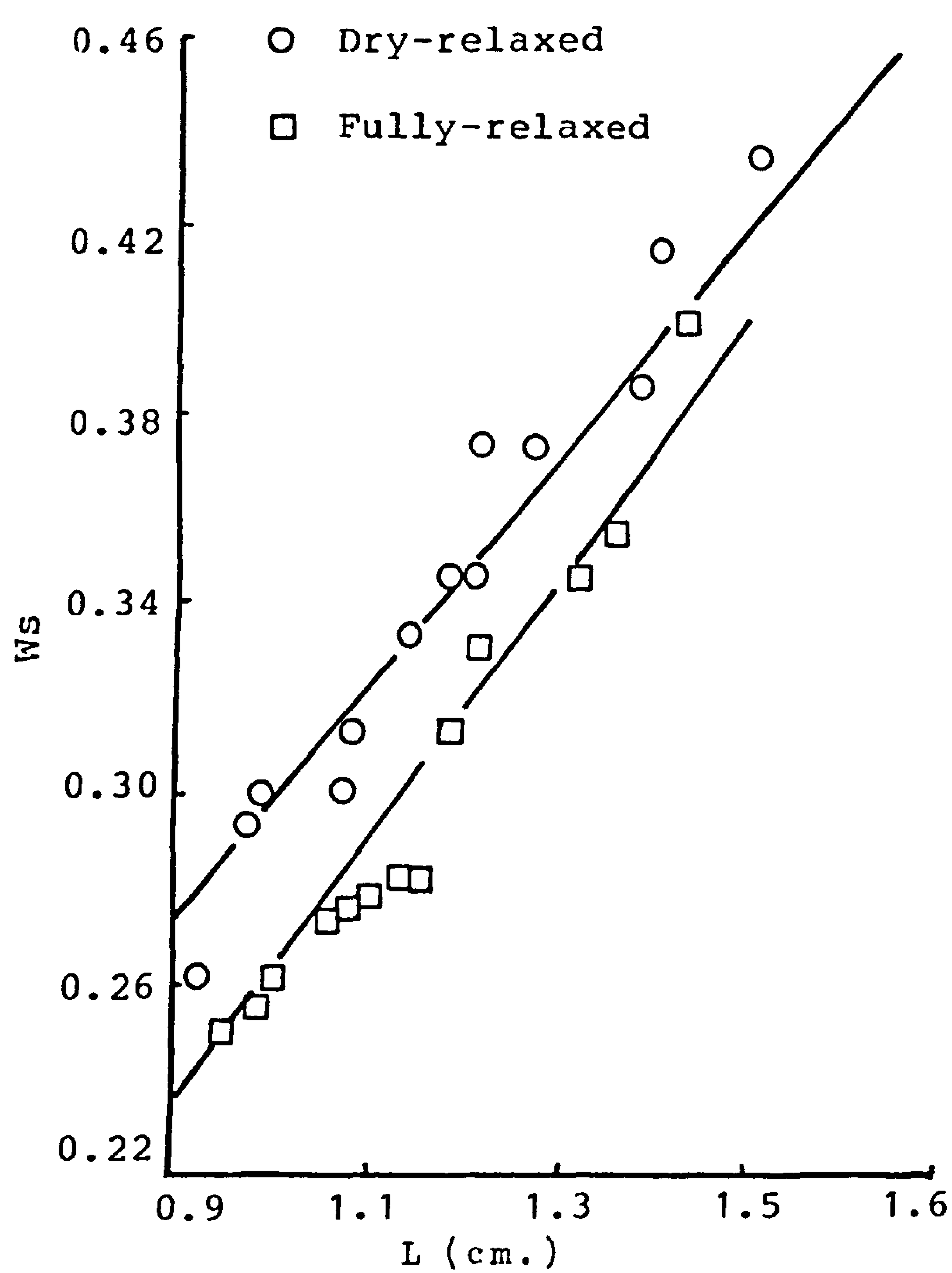

Fig 17: Plot wale spacing against loop length for two-end fabrics in both dry- and fully-relaxed state.

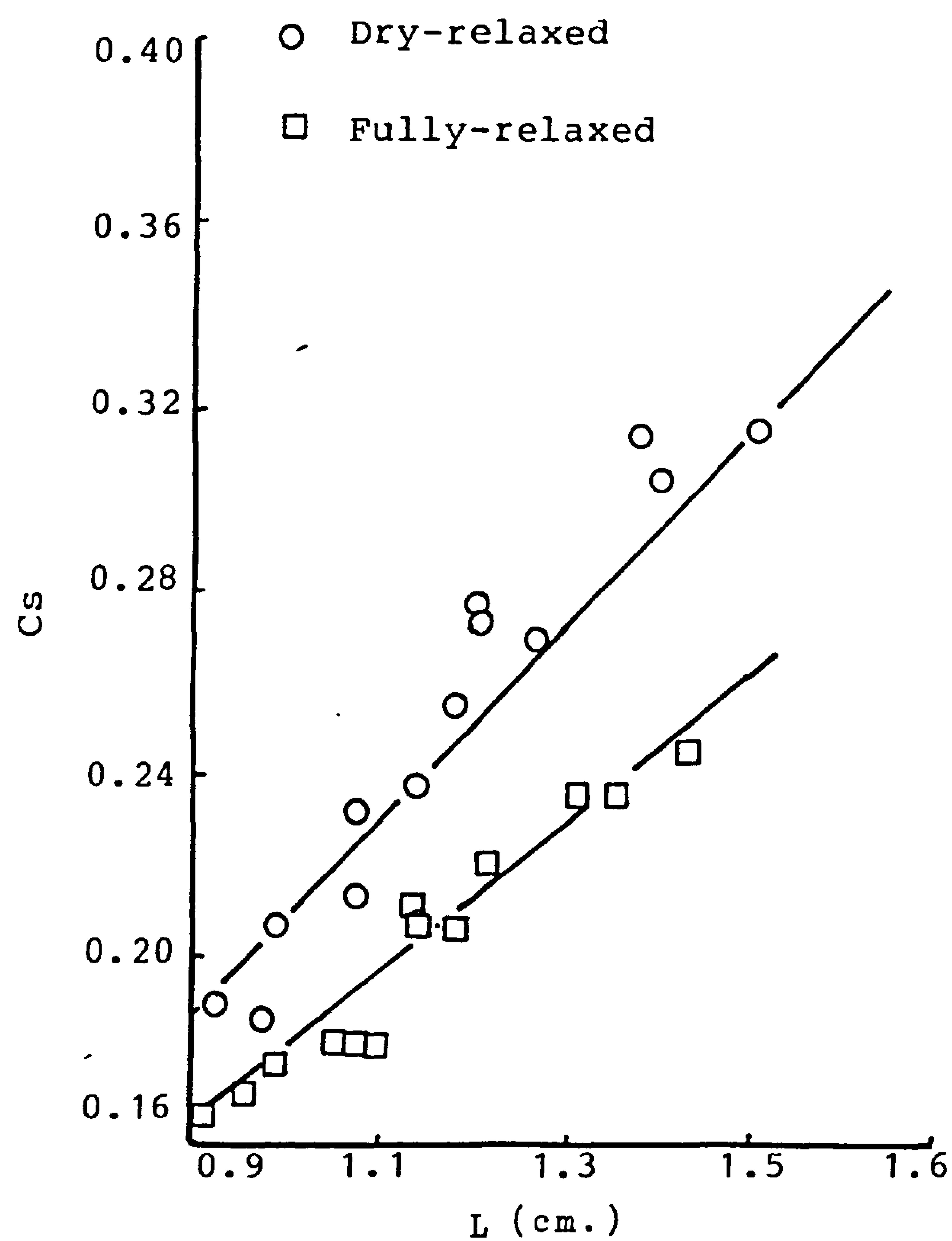

Fig 18 Plot course spacing against loop length for two-end fabrics in both dry- and fully-relaxed state.

dry-and fully-relaxed states were plotted against cover factor K. This is shown in Figs. 19-26. It can be seen from Figs. 19-22 that the correlation coefficients for Kc and Kw for the two-end fabrics are not significant. Those correlations for the one-end fabrics which show any significance indicate a negative regression for Kc and Kw. It can also be seen that the correlation coefficients were not greatly affected by the type of relaxation. The correlations for Ks are worse except, possibly,for the dry-relaxed one-end fabrics which indicates a positive regression. Such correlations may suggest that Ks is independent of cover factor and this is generally in agreement with most researchers in this field.

From the plots in Figs. 19-22, the relationship between the shape factor as the ratio Kc/Kw and the cover factor K, is expected to be what is shown in Figs. 25 and 26. In Fig. 25, for the fabrics made from one-end of yarn, the shape factor decreases as the cover factor increases in both dry-relaxed and fully-relaxed states of the relaxation although the shape factor is more correlated with cover factor when the fabrics are in fully-relaxed state (r = 0.88) than when the fabrics are in dry-relaxed state (r = 0.74). This is similar to the results obtained by Fletcher and Roberts (73) for cotton and opposite to what Knapton

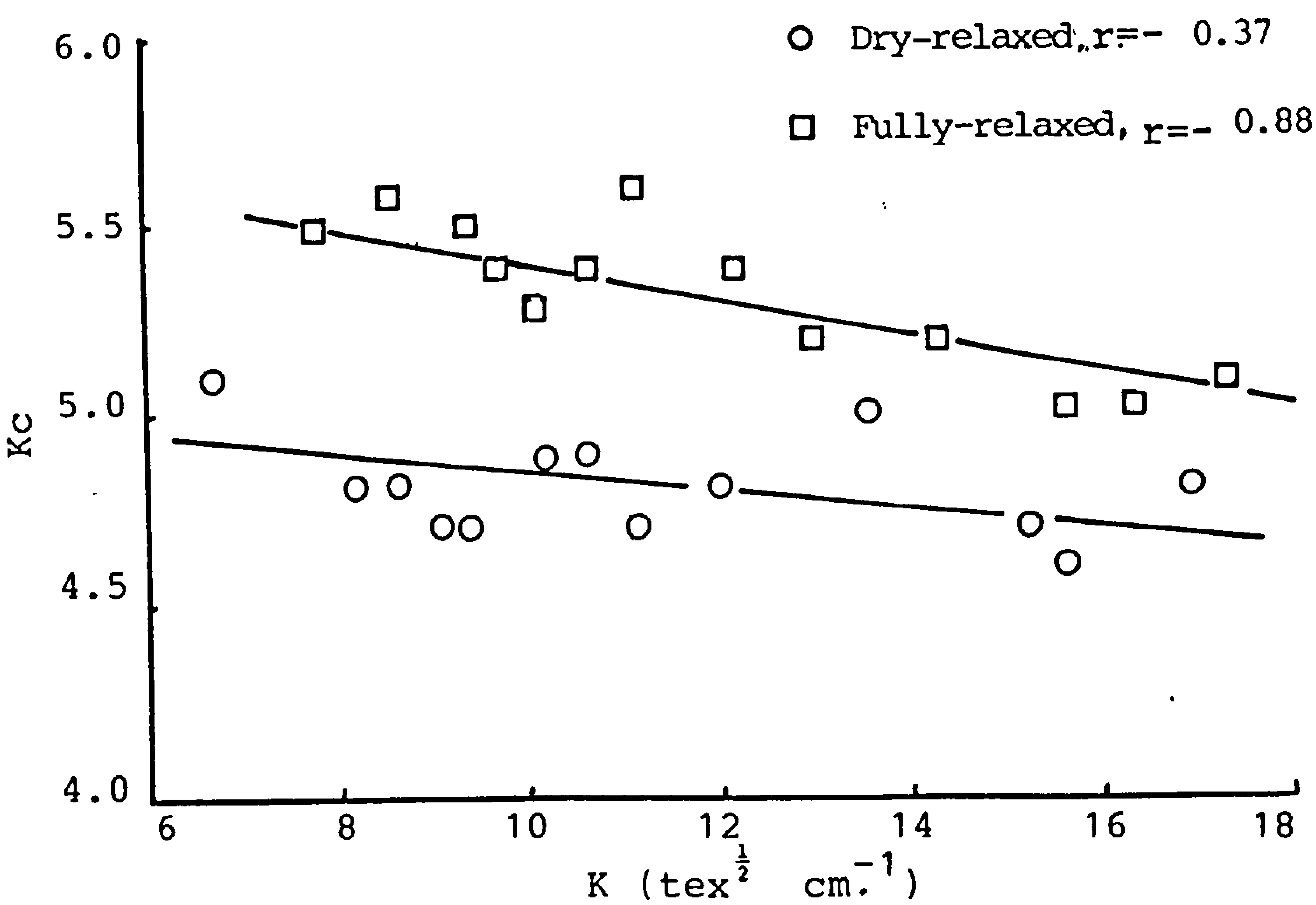

Fig 19 : Plot Kc against cover factor K for dry- and fully-relaxed one-end fabrics.

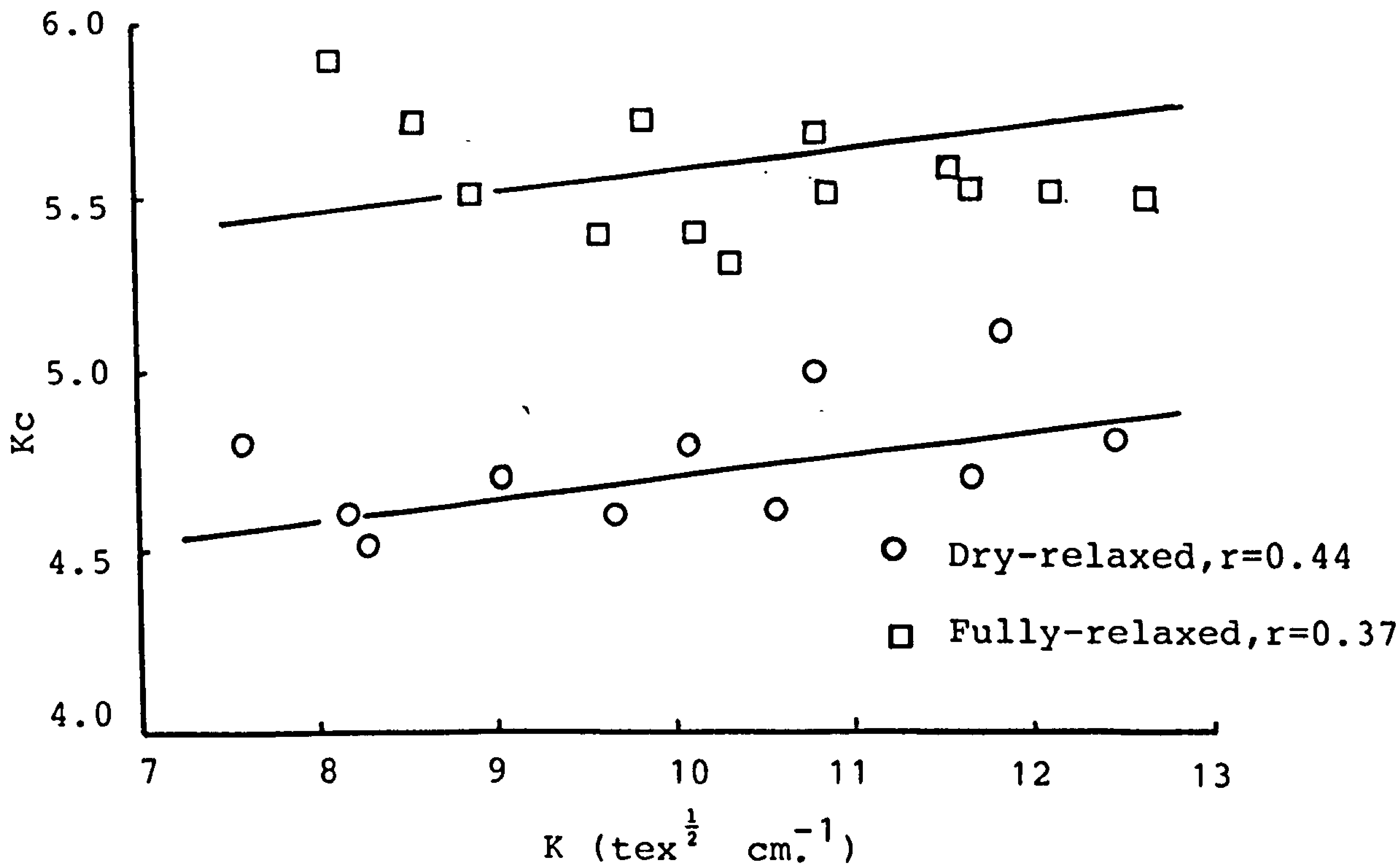

Fig 20 : Plot Kc against cover factor K for dry and fully-relaxed two-end fabrics.

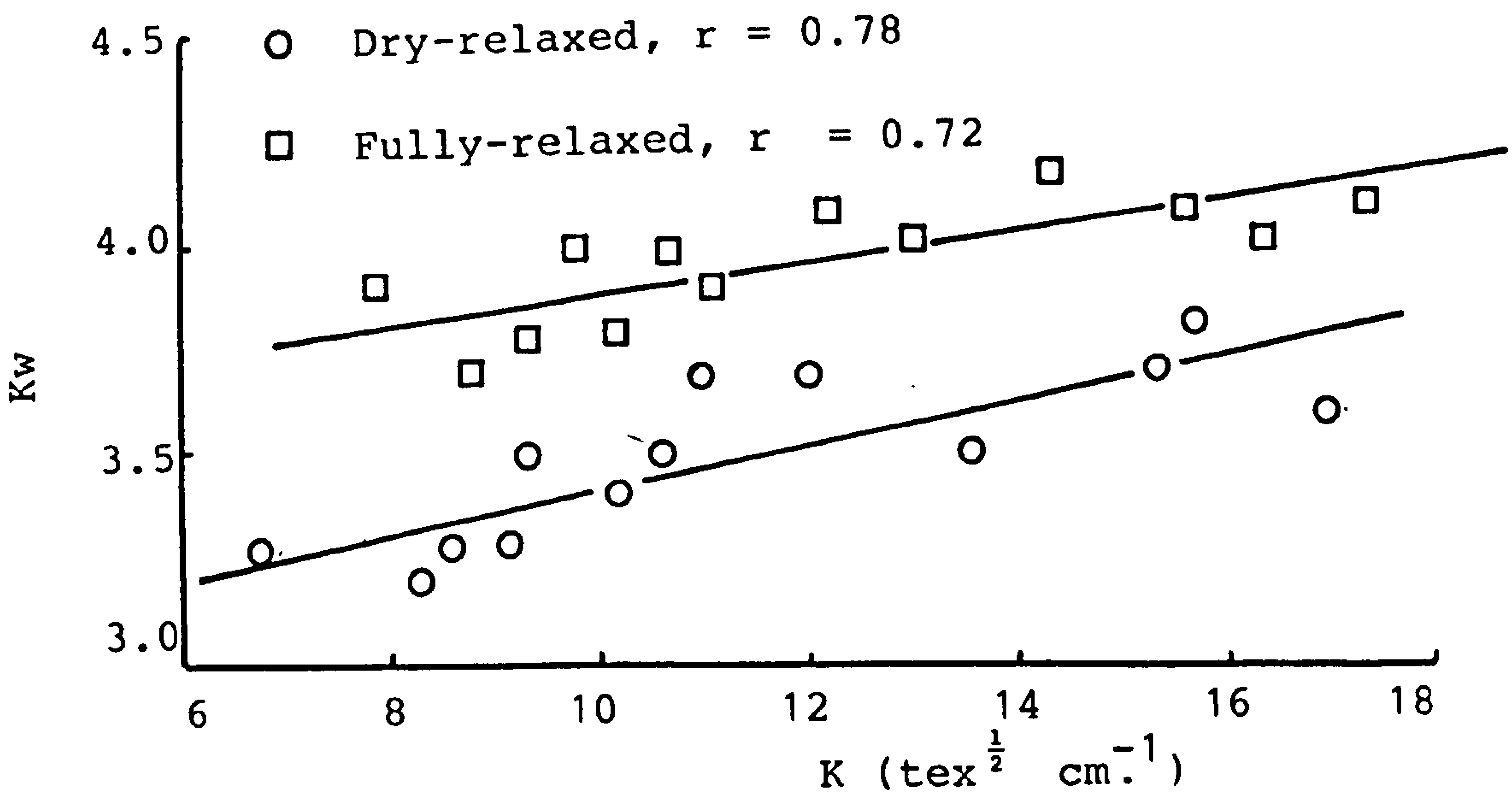

Fig 21: Plot Kw against cover factor K for dry- and fully relaxed one-end fabrics.

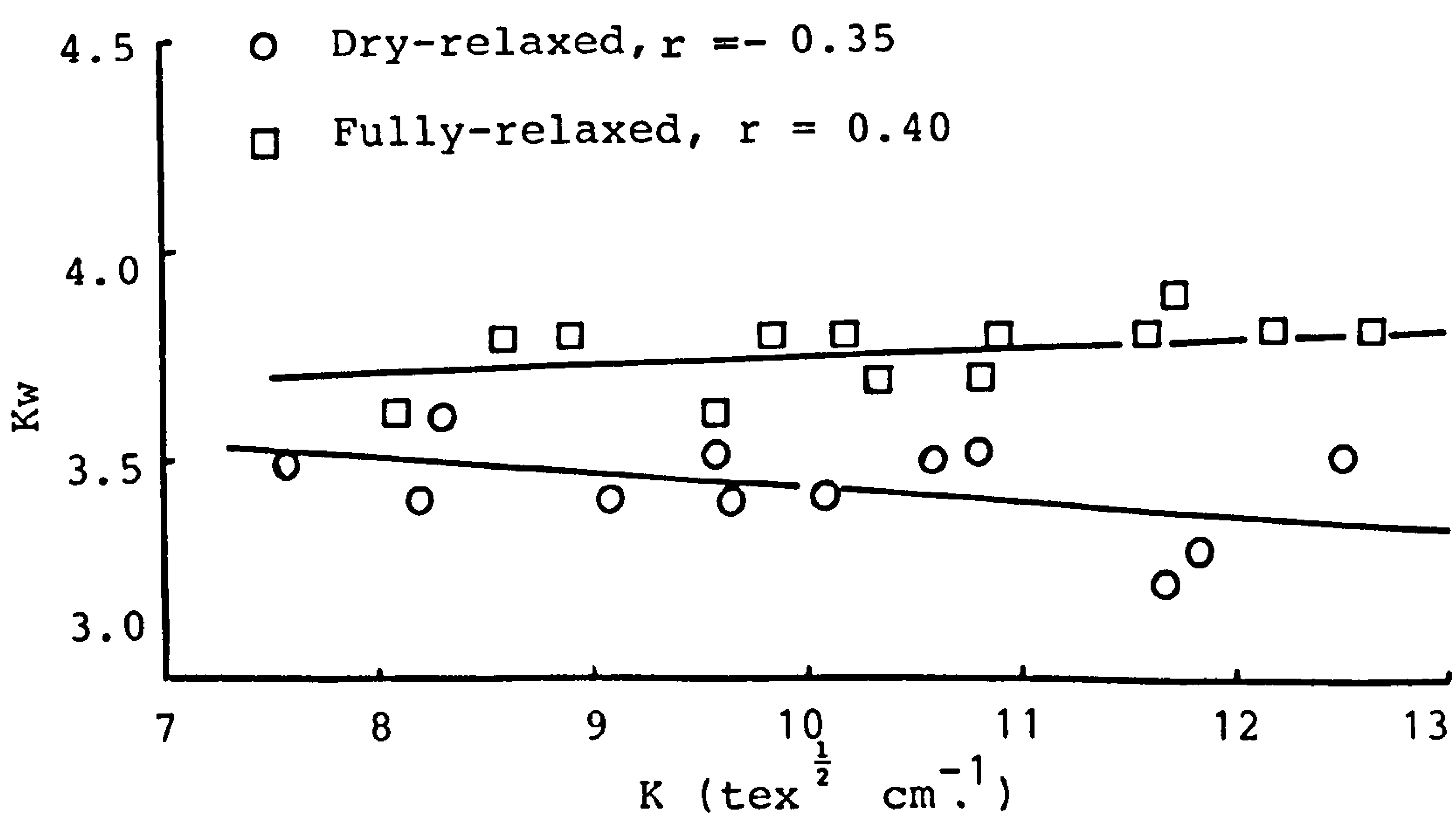

Fig 22: Plot Kw against cover factor K for dry- and fully-relaxed two-end fabrics.

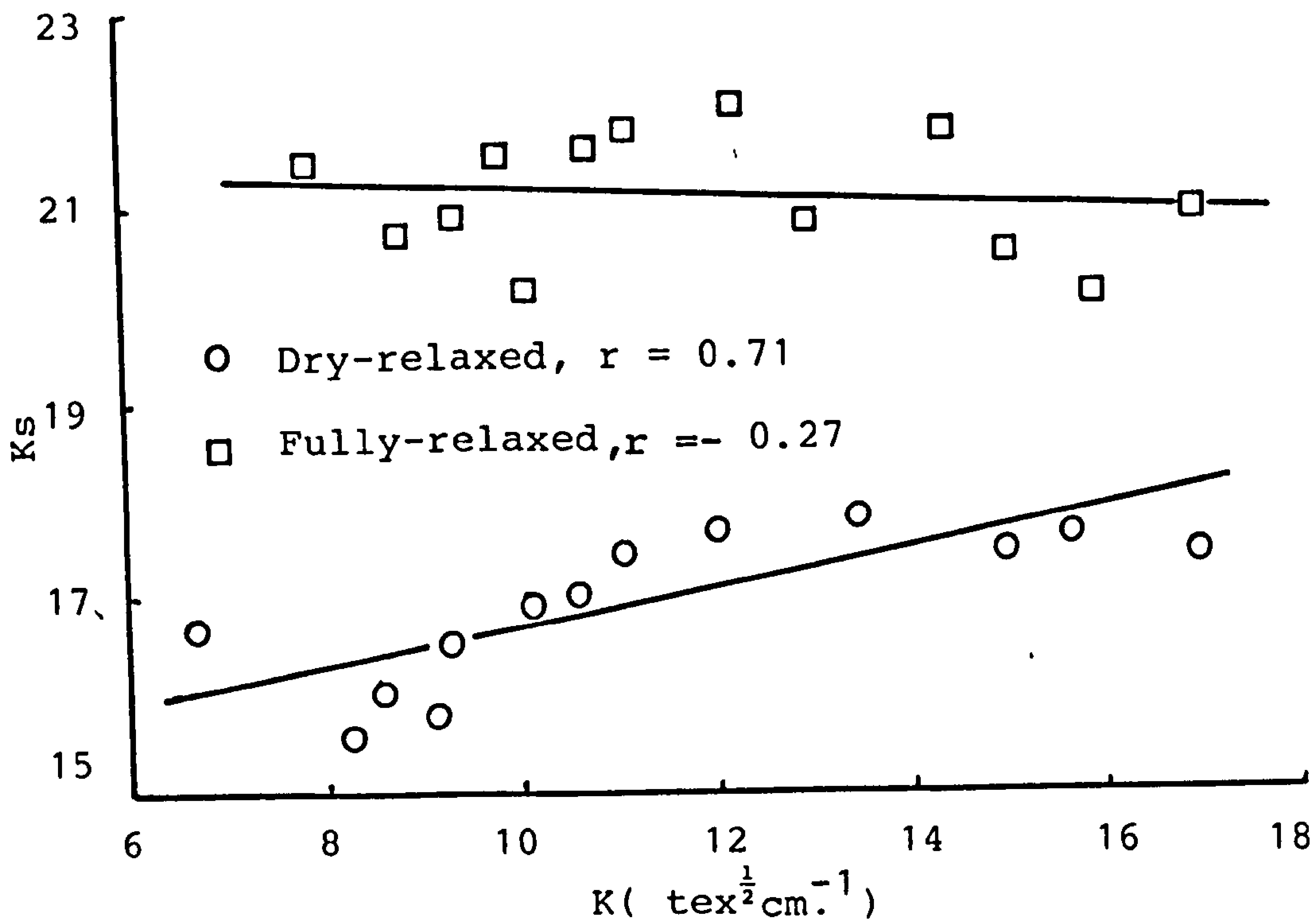

Fig 23 : Plot Ks against cover factor K for dry- and fully-relaxed one-end fabrics.

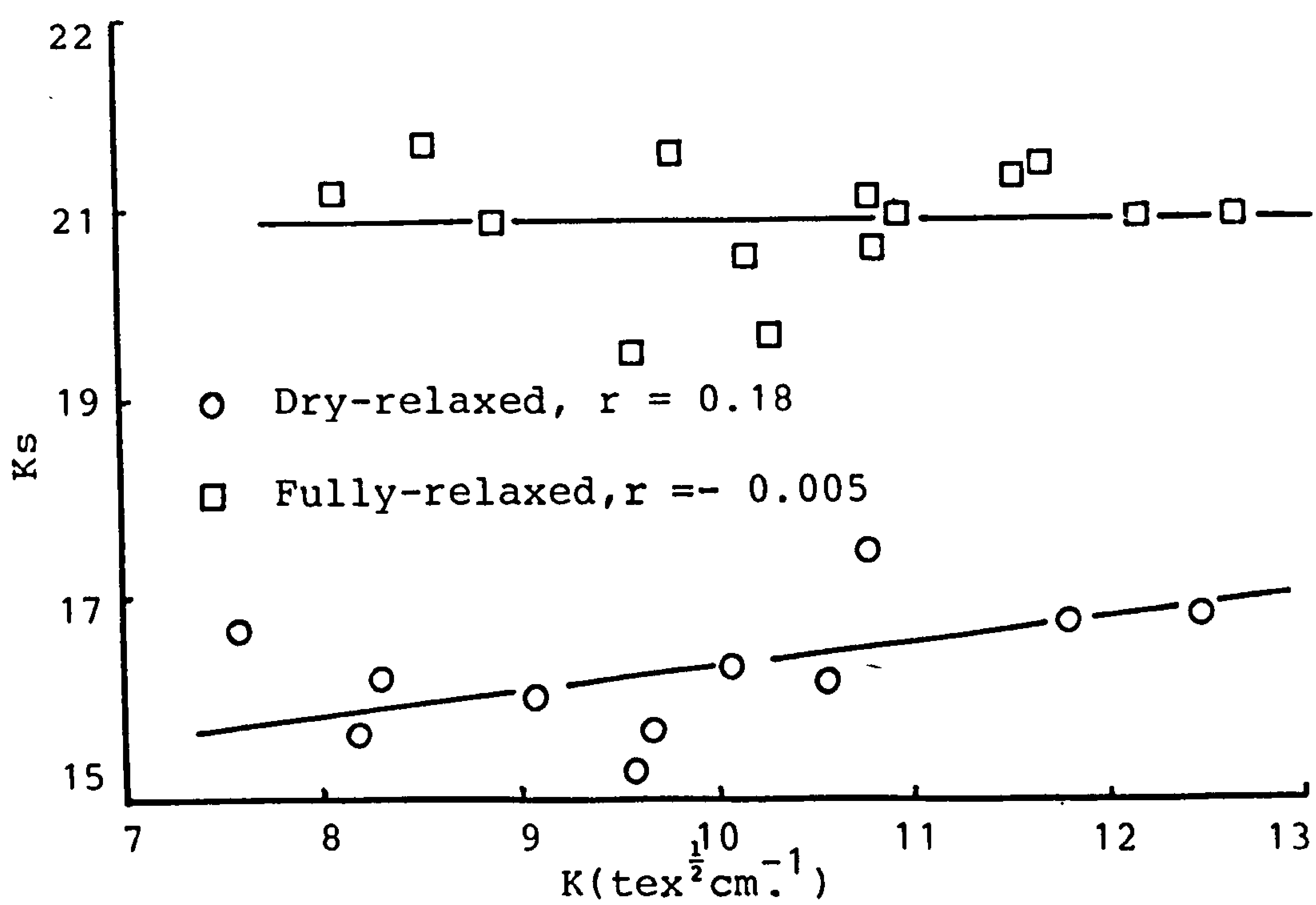

Fig 24 : Plot Ks against cover factor K for dry and fully-relaxed two-end fabrics.

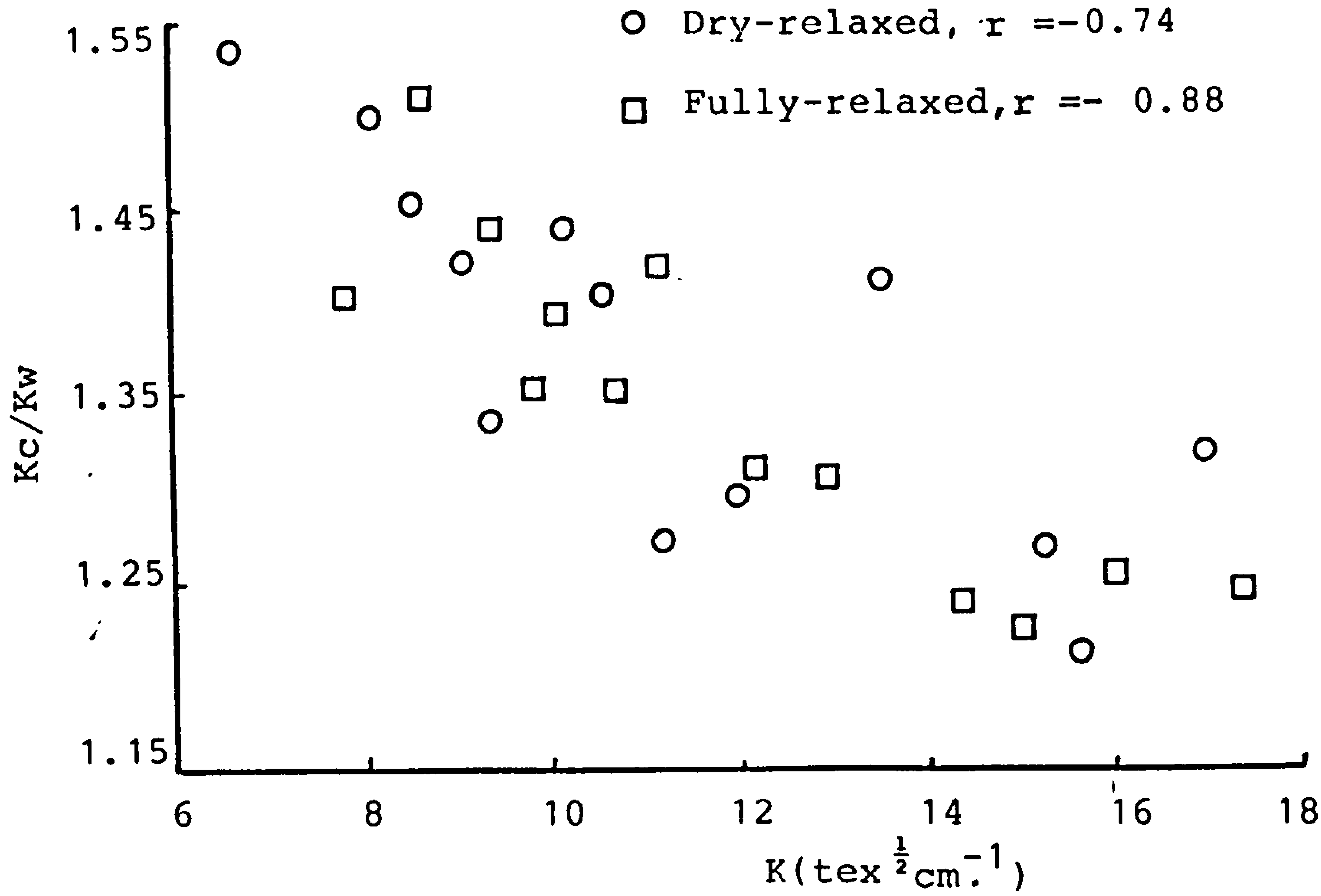

Fig 25 : Plot Kc/Kw against cover factor K for dry- and fully-relaxed one-end fabrics.

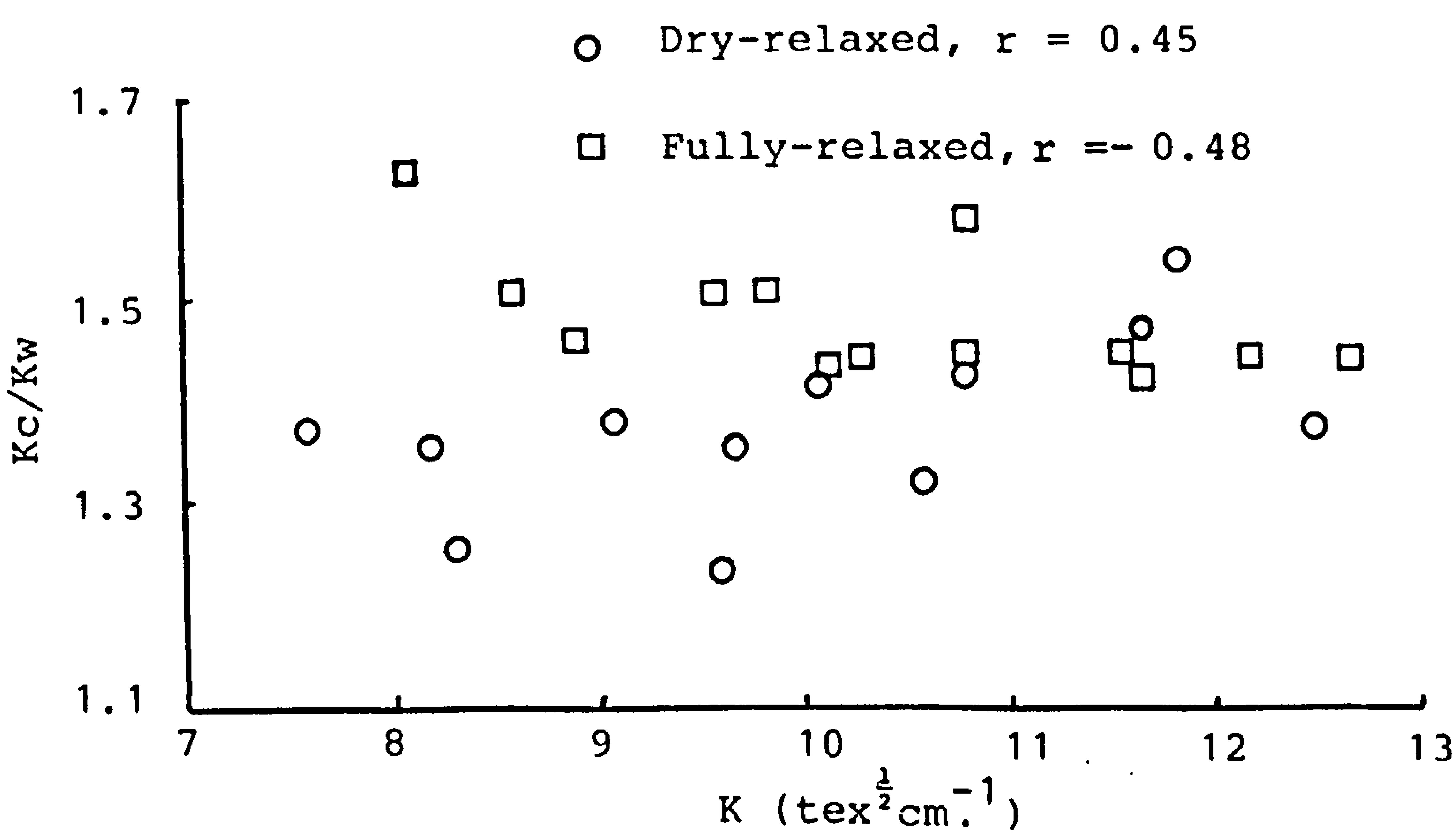

Fig 26 : Plot Kc/Kw against cover factor K for dry- and fully-relaxed two-end fabrics.

et al [45] obtained. The independence of the shape factor and cover factor for the fabrics made from two-ends of yarn, shown in Fig. 26 is in general agreement with that obtained by Munden [40] and in disagreement with that obtained by Knapton et al [45].

The overall results show that the values of Kc, Kw and Ks increase as the treatment progresses. Similar results were obtained by Postle [80] and many other researchers in this field. This is obviously due to shrinkage resulting from the treatment.

5.2 Fabric thickness

The measurement of fabric thickness could be critically affected by the method and amount of pressure used. Postle [51] suggested that at "low" pressure up to 0.5 lb/in^2 ($35.1g/cm^2$, $3.4kN/m^2$), the thickness value should be a function of the number of fibre protruding from the surface of the fabric and therefore, related to the aesthetic qualities of the fabric. At a pressure of 1.0lb/in ($70.3g/cm^2$, $6.9kN/m^2$), the fabric thickness should be related to the body of the fabric after all surface hairs have been flattened and is thus a function of the geometry of the plain-knitted structure. Edwards[48] had different views. He considered that $70.3g/cm^2$ pressure is generally high for knitted fabrics and, while Marsh[81] has suggested $10g/cm^2$ ($0.1kN/m^2$)

as a reasonable value, he recommended $1g/cm^2 (0.01kN.m^2)$ as more favourable figure for knitted fabrics. Knapton[45] used the pressure $0.04lb/m^2$ ($2.8g.cm^{-2}$; $0.27kN.m^{-2}$) which is recommended by the American Society for Testing and Materials (ASTM)[82].

In view of these differences, the pressures used in the present work to measure the fabric thickness are $1.3g.cm^{-2}$ ($0.13\ kN.m^{-2}$), $2.2g.cm^{-2}$ ($0.22kN.m^{-2}$) and $4.4g.cm^{-2}$ ($0.43\ kN.m^{-2}$). This third pressure is considered to affect the fabric body and therefore to measure what is termed "structural or geometrical" thickness of the fabric*. The first pressure, is considered to affect the surface of the fabric and the second is in between, which reflects the feature of the effects of both other pressures.

The structural unit cell, the smallest repeated unit in the fabric is considered a three dimensional structure and therefore the results shown in Table 14 and 15 represent the degree of curvature of the knitted loop out of the fabric plane.**

The ratio of fabric thickness (t) to loop length(L), is considered a dimensionless parameter which gives a

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* It can be seen from appendix IV that this pressure is within the range of the pressures likely to affect the fabric body and therefore it may be reasonably regarded as a pressure which can be used to measure the structural thickness of the fabric.

** These results were obtained by using the Shirley Tester. For comfirmation, an Instron Tensile Testing Machine was used to measure the thickness of two fabrics and the results, as shown in appendix V , are in agreement with the above results.

Table 14 : Fabric thickness in dry- and fully-relaxed state: One-end

Dry-relaxed fabrics							Fully-relaxed fabrics						
Fabric No.	loop length L (mm)	Thickness (t) in mm under pressure : PI $0.13 KN.m^{-2}$	PII $0.22 KN.m^{-2}$	PIII $0.43 KN.m^{-2}$	t_1/L *	t_3/L *	Fabric No.	loop length L (mm)	Thickness (t) in mm under pressure : PI $0.13 KN.m^{-2}$	PII $0.22 KN.m^{-2}$	PIII $0.43 KN.m^{-2}$	t_1/L *	t_3/L *
21	4.8	2.03	1.61	1.12	0.42	0.23	21	4.7	2.28	2.07	1.52	0.49	0.32
23	5.3	2.07	1.61	1.08	0.39	0.20	23	5.2	2.64	2.14	1.55	0.51	0.30
11	6.0	2.00	1.51	1.04	0.33	0.17	11	5.7	2.63	2.22	1.67	0.46	0.29
12	6.8	1.90	1.44	1.00	0.28	0.15	6	6.3	2.52	1.88	1.18	0.40	0.19
6	7.3	1.66	1.27	0.93	0.23	0.13	12	6.7	2.69	2.33	1.75	0.40	0.26
13	8.0	1.71	1.32	0.94	0.21	0.12	7	7.4	2.59	1.88	1.25	0.35	0.17
8	8.9	1.54	1.25	0.91	0.17	0.10	8	8.1	2.59	1.91	1.24	0.32	0.15
14	9.1	1.67	1.35	1.00	0.18	0.11	14	8.5	2.90	2.45	1.88	0.34	0.22
15	9.5	1.53	1.22	0.89	0.18	0.09	15	8.8	3.02	2.61	1.96	0.34	0.22
9	9.8	1.66	1.25	0.88	0.17	0.08	9	9.3	2.71	2.06	1.34	0.34	0.14
10	12.1	1.62	1.34	0.91	0.13	0.07	10	10.4	2.77	2.34	1.88	0.27	0.18

* The subscripts refer to the different pressures.

Table 15: Fabric thickness in dry- and fully-relaxed state: two-ends

Dry-relaxed fabrics							Fully-relaxed fabrics						
Fabric No.	loop length L (mm)	Thickness (t) in mm under pressure: PI $0.13 KN.m^{-2}$	PII $0.22 KN.m^{-2}$	PIII $0.43 KN.m^{-2}$	t_1/L	t_3/L	Fabric No.	loop length L (mm)	Thickness (t) in mm under pressure: PI $0.13 KN.m^{-2}$	PII $0.22 KN.m^{-2}$	PIII $0.43 KN.m^{-2}$	t_1/L	t_3/L
1	9.3	2.31	2.08	1.60	0.25	0.17	24	9.1	3.64	3.15	2.53	0.40	0.28
24	9.7	2.53	1.95	1.54	0.26	0.16	25	9.5	3.69	3.23	2.61	0.39	0.27
25	9.8	2.45	1.99	1.53	0.25	0.16	26	10.0	3.80	3.36	2.81	0.38	0.28
2	10.7	2.49	2.05	1.57	0.23	0.15	2	10.6	3.73	3.32	2.70	0.35	0.25
26	10.8	2.42	1.97	1.50	0.22	0.14	17	10.7	3.71	3.13	2.46	0.35	0.23
3	11.4	2.35	1.97	1.55	0.21	0.14	27	10.8	3.83	3.34	2.70	0.35	0.25
27	11.8	2.37	1.92	1.52	0.20	0.13	28	11.4	3.83	3.36	2.75	0.34	0.24
28	12.0	2.29	1.91	1.51	0.19	0.13	18	11.8	3.58	2.91	2.23	0.30	0.19
4	12.7	2.32	1.95	1.54	0.18	0.12	4	12.1	3.91	3.45	2.85	0.32	0.23
5	13.8	2.28	1.94	1.54	0.17	0.11	5	13.1	3.93	3.51	2.86	0.30	0.22
19	14.0	2.43	2.13	1.96	0.17	0.14	19	13.5	3.74	2.98	2.27	0.28	0.17
20	15.1	2.60	2.27	1.84	0.17	0.12	20	14.3	3.81	3.03	2.34	0.27	0.16

comparative indicator of the fabric thickness at any given pressure. The parameters $^{t}1/_L$ and $^{t}3/_L$ have been plotted against cover factor K for all fabrics in both dry- and fully-relaxed state. This is shown in Figs. 27-30. It can be seen from these Figs. that the relationship between $^{t}/_L$ and K is linear and that the value of $^{t}/_L$ increases as the value of K increased.

A regression analysis of this relationship was carried out and the results were given in Table 16. From this table, the correlation coefficient for all fabrics are highly significant, but they are higher for the fabric

Table 16: Results of regression analysis of all fabrics in both dry- and fully-relaxed state.

Number of ends	State of relaxation	Pressure I		Pressure III	
		Regression equation	Corre. Coefft	Regression equation	Corre. Coefft
One	Dry	t/L=0.03K - 0.09	0.99	t/L=0.016K - 0.04	0.99
	Complete	t/L=0.02K + 0.10	0.96	t/L=0.017K + 0.02	0.84
Two	Dry	t/L=0.02K - 0.01	0.96	t/L=0.010K + 0.040	0.84
	Complete	t/L=0.03K + 0.04	0.98	t/L=0.026K - 0.034	0.91

in the low pressure than for the fabrics in high pressure. This is probably due to the variation in t/L values caused by high pressure which affects the body of the loop. On the other hand, the correlation coefficient for fabrics made from singles yarn in both low and high

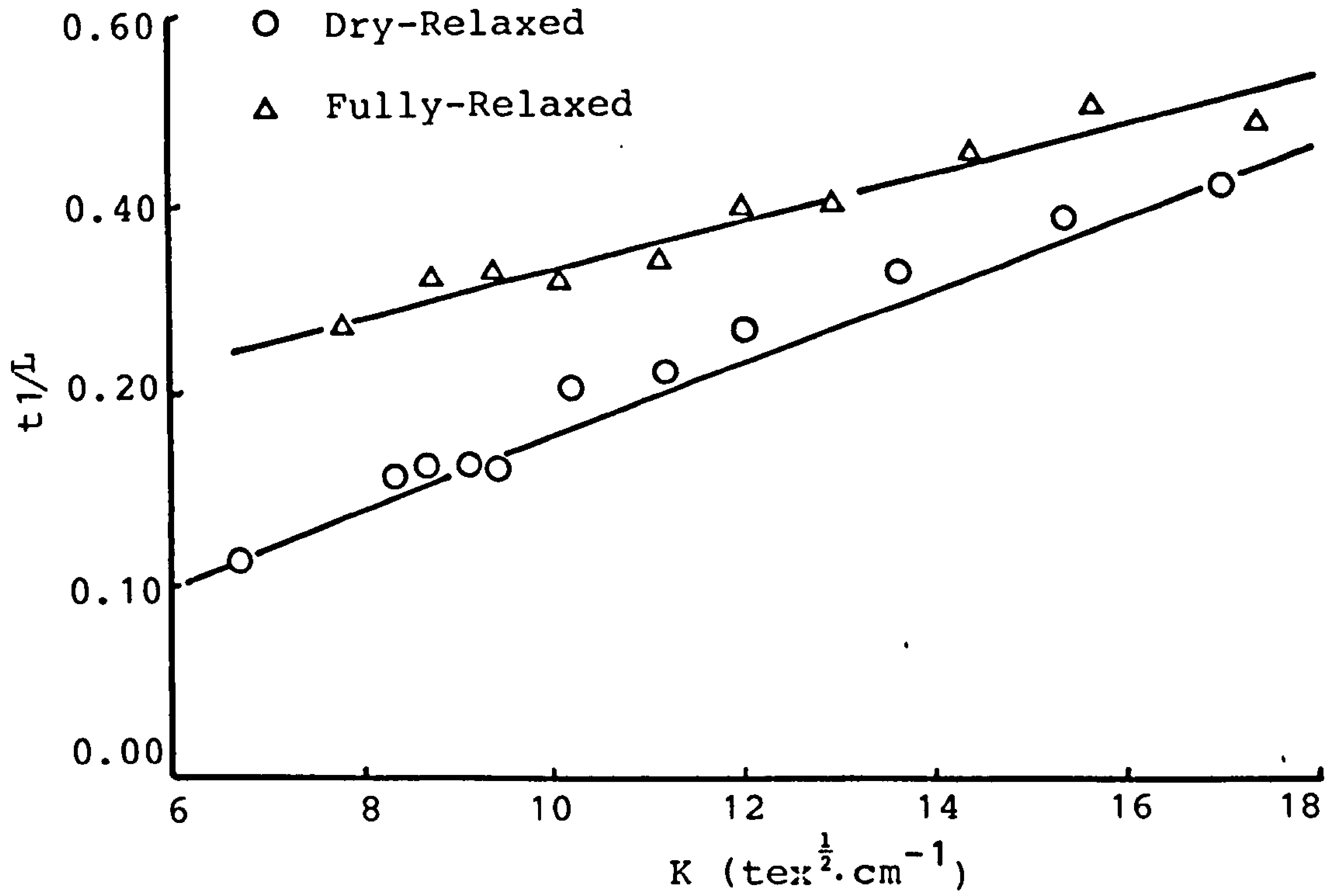


Fig 27 : Plot t1/L against cover factor (K) for dry- and fully-relaxed one end fabrics.

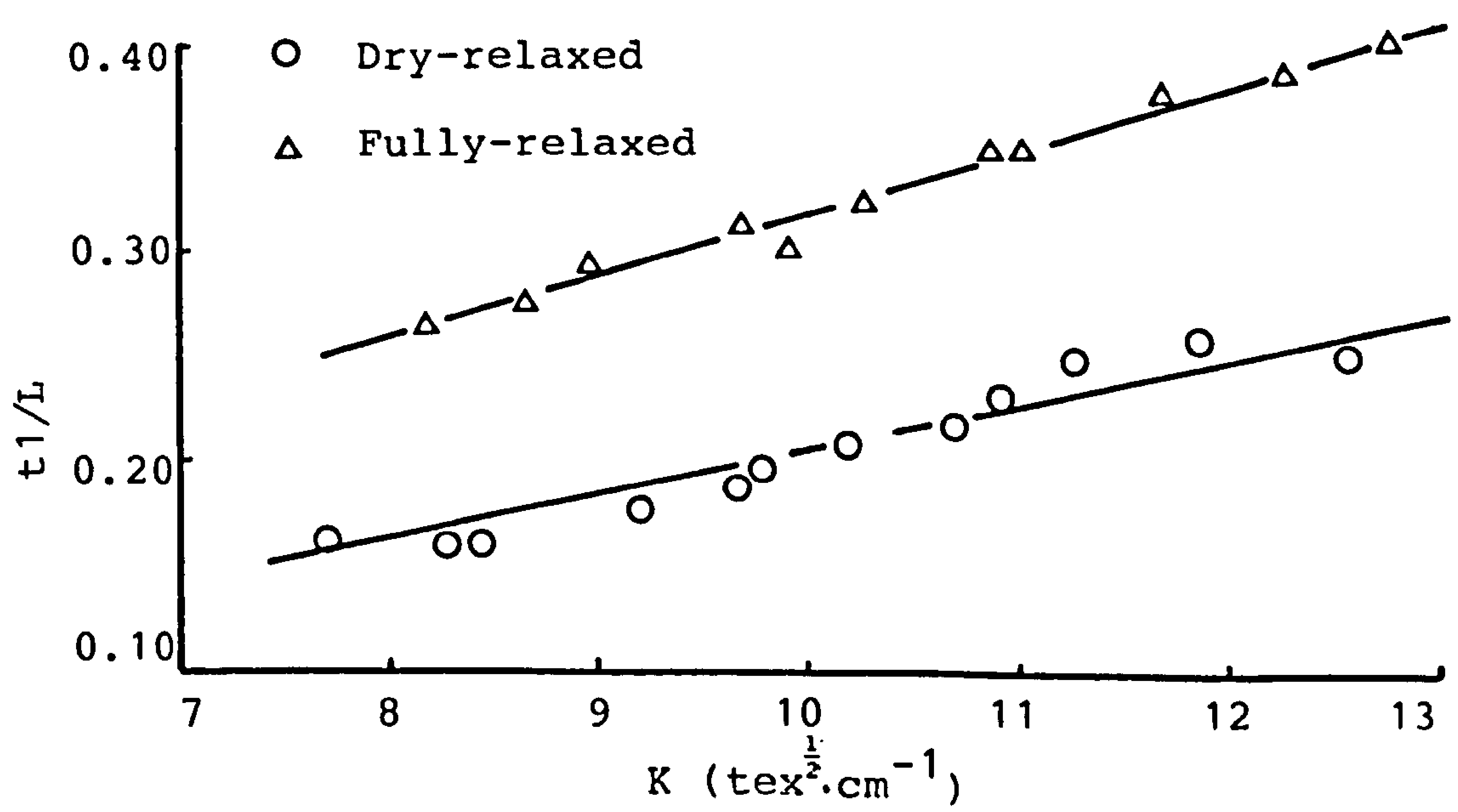


Fig 28 : Plot t1/L against cover factor (K) for dry- and fully-relaxed two-end fabrics.

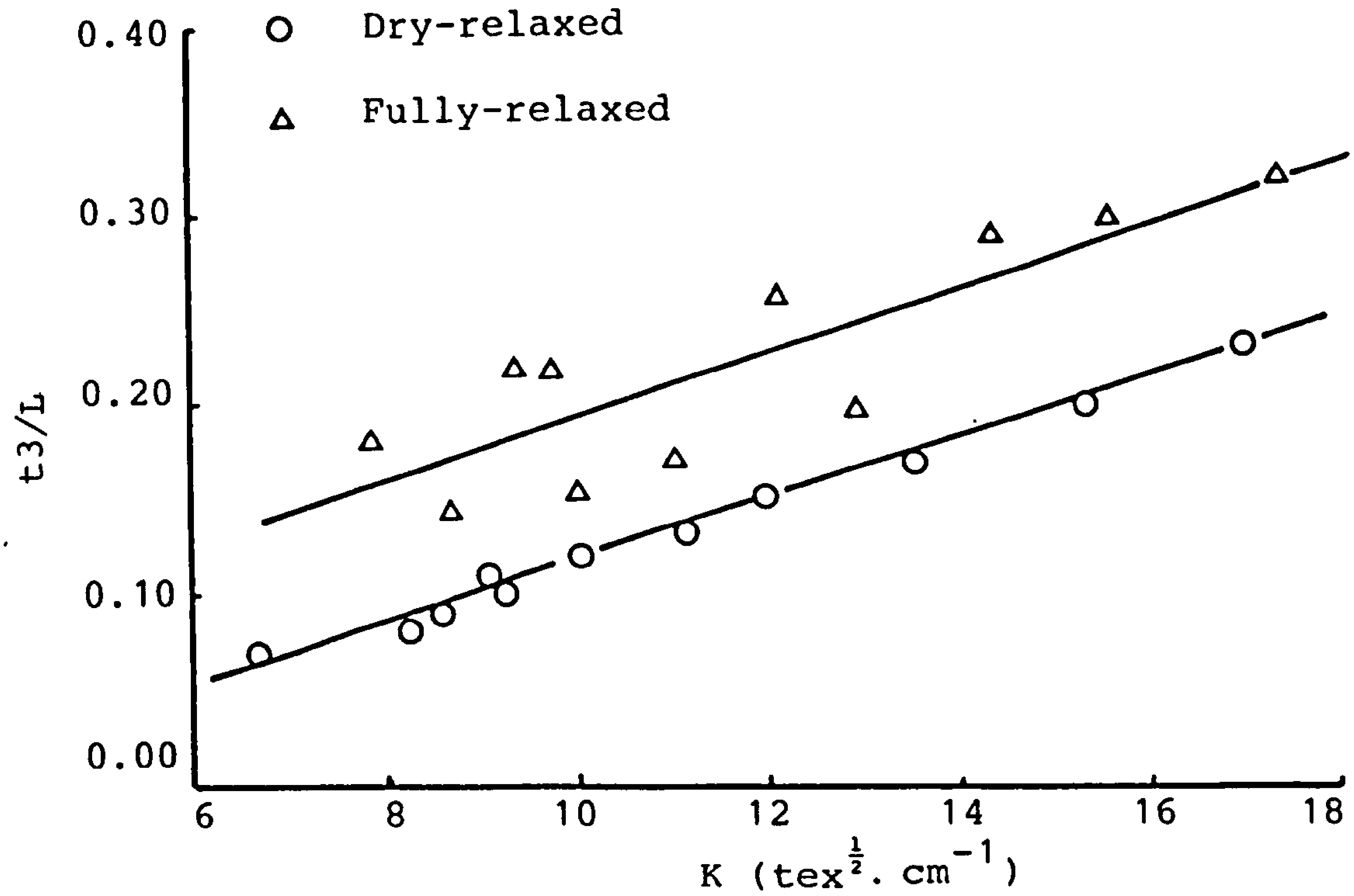


Fig 29 : Plot t3/L against fabric cover factor (K) for dry- and fully-relaxed one-end fabrics.

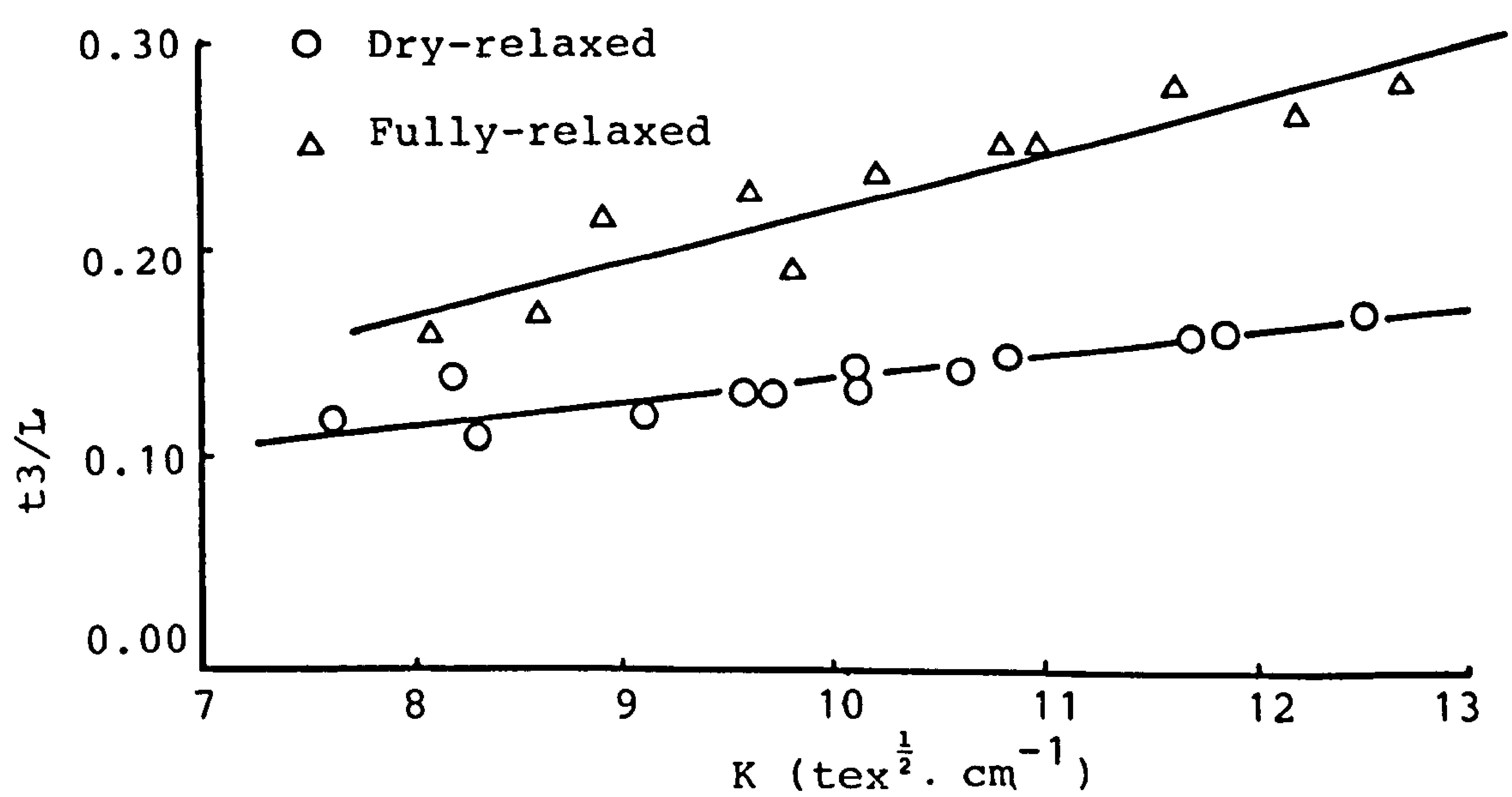


Fig 30 : Plot t3/L against cover factor (K) for dry- and fully-relaxed two-end fabrics.

pressure is higher when the fabrics are in a dry-relaxed state than when they are in a fully-relaxed state, and the opposite picture for the fabrics made from doubled yarns. For the one-end fabrics, this may be because the loop in the dry-relaxed state is easier to deform under any given pressure than when it is in a fully-relaxed state and for the two-end fabrics, in addition to that reason, is probably due to random yarn re-arrangement within the structural unit cell.

In comparing the results given in Table 16 with those obtained by Postle(50) using similar analysis for fully-relaxed fabric, there are slight differences in the magnitude of the slopes and the intercepts and the values of correlation coefficients. These differences may arise because Postle tested a very wide range of different fabrics in yarn type and structure. Leaf(83) suggested that in such a case the regression equation should, for each yarn type, take the following form:

$$t/L = a_y K + b_y$$

where, a_y and b_y are a function of yarn type.

Smirfitt(49) suggested that fabric thickness could be related to the loop length in the following form:

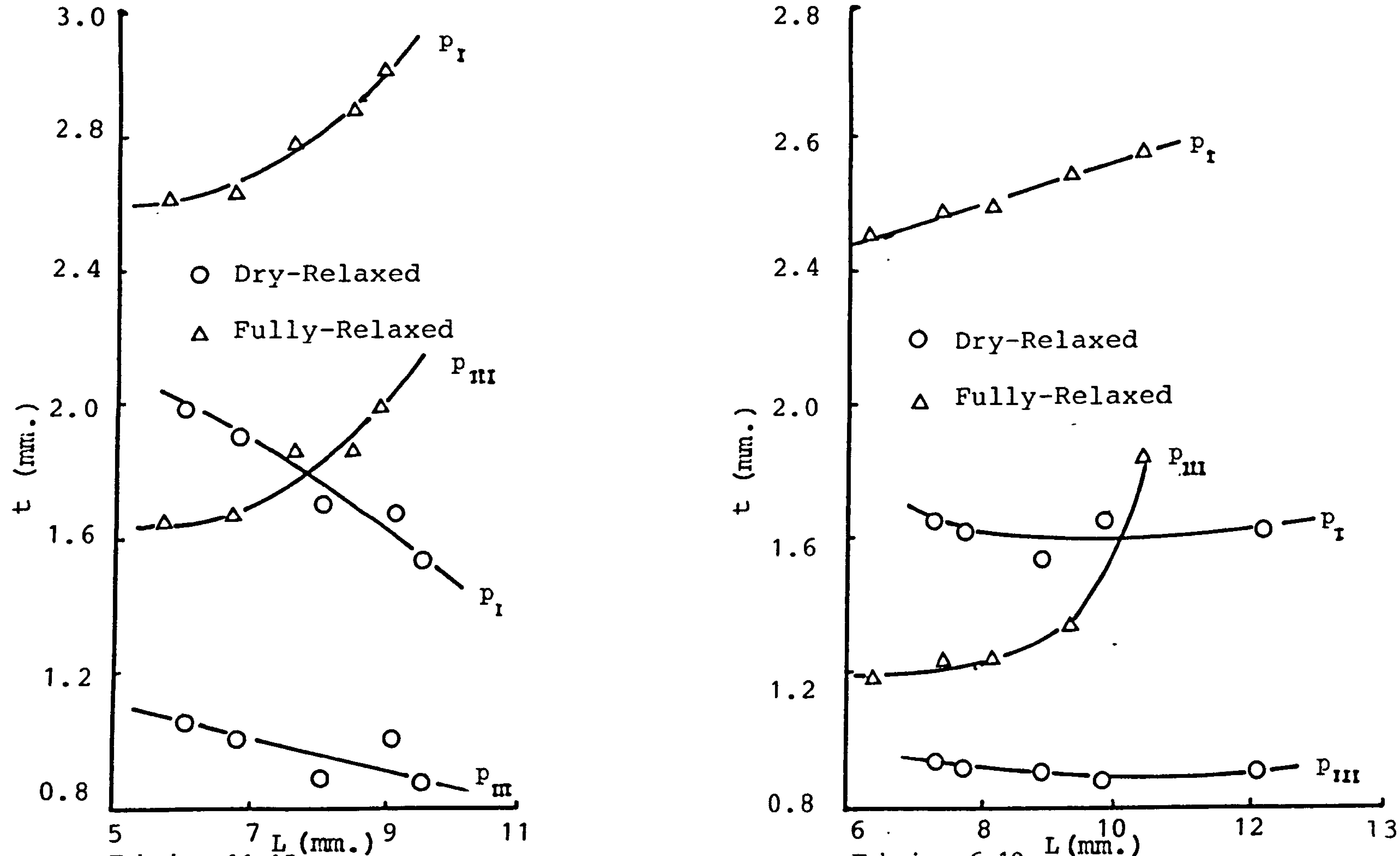
$$(t/d) = 0.09\ (L/d) + 1$$

thus, the thickness increased as the loop length increased.

Knapton et al [45] on the other hand concluded from their experimental work, that fabric thickness is independent of loop length in the fully-relaxed state only, but in one of their two cases (fabrics made from 1/26s)they used only three fabrics, which in the opinion of the author of the present work is not enough to reach such a conclusion. In dry- and wet-relaxed state, they noted, the thickness decreased linearly as the loop length increased for fabric made from 1/26s yarn and non-linearly for the fabrics made from 2/26s yarns.

The results in Tables 14 and 15 have been separated to show groups of fabrics, each of them knitted either on a different type or different gauge of machine and the fabric thickness plotted against loop length (Figs. 31 and 32). The relationship between the fabric thickness measured under low and high pressure and loop length shows a general agreement with those found by Knapton for dry-relaxed fabric only, while in the fully-relaxed state, this relationship shows an agreement with Postle's findings, i.e. fabric thickness, generally increases as the loop length increases.

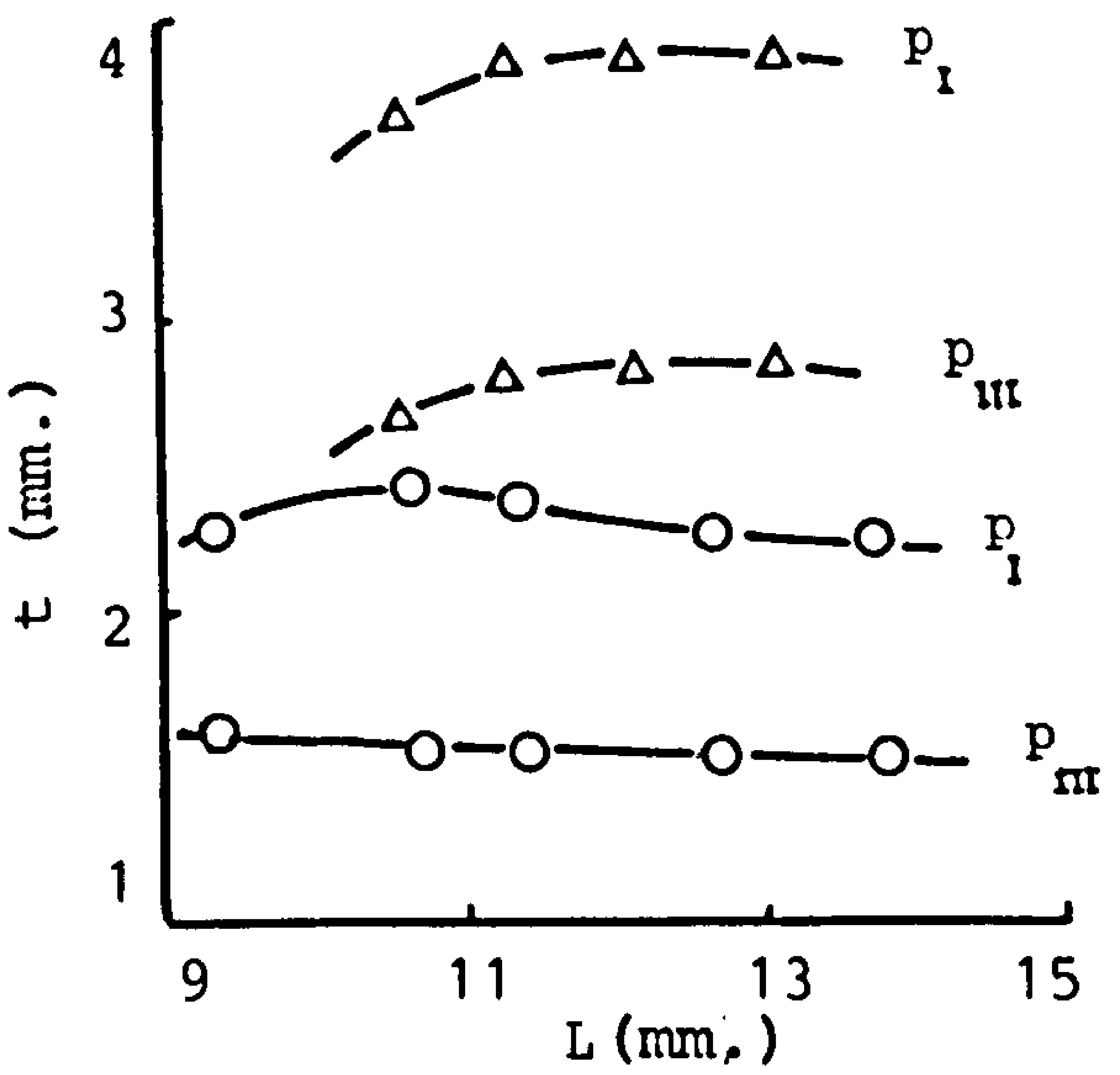
It can be noted form Figs. 31 and 32, that the fabric thickness shows some dependence on the type and the gauge of the machine used to knit a given yarn. Similar observation had been reported by Edwards [48] .



Fabrics 11-15
Manual V-Bed Machine gauge 10

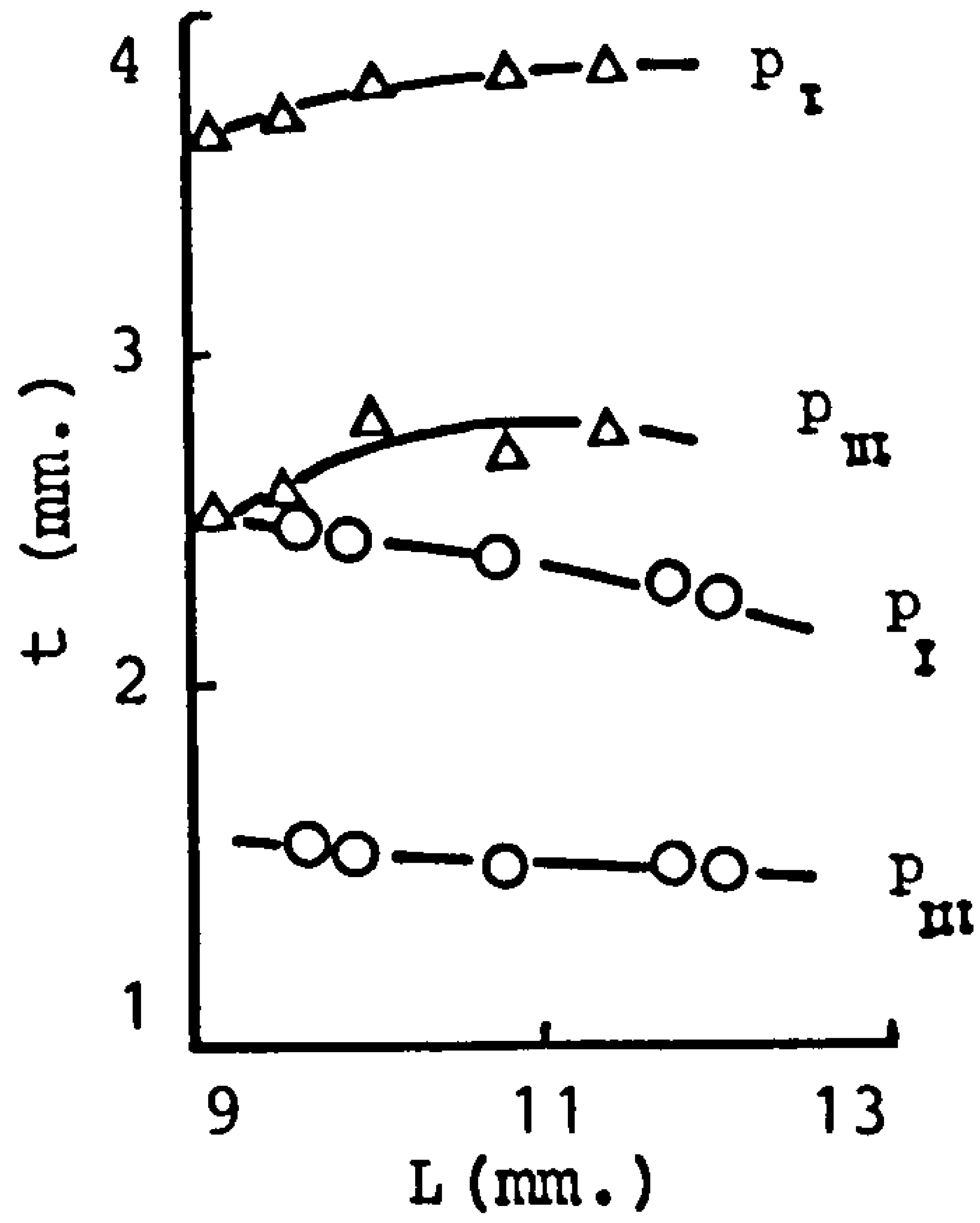
Fabrics 6-10
Manual V-Bed Machine gauge 8

Fig. 31 : Plot thickness (t) against loop length (L) for fabrics made from one end in dry- and fully-relaxed state under pressures P_I and P_{III}



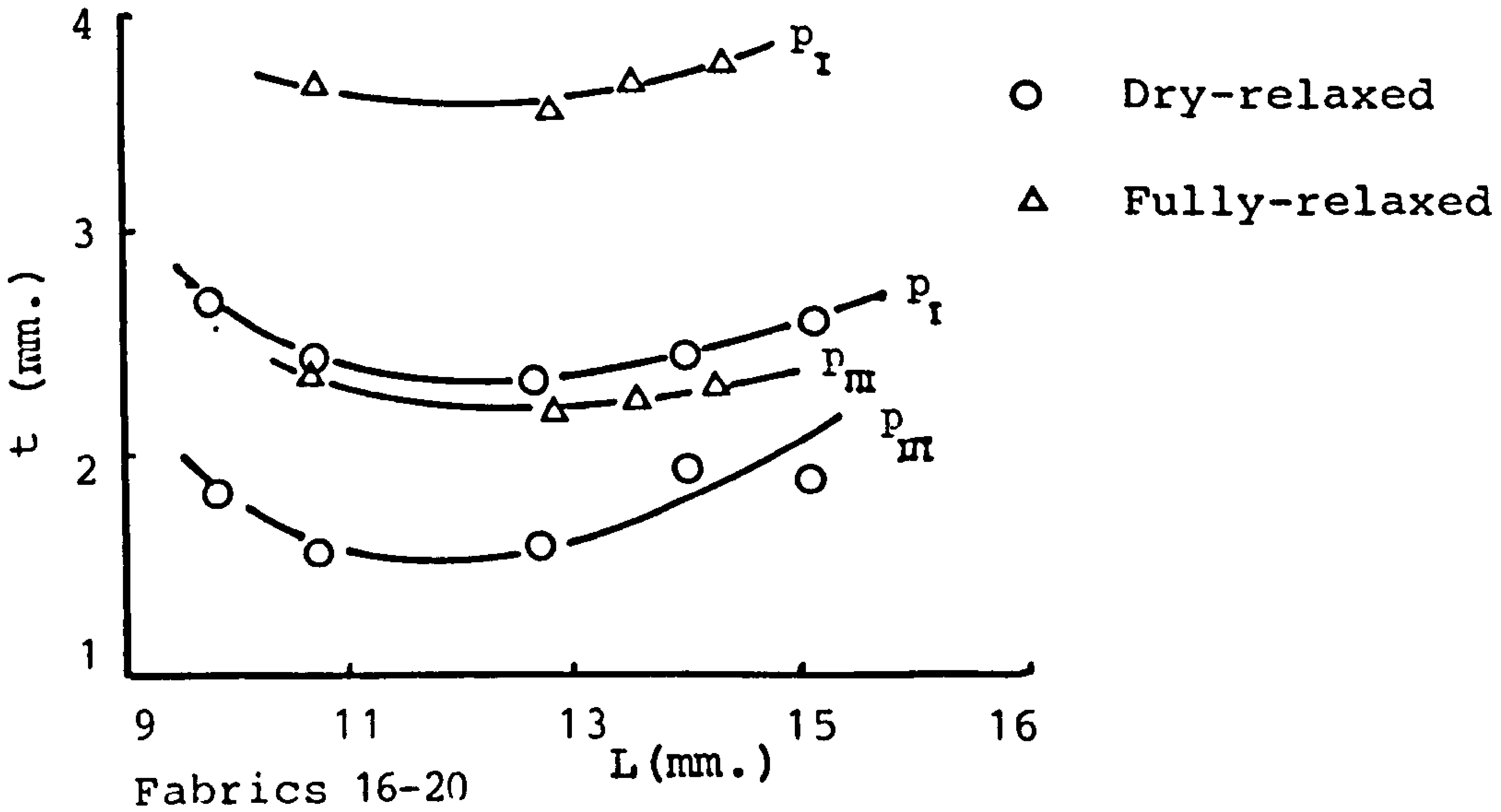
Fabrics 1-5

Manual V.Bed machine gauge 5



Fabrics 24-28

Power circular purl machine gauge 5



Fabrics 16-20

Manual Flat Purl Machine gauge 5

Fig 32 : Plot thickness (t) against loop length (L) for fabrics made from two ends in dry- and fully-relaxed states, under pressure P_I and P_{III}

It appears, that although the fabric thickness has some dependence on loop length and machine type, there is however a direct proportionality between t/L and the fabric cover factor. This is in general agreement with Peirce's argument that the thickness is a function of yarn diameter although the thickness measured here is much greater than twice the diameter as predicted by Peirce's geometry(see appendix IV).

5.3 Air permeability

Air permeability is defined as the volume of air passing per second through a square centimeter of the fabric at a pressure difference of 1cm.head of water.

Several workers have studied the air permeability of the fabric from plain and rib constructions and each of them has related it to different parameter. Jhangiani [84] and Feltaous [15] have studied 1x1 rib fabric, but only the latter studied in detail the relationship between the air permeability and the structural unit cell constituent length.

Ugbolue [70], related the air permeability of plain knitted fabric to the fabric bulk at different pressure levels and to cover factor. Although it is possible to relate the air permeability to cover factor K and also to knitted-fabric cover C which is defined by Postle and Munden [85] as the fraction of the fabric area that is actually occupied by the yarn, i.e. $C=\frac{\text{area of yarn}}{\text{area of fabric}}$, it is thought that, this factor indicates only the covering properties of the uniform plane surface of the fabric.

Since the knitted fabric could be viewed as three-dimensional structure, structural effects in the loop may affect the air permeability of the fabric. Due to these effects a difference between the air permeability results for the back and face of the fabric observed in Ugbolue's and in the present work.

In view of the above reason, a parameter which characterises the fabric packing has been introduced. This parameter, knitted-fabric volume factor is defined as the ratio of volume occupied by the structural unit cell to that occupied by the yarn, i.e.

$$V_F = 4 \frac{Cs.Ws.t}{d^2 L \pi}$$

where, Cs and Ws-Course and wale spacing respectively.

t - Fabric thickness

L - Loop length

d - Yarn diameter

If Peirce's assumption of the fabric thickness $t = 2d$, is accepted then, the above factor will be:

$$V_F = \frac{8}{\pi} \frac{Cs.Ws.}{d\ L}$$

In this case, if the space of one unit cell is fully occupied by the yarn, the knitted-fabric volume factor reaches its minimum value $V_F = 1$, when the area occupied by the yarn is equal to $\frac{8}{\pi} = (2.5)$ times the area occupied by the structural unit cell.

The results of the measured air permeability A_p and the calculated knitted-fabric volume factor V_F are given in Tables 17 and 18. Values of the measured air permeability A_p are plotted against knitted fabric volume factor V_F for the fabrics made from one end and the fabrics made from two ends of yarn both dry- and fully-relaxed states.

A regression analysis was carried out on the results shown in Figs. 33 and 34. The following regression equations were obtained from this analysis.

For the fabrics made from one-end yarn:

$A_p = 65.9\ V_F - 180.6$, with correlation coefficient $r = 0.94$, for dry-relaxed fabrics.

$A_p = 24.2\ V_F - 6$, with correlation coefficient, $r = 0.98$, for fully-relaxed fabrics.

For the fabrics made from two-ends yarn:

$A_p = 56.8\ V_F - 57.3$, with correlation coefficient, $r = 0.92$, for dry-relaxed fabrics.

$A_p = 41.5\ V_F - 30.1$, with correlation coefficient, $r = 0.95$, for fully-relaxed fabrics.

From above, it is clear that linear relationship between the air permeability A_p and knitted fabric volume factor V_F exists. The correlation coefficients for all fabrics are highly significant. It is interesting to note that these correlation coefficients are higher than those reported in Ugbolue's [70] work in which he analysed the relationship of A_p with bulk density B.

From regression analysis, it can be noted, that the slopes and the intercepts for dry-relaxed fabrics

Table 17: Some physical properties of dry- and fully-relaxed fabric made from one end

Dry-Relaxed					Fully-Relaxed				
Fabric No	Fabric Weight g/m^2	Fabric Thickness t_1(mm)	Airflow Ap $cm^3/sec/cm^2$	Knitted Fabric Volume Factor V_F	Fabric No	Fabric Weight g/m^2	Fabric thickness t_1(min)	Airflow Ap $cm^3/sec/cm^2$	Knitted Fabric Volume Factor V_F
21	266	2.03	116	4.49	21	305	2.28	67	3.06
23	245	2.07	115	5.13	23	268	2.64	79	4.06
11	200	2.00	149	5.50	11	260	2.633	94	4.13
12	175	1.90	204	5.85	6	225	2.52	111	4.62
6	166	1.66	222	5.60	12	225	2.69	112	4.87
13	137	1.71	267	6.55	7	199	2.59	137	5.31
8	127	1.54	317	6.67	8	170	2.59	149	6.23
14	120	1.67	320	7.74	15	166	3.02	160	7.35
15	117	1.53	325	7.82	9	154	2.71	170	7.24
9	116	1.66	343	8.25	10	139	2.77	190	8.10

Table 18: Some physical properties of dry- and fully-relaxed fabrics made from two-ends yarn

Dry-relaxed					Fully-relaxed				
Fabric No	Fabric Weight g/m^2	Fabric thickness t_1 (mm)	Air flow A_p $cm^3/sec/cm^2$	Knitted Fabric Volume Factor V_F	Fabric No	Fabric Weight g/m^2	Fabric thickness t_1 (mm)	Air flow A_p $cm^3/sec/cm^2$	Fabric Knitted Volume Factor V_F
24	236	2.53	100	2.94	24	318	3.64	67	2.35
25	213	2.45	106	3.15	25	302	3.69	69	2.48
26	207	2.42	126	3.21	26	292	3.80	79	2.65
3	198	2.36	139	3.29	27	270	3.83	88	2.87
27	185	2.37	144	3.53	3	244	3.93	97	3.29
28	167	2.29	158	3.77	28	247	3.83	98	3.16
4	171	2.32	174	3.71	18	244	3.58	113	3.00
5	157	2.28	177	3.99	4	223	3.91	117	3.61
19	151	2.43	210	4.41	5	217	3.95	124	3.71
20	148	2.60	190	4.77	20	200	3.81	134	3.90

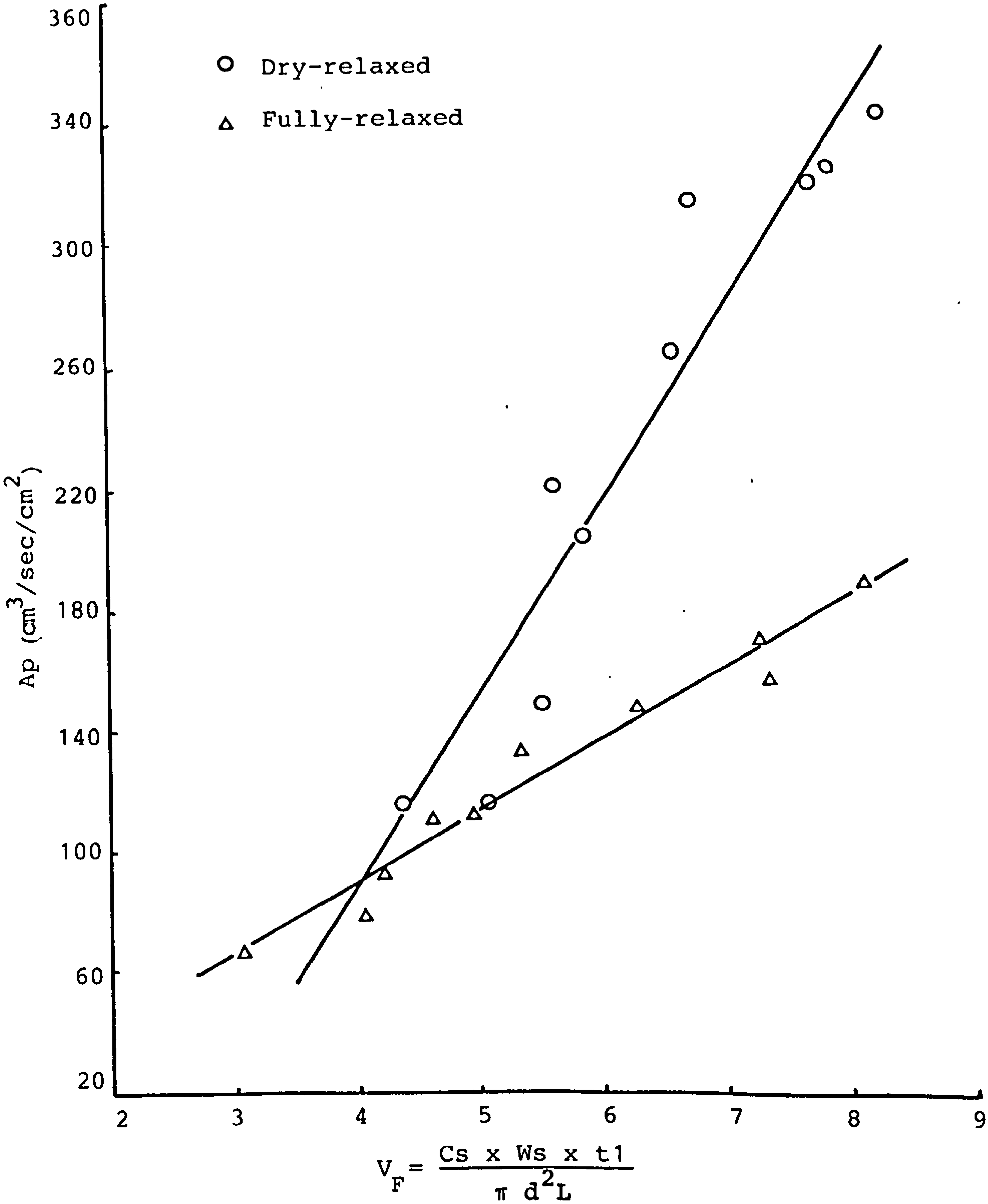


Fig 33 : Plot air permeability Ap against knitted fabric volume factor V_F for dry- and fully-relaxed one-end fabrics.

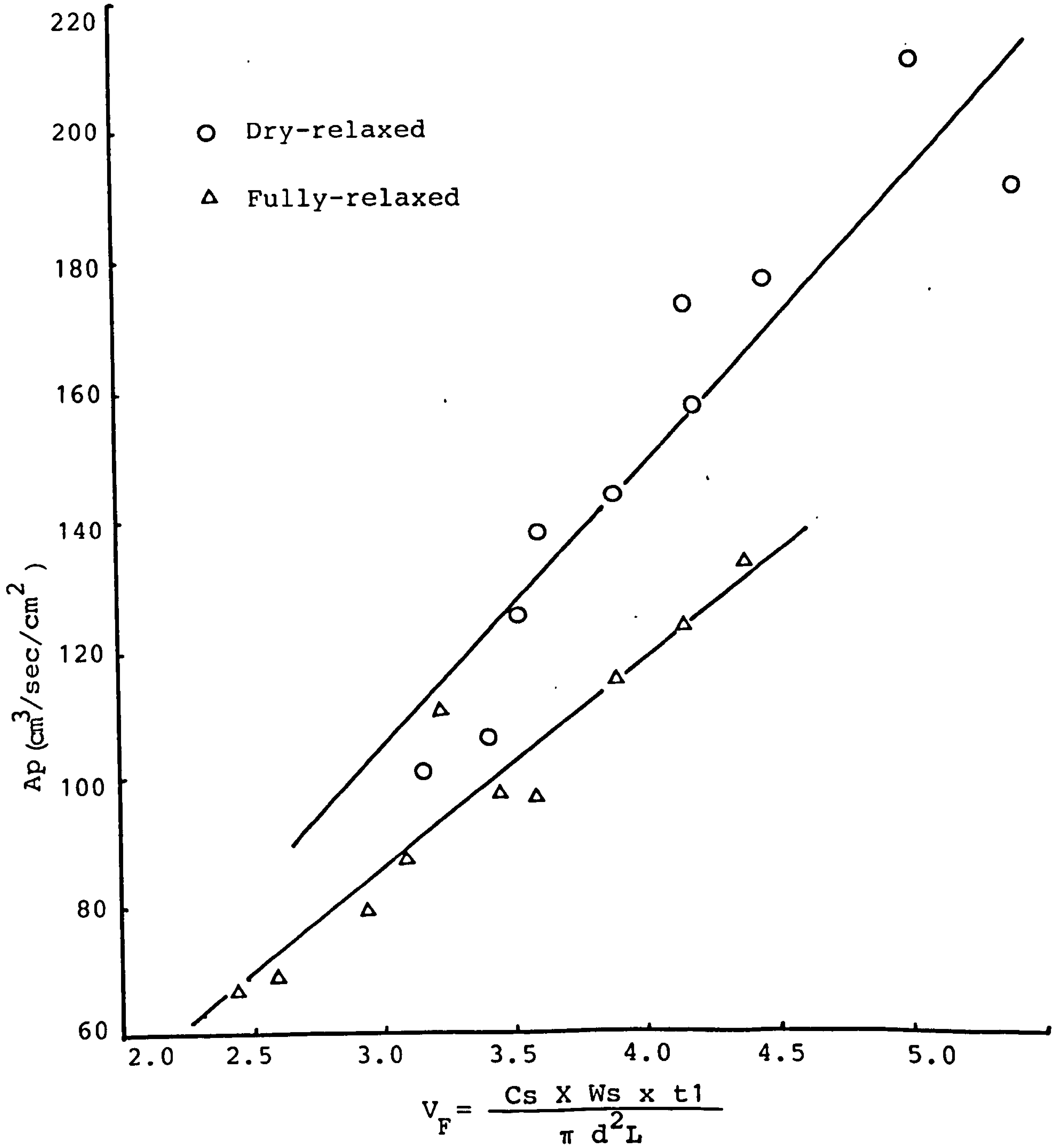


Fig 34 : Plot of air permeability Ap against knitted fabric volume factor V_F for dry- and fully-relaxed two-end fabrics.

are higher than those for fully-relaxed fabrics, and much higher for the fabrics made from two ends of yarn. On the other hand, the correlation coefficients of fully-relaxed fabrics are higher than those of dry-relaxed fabrics. This suggests that not only does the fabric resistance to air flow increase as the treatment progresses and the yarn diameter increases, but also because the fabrics become more regular due to the reduction in the degree of structural variation resulting from the treatment. In addition to that, by comparing the best fit lines in Fig. 33 with those in Fig.34, it seems possible that yarn re-arrangement resulting from the treatment may have occurred. This is indicated by a very considerable drop in values of intercept from dry-relaxed state to fully-relaxed state for fabrics made from one end. It dropped from 180.6 to 6.0, which led the lines to overlap, while, for fabrics made from two ends the reduction is only 57.3 to 30.1. The reduction in structural variation resulting from the treatment, is indicated by the fact that the points round the lines are spreading more when the fabrics are in dry-relaxed state than when they are in the fully-relaxed state for both one- and two-end fabrics.

The fabric resistance to air flow reaches its maximum, when the fabric volume cover reaches its minimum value, $V_F = 1$. This is an extreme in which the air flow, theoretically, cannot pass through the fabric. Physically, however, even in such extreme case some air flow can pass through between the fibres.

5.4 Fabric abrasion resistance

In actual use, some parts of the garments are subjected to abrading action and consequently to wear. Although the laboratory test on fabric abrasion is merely to give simulation of the abrasive action on fabric, most wool knitted fabrics, in actual wear or in laboratory test form pills after they are subjected to rubbing action. These pills contain certain loose broken fibres in the form of small spherical bundles anchored to the fabric surface by one or more unbroken fibres. The other loose broken fibres which are not attached to the fabric are lost during abrasion. The degree of formation and the rate of growth of the pills depends on the fabric structure or construction and the type and the quality of the fibres from which that fabric has been knitted.

Since the fabrics were knitted with different loop length, each specimen tested for abrasion is different in in weight and there is a possibility that the actual weight loss might be the same for several specimens. It is felt that the best assessment of the wearing property of the fabric in relation to the geometrical parameters to express the weight loss as % loss rather than as actual loss.

The results of abrasion test for fabrics in both dry- and fully-relaxed states are shown in Table 19, for fabrics made from one end of yarn and in Table 20 for fabrics made from two ends. The results at the end of 2000 cycles for the fabrics made from one end and two ends were plotted against loop length and then against inverse cover ($C^* = \frac{1}{SxdxL}$). This is shown in Figs. 35, 36, 37 and 38 respectively. From Figs. 35 and 37, the relationship between the percentage weight loss and loop length and fabric cover for the fabrics made from one end is fairly linear, while the relationship with loop length for fabrics made from two ends of yarn is non-linear(Fig. 36) and the relationship with inverse cover C^*(Fig .38) shows a considerable spread of points to the extent that may suggest independence of percentage weight loss from fabric cover.

The relationship between percentage weight loss and loop length was also determined at 400 cycles intervals up to 2000 cycles. Typical graphs of percentage weight loss against number of cycles are shown in Fig. 39 indicating that the rate of wear was fairly linear.

The plots of percentage weight loss against loop length for all fabrics in both the dry- and fully-relaxed state at all cycle intervals showed, as can be seen

Table 19: Abrasion resistance of dry- and fully-relaxed fabrics made from one end of yarn

Dry-relaxed						Fully-relaxed					
Fabric No	Percentage loss in fabric weight by abrasion after:					Fabric No	Percentage loss in fabric weight by abrasion after:				
	400 cycles	800 cycles	1200 cycles	1600 cycles	2000 cycles		400 cycles	800 cycles	1200 cycles	1600 cycles	2000 cycles
21	0.53	0.87	0.99	1.12	1.51	21	0.45	1.02	1.44	1.86	2.23
23	0.26	0.61	0.96	1.19	1.50	23	0.15	0.58	1.12	1.62	2.14
11	0.19	0.49	0.87	1.10	1.43	11	0.33	0.73	1.24	1.73	2.24
12	0.35	0.77	1.21	1.74	2.21	12	0.27	0.77	1.41	1.98	2.57
6	0.34	0.69	1.21	1.65	2.18	7	0.30	0.88	1.56	2.48	2.72
13	0.51	1.12	1.68	2.31	2.94	8	0.26	0.77	1.46	2.41	3.18
8	1.06	1.43	1.94	2.59	3.19	15	0.32	0.72	1.37	2.00	3.02
15	0.90	1.53	2.33	3.00	3.83	9	0.38	0.98	1.81	2.73	3.80
10	0.50	1.18	2.02	2.74	4.76	10	0.35	0.91	1.89	3.04	4.49

Table 20: Abrasion resistance of dry- and fully-relaxed fabrics made from two ends of yarn

Dry-relaxed						Fully relaxed					
Fabric No	Percentage loss in fabric weight by abrasion after:					Fabric No	Percentage loss in fabric weight by abrasion after:				
	400 cycles	800 cycles	1200 cycles	1600 cycles	2000 cycles		400 cycles	800 cycles	1200 cycles	1600 cycles	2000 cycles
1	0.29	0.45	1.06	1.58	2.04	24	0.22	0.59	1.14	1.54	2.37
25	0.67	1.05	1.55	2.10	2.55	1	0.58	1.09	1.73	2.44	3.12
2	0.62	1.12	1.55	2.17	2.73	2	0.66	1.14	1.93	2.64	3.52
3	0.64	1.22	1.72	2.23	2.75	3	0.83	1.42	2.21	3.01	3.98
28	0.39	0.78	1.27	1.83	2.45	18	0.38	0.93	1.70	2.62	3.44
4	0.24	0.51	0.97	1.52	2.56	5	0.10	0.46	1.22	2.09	2.93
5	0.27	0.79	1.66	2.55	3.48	19	0.30	0.77	1.55	2.48	3.42
20	0.49	0.97	1.81	2.56	3.31	20	0.24	0.90	1.79	2.69	3.64

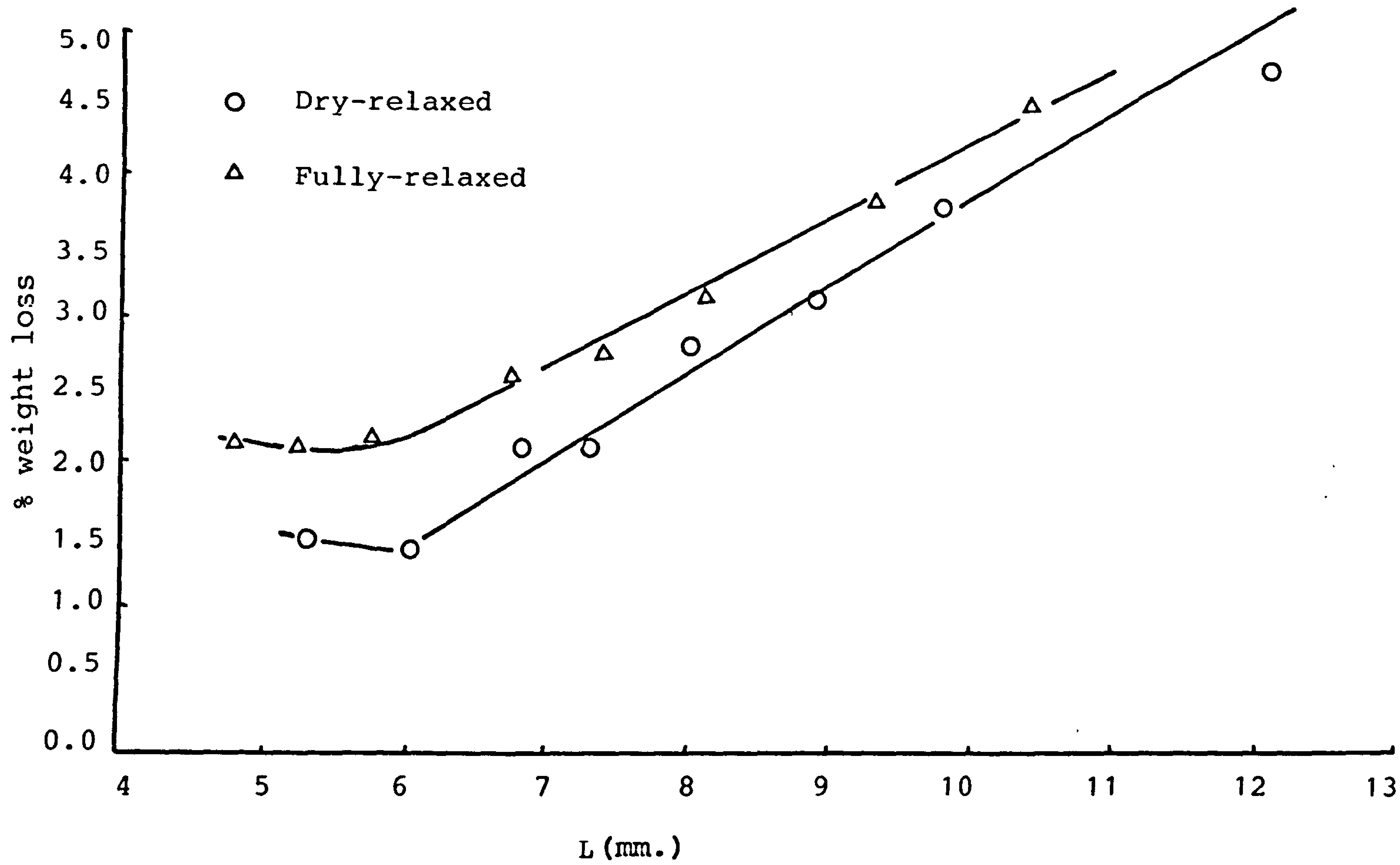


Fig 35: Plot of percentage weight loss against loop length, L for dry- and fully-relaxed one-end fabrics at 2000 cycles.

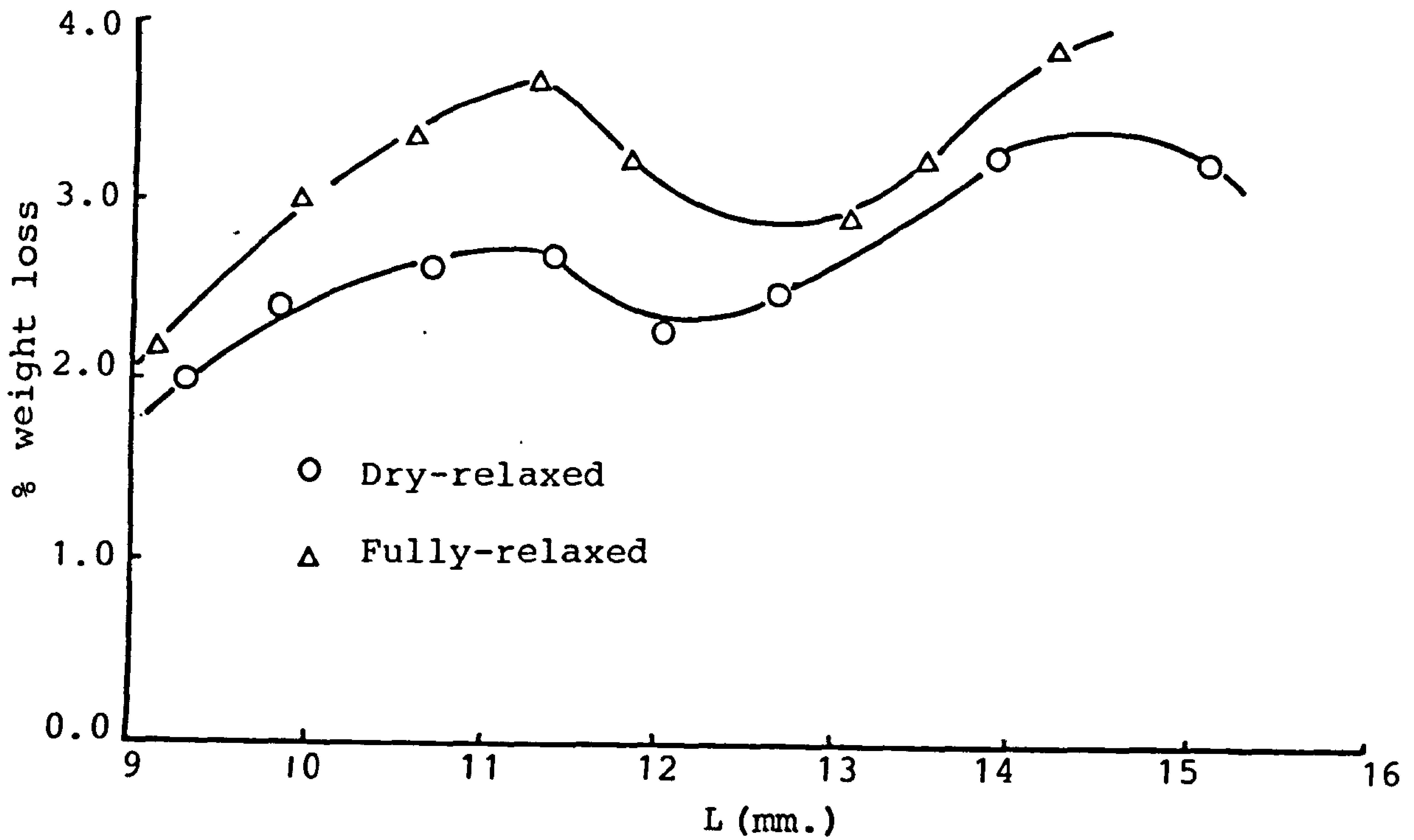


Fig 36 : Plot of percentage weight loss against loop length, L for dry- and fully-relaxed two-end fabrics at 2000 cycles.

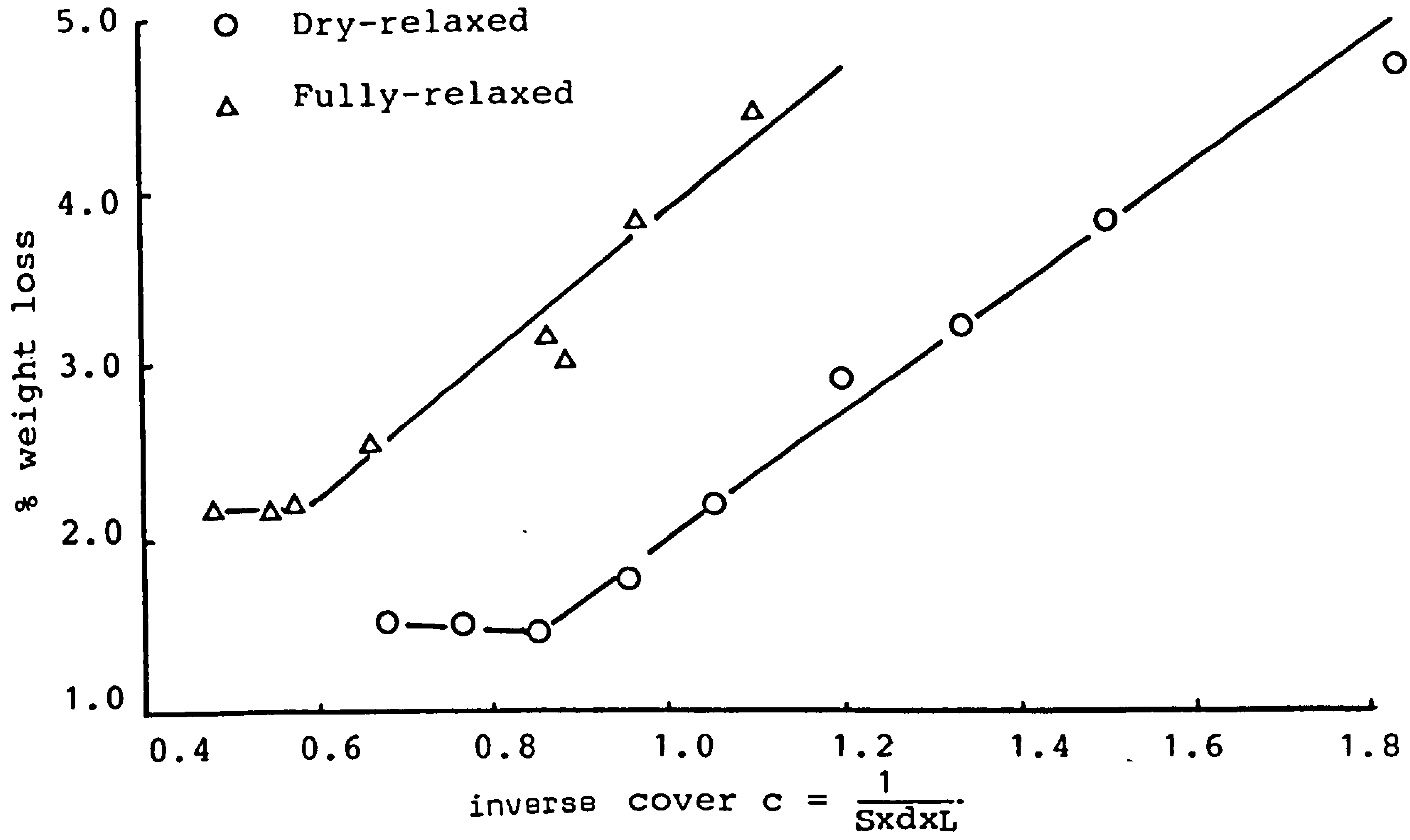


Fig: 37. Plot of percentage weight loss against C* for dry- and fully-relaxed one-end fabrics at 2000 cycles.

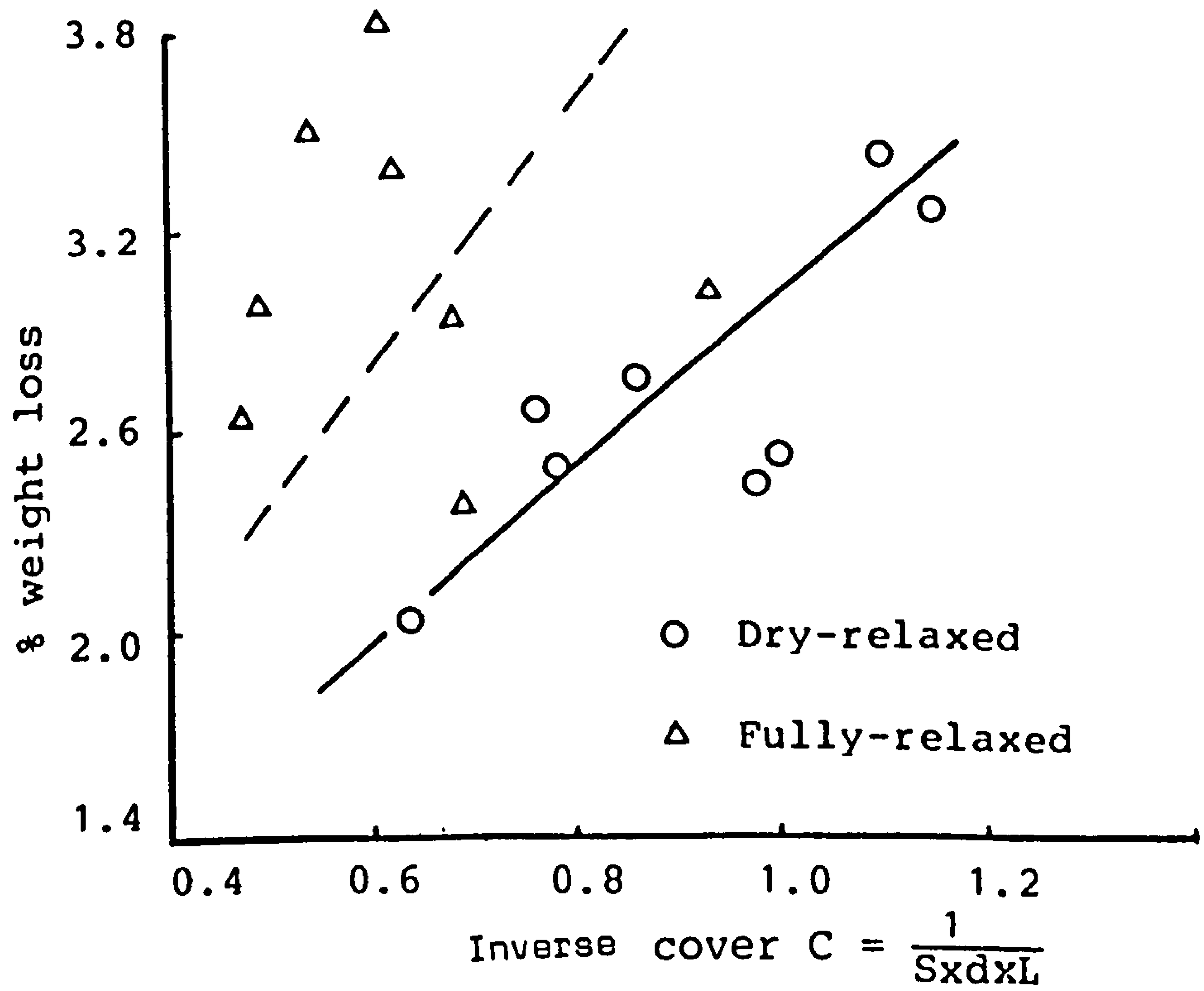


Fig 38 : Plot of percentage weight loss against C* for dry- and fully-relaxed two-end fabrics at 2000 cycles.

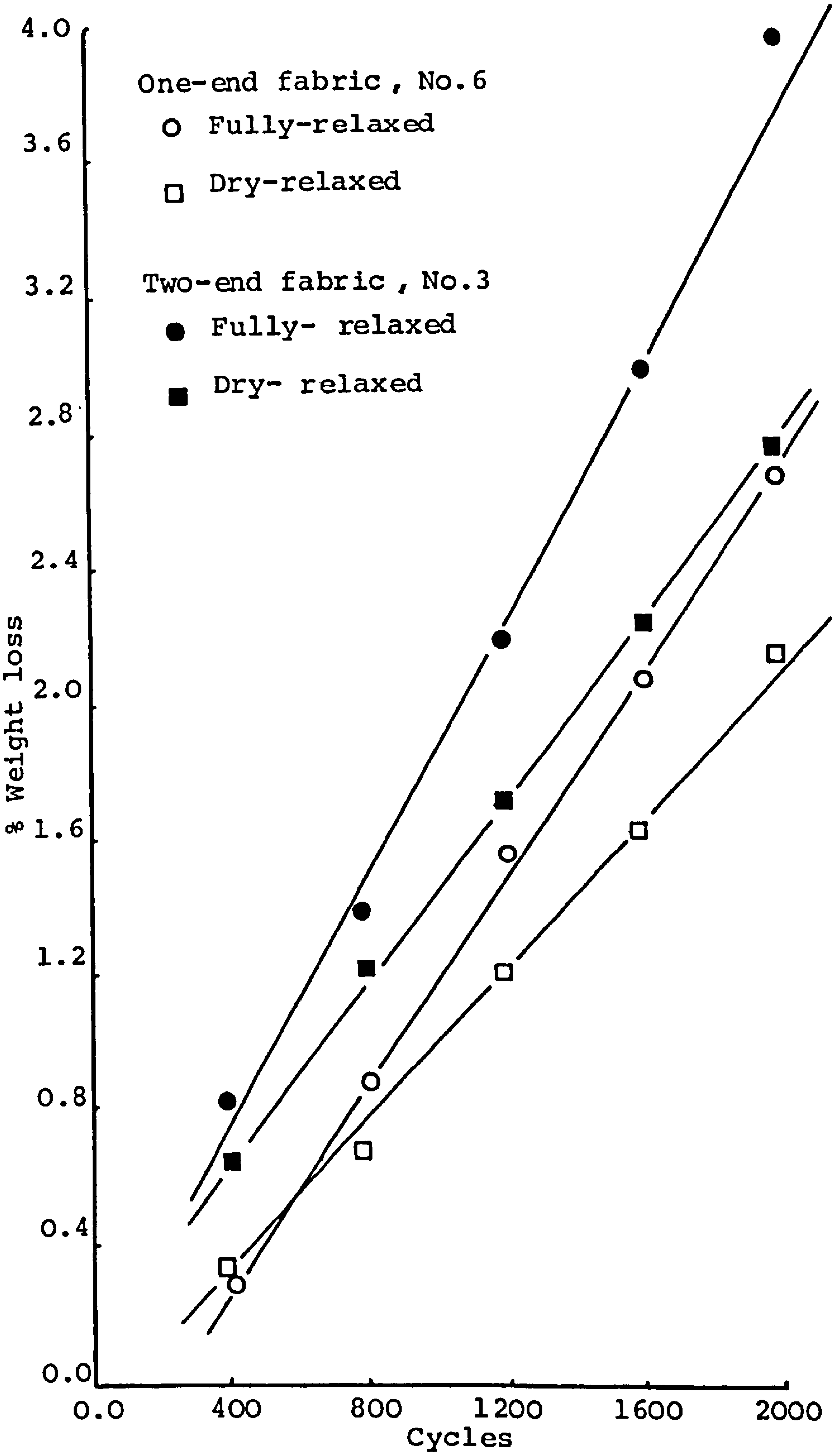


Fig.39: Plot of number of cycles against % weight loss for one-and two-end fabrics in both dry-and fully-relaxed state.

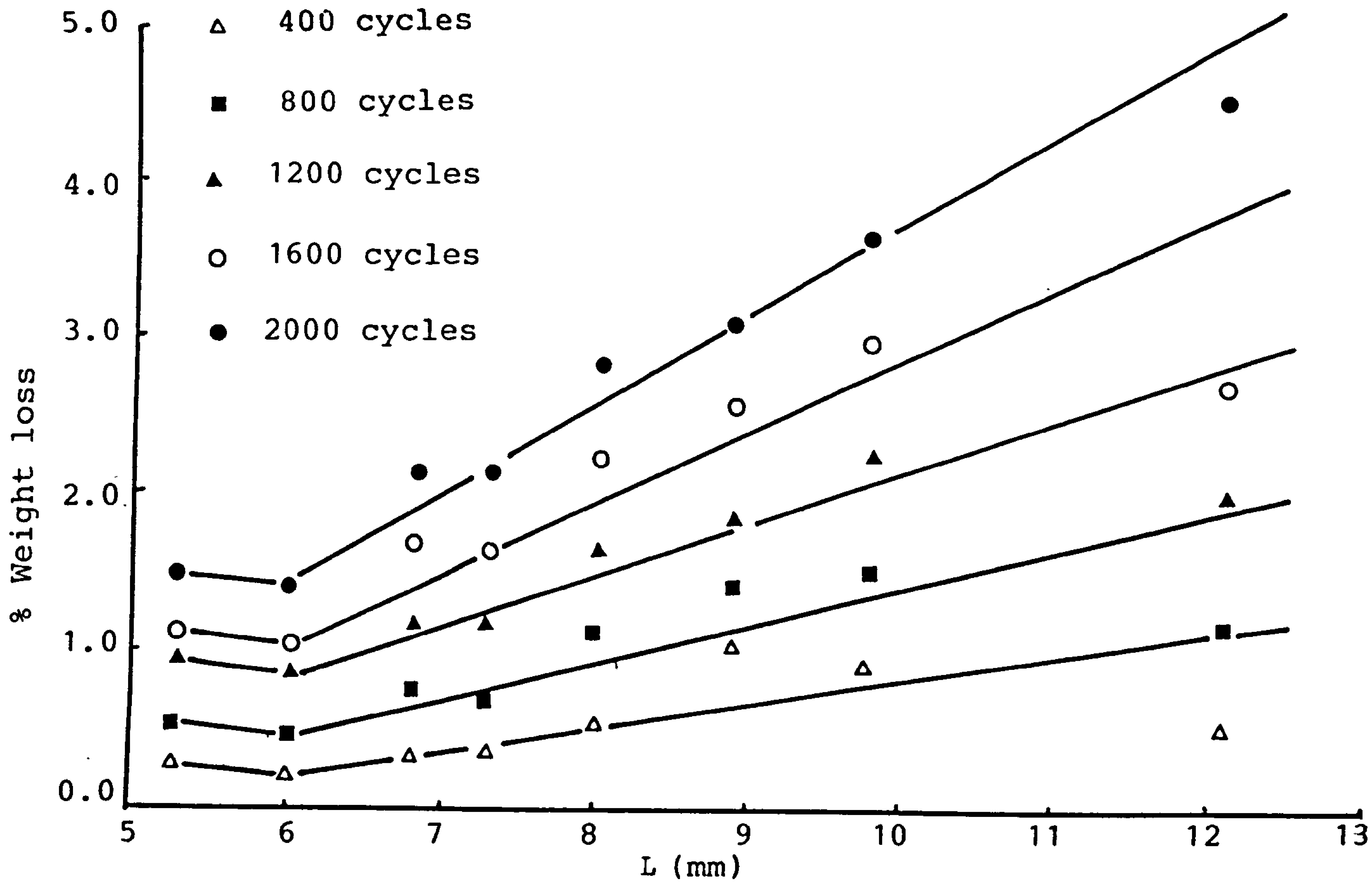


Fig 40: Plot of percentage weight loss against loop length L for dry-relaxed one-end fabrics in the five intervals of abrasion.

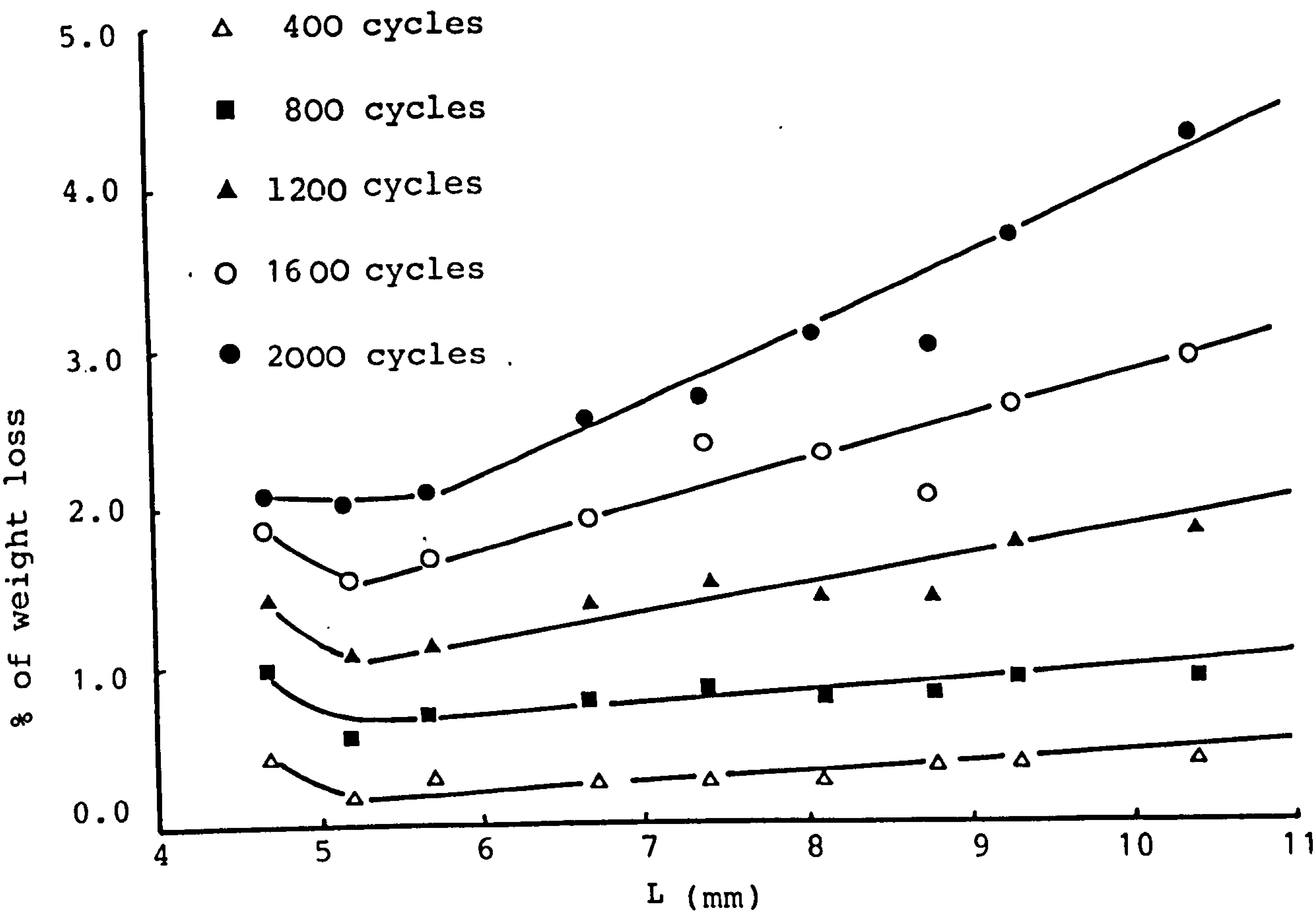


Fig 41: Plot of percentage weight loss against loop length L, fully-relaxed one-end fabrics in the five intervals of abrasion.

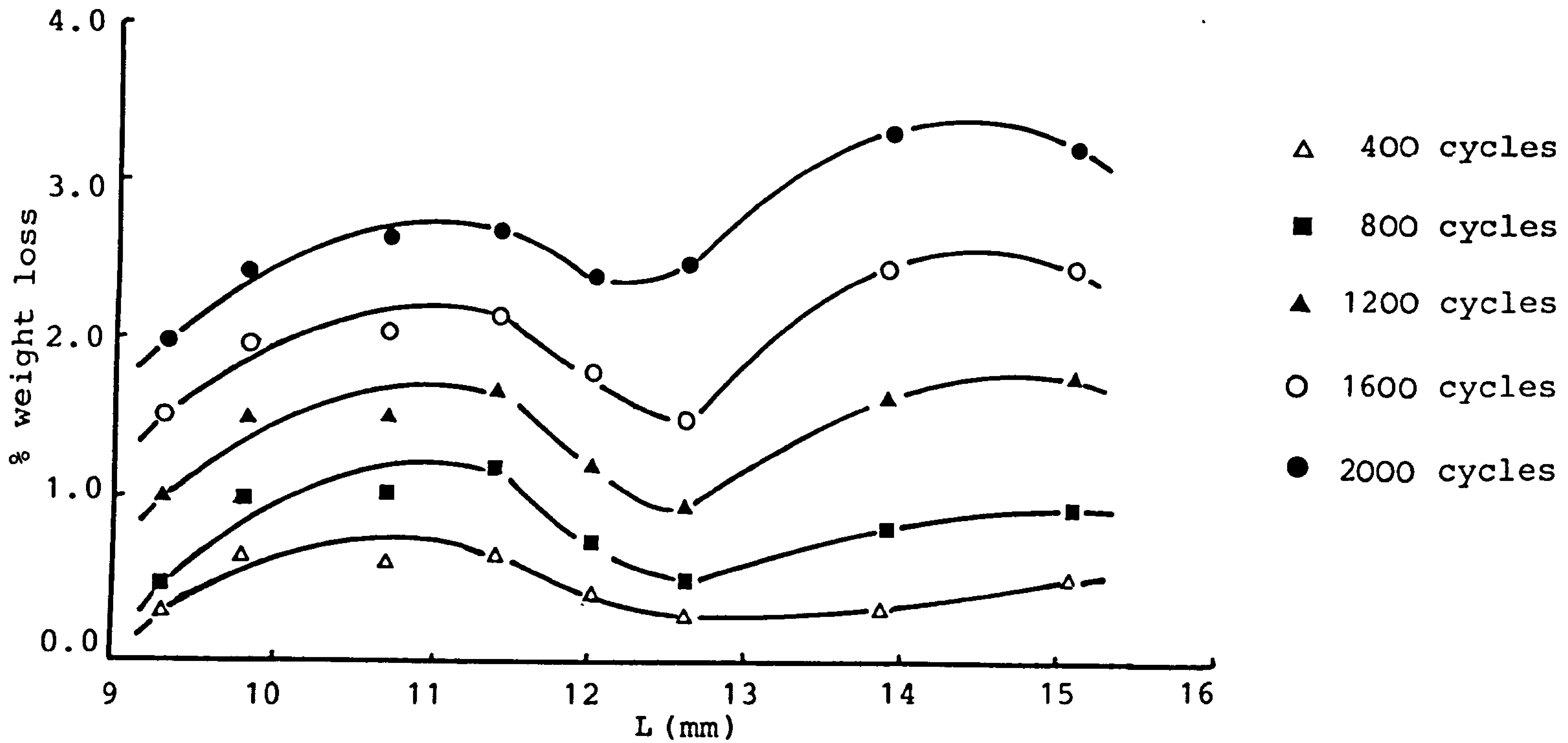


Fig. 42 : Plot of percentage weight loss against loop length L for dry-relaxed two-end fabrics in the five intervals of abrasion.

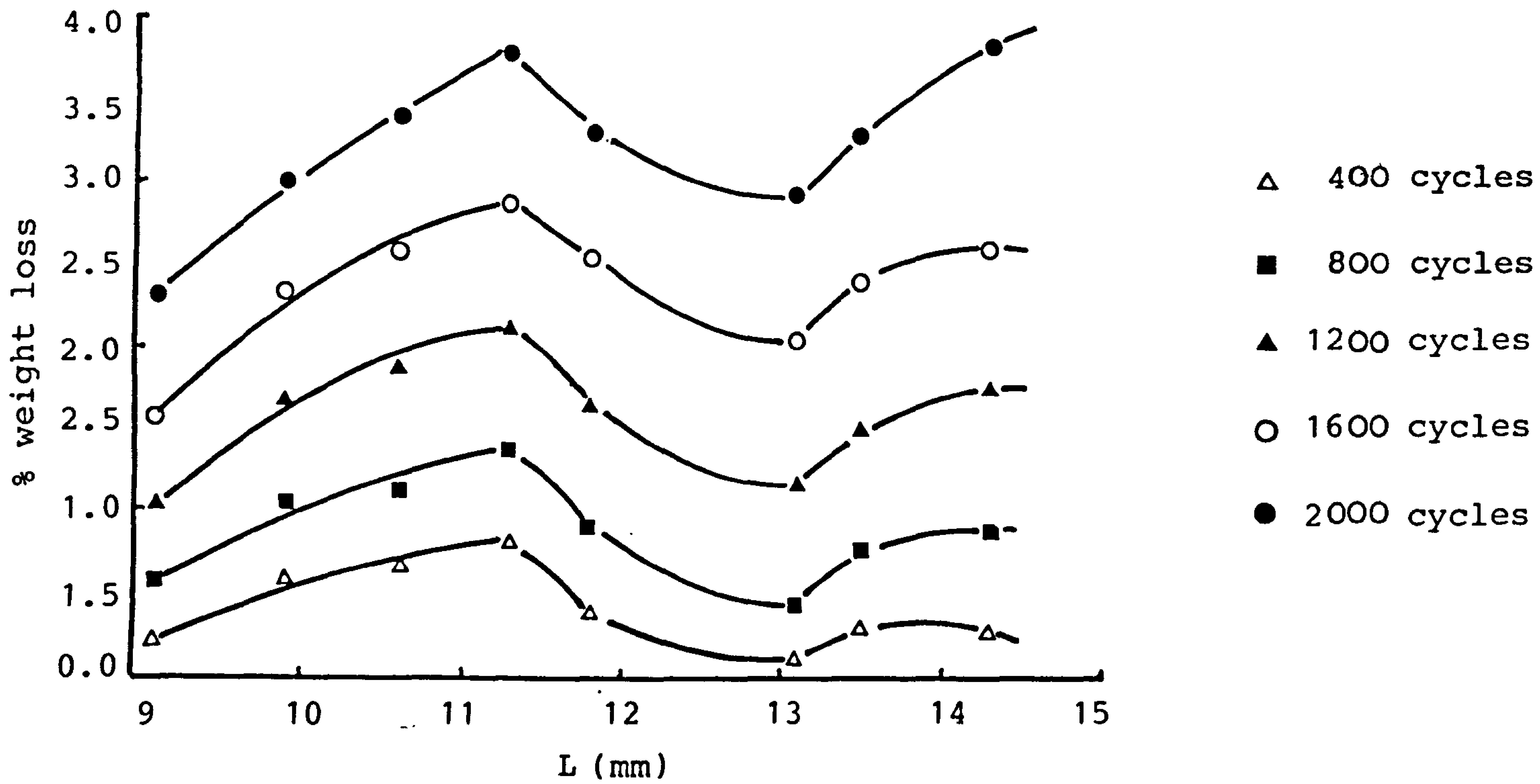


Fig 43: Plot of percentage weight loss against loop length L for fully-relaxed two-end fabrics in the five intervals of abrasion.

from Figs. 40-43, much the same behaviour as at 2000 cycles. The fully-relaxed fabrics made from one end of yarn show a greater percentage weight loss, particularly at the initial stages, than the dry-relaxed made from the same yarn. This is probably due to an increase in fabric hairniness resulted from the treatment. Similarly the percentage weight loss in the early stages as well as in the late stages of abrasion for fabrics made from two end as can be seen from Figs. 42 and 43 is more when the fabrics are in the fully-relaxed state than when they are in the dry-relaxed state. It could also be noted from Fig. 36 that the relationship between percentage weight loss and the loop length for two-end fabrics in both states of relaxation is non-linear and it takes, for the range of loop length used in this work (from very tight to very slack fabric) the form of waves. The only possible explanation is that since the singles yarns are "free" (untwisted) they may change their position relative to each other during the abrasion action as well as during the knitting action. This may explain the more random relationship of % weight loss with fabric cover factor C shown in Fig. 38.

From the tables and Figs. in this section, it could be concluded that the main reason for increasing percentage weight loss with an increasing loop length is that, when the yarn area in contact with the abradant decreases, more inter-yarn movement is possible and the rubbing action will increase within each cycle interval.

CHAPTER 6

TENSILE PROPERTIES OF PLAIN KNITTED FABRICS

6.1 Theory

The maximum extension of plain-knitted fabric is a limit reached when the yarns jam against each other and the fabric cannot continue to deform by the mechanism of yarn sliding which will depend not only on the space between the yarn within the structural unit cell, but also on the compression properties of the yarns. Further extension to the point of break, will then, depend on the tensile properties of the yarn.

In the present analysis, the effect of jamming will be ignored, and the tensile properties of the yarn will be considered. On this basis, the analysis is carried out to determine the minimum and maximum values of course spacing, wale spacing and the amount of fabric extension in both coursewise and walewise direction. When the fabric is extended to its maximum limit, it will take the form shown in Figs. 44 and 45 [42,63].

6.1.1 Extension in length (Walewise)

The extended fabric in the walewise direction takes the form shown in Fig. 44 . From this Fig., the length of yarn in one structural unit cell is the sum of the segments a-b, b-c, c-d, d-e and e-f. Segment c-d is a semi-circle and each of the segments a-b and e-f is a

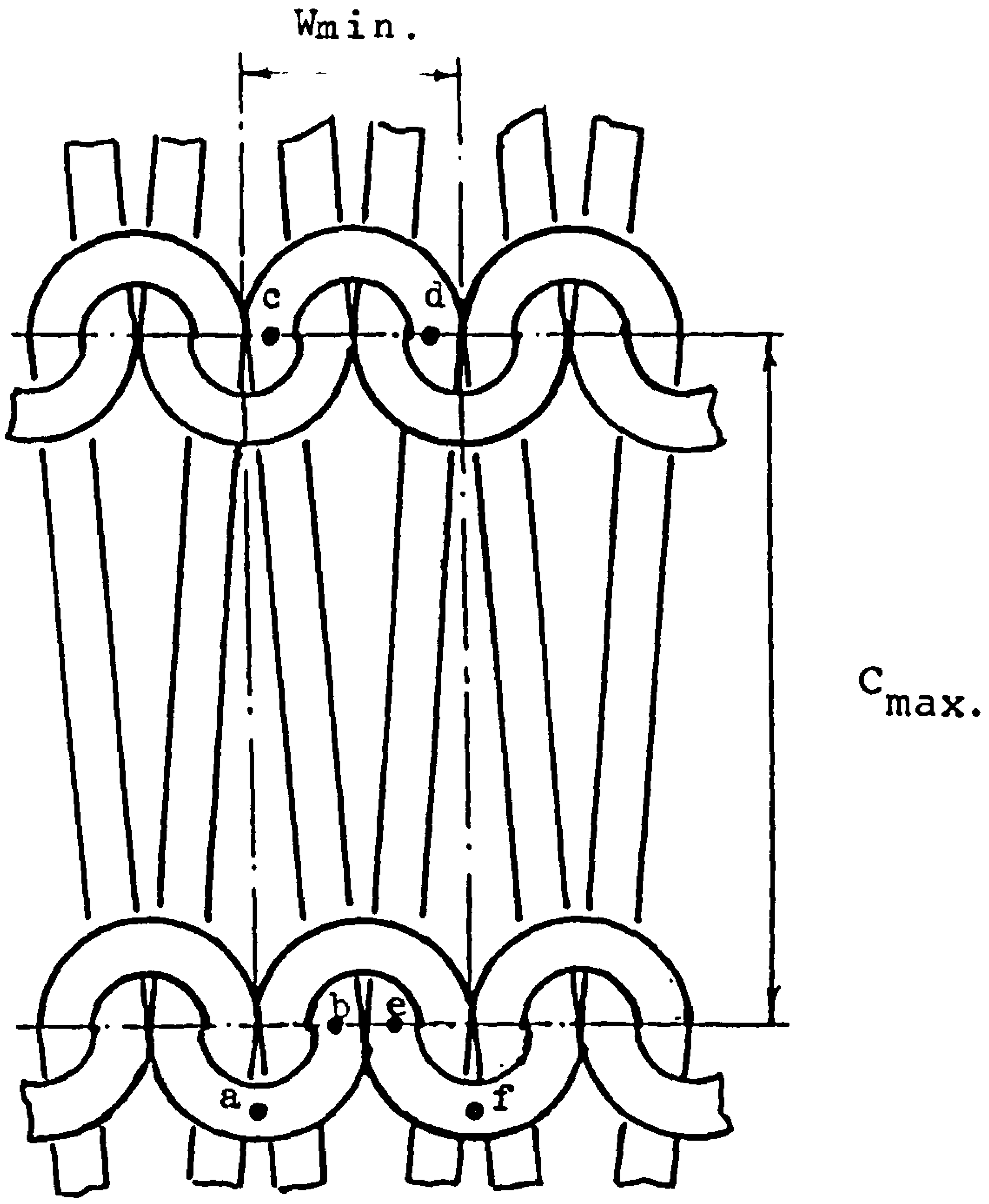


Fig 44: Fabric under maximum walewise extension.

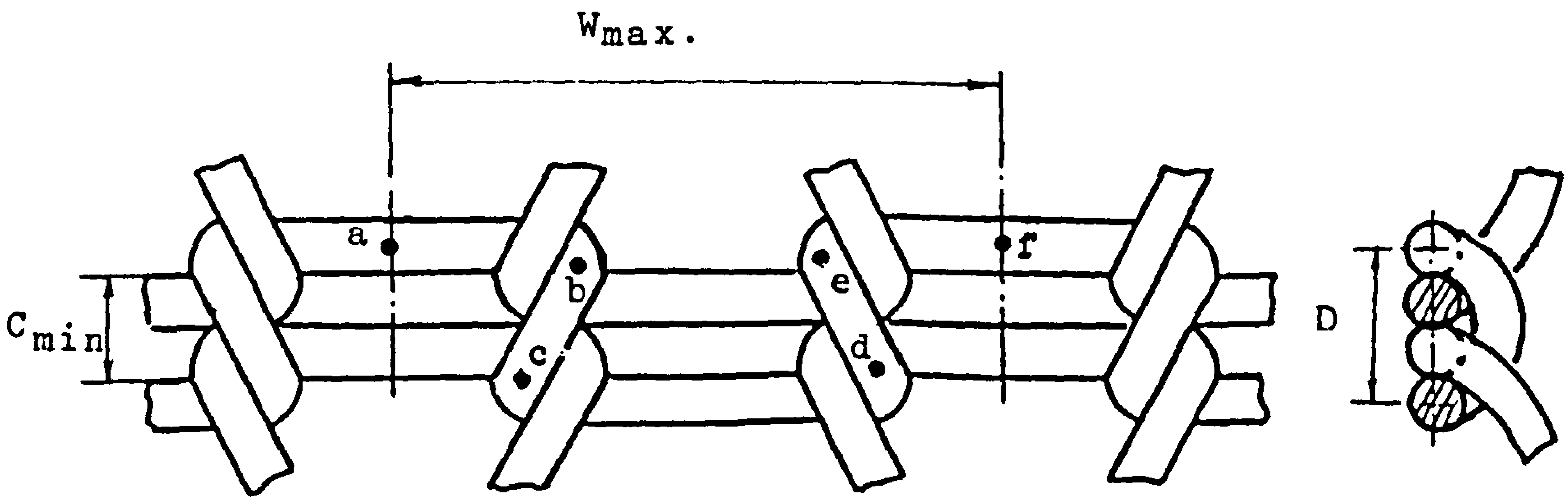


Fig 45: Fabric under maximum coursewise extension.

quarter of a circle, making in all a circle with diameter $D = 3d$, where d is the effective yarn diameter, which, from consideration of compressibility, Smirfitt[49] assumed to be half the observed diameter of a free yarn. If the inclination of the segments b-c and d-e is considered, then

$$b\text{-}c + d\text{-}e = \frac{2C_{max}}{\cos \phi}$$

where ϕ is the angle between the side of the loop and the wale direction, and the loop length

$$L = \frac{2C_{max}}{\cos \phi} + 3\pi d$$

$$C_{max} = \frac{(L - 3\pi d)\cos \phi}{2} \qquad \text{———— (1)}$$

At the break point, the value of Cos ϕ approaches 1 and considering that Cos $\phi = 1$, the maximum course spacing will be:

$$C_{max} = \frac{L - 3\pi d}{2} \qquad \text{———— (1a)}$$

The extension of the fabric in the walewise direction will be :

$$E_W = \left(\frac{C_{max} - C_s}{C_s}\right)100 = \left(\frac{C_{max}}{C_s} - 1\right)100 = \left(\frac{L - 3\pi d}{2C_s} - 1\right)100 \qquad \text{———— (2)}$$

The extension of the fabric at the point of break where the yarn is also extended to its maximum limit will be :

$$E_W = \left\{\frac{(L + \xi L) - 3\pi d}{2C_s} - 1\right\}100 \qquad \text{———— (3)}$$

Where, ξ is the extensibility of the yarn expressed in absolute fractional value (for dry-relaxed yarn $\xi = 0.11$ and for fully-relaxed one $\xi = 0.22$).

From the dimensional properties of the fabric in relaxed state,

$$Cs = \frac{L}{Kc} \quad \text{——————} \quad (4)$$

the equation (3) may be re-written in the following form:

$$E_w = \left[\frac{\{(L + \xi L) - 3\pi d\}\ Kc}{2L} - 1\right]100 \quad \text{——————} \quad (3a)$$

It can easily be seen from Fig.44 that the minimum value of wale spacing when the fabric is extended to its limit will be:

$$Wmin = 4d \quad \text{——————} \quad (5)$$

6.1.2 <u>Extension in width (coursewise)</u>

from Fig.45, the length of yarn in the extended structural unit cell will be the sum of the segments a-b, b-c, c-d, d-e and e-f. The segments b-c and e-d in sum (Fig.45 side view), take the form nearer to an ellipse than to a circle, but for simplification in the analysis these segments were considered to be approximately circular with diameter (D= 3d) and the segments a-b, c-d and e-f are approximately equal to Wmax. The length of yarn, therefore, in one structural unit cell is:

$$L = Wmax + 3\pi d \quad \text{then,}$$

$$Wmax = L - 3\pi d \quad \text{——————} \quad (6)$$

By analogy to what has been done before, fabric extension in the coursewise direction is:

$$E_c = \left(\frac{Wmax - Ws}{Ws}\right)100 = \left(\frac{L - 3\pi d}{Ws} - 1\right)100 \quad \text{——————} \quad (7)$$

Also, if the yarn extension is considered, the fabric extension will be:

$$E_c = \{\frac{(L + \xi L) - 3\pi d}{Ws} - 1\} 100 \text{ ——————— } (8)$$

Wale spacing of the fabric in the relaxed state is:

$$Ws = \frac{L}{Kw} \text{ ——————— } (9)$$

The equation (8) will be:

$$E_c = [\frac{\{(L + \xi L) - 3\pi d\} Kw}{L} - 1] 100 \text{ ——————— } (8a)$$

It can also be easily seen from Fig.45, that the minimum value of course cpacing when the fabric is extended to its limit, will be equal to twice the effective diameter of the yarn:

$$Cmin = 2d \text{ ——————— } (10)$$

From the above analysis, if expression (6) is divided by expression (1a), the ratio of fabric maximum extended in width to the fabric maximum extended in length will be:

$$\frac{Wmax}{Cmax} = \frac{2(L - 3\pi d)}{(L - 3\pi d)} = 2 \text{ ——————— } (11)$$

This also correponds to the ratio of expression(5) to the expression (10), i.e. :

$$\frac{Wmin}{Cmin} = \frac{4d}{2d} = 2 \text{ ——————— } (12)$$

The values which may be obtained by the expressions 11 and 12 are very close to those obtained by Popper [63].

6.1.3 Tensile Strength of Plain-Knitted Fabric

6.1.3.1 Walewise

By assuming the extended loop is a triangle, as shown in Fig.46, the tan $\emptyset$ will be *:

$$\tan \emptyset = \frac{3d}{2C_{max}}$$

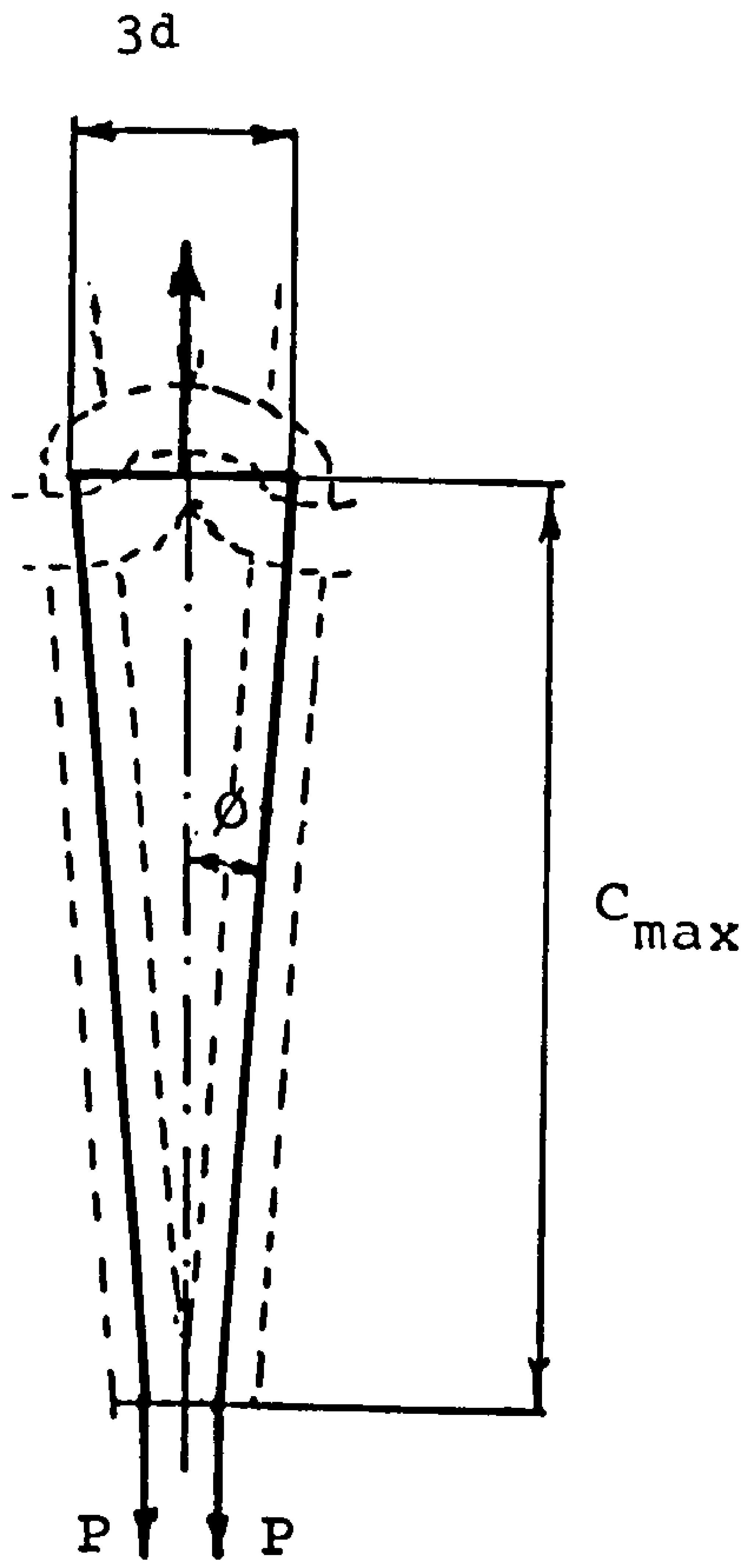


Fig.46: Triangle of the loop

* It is clear from closer examination of Fig.46 that a better expression for tan$\emptyset$ might be $\frac{d}{C_{max}}$ but since the value assumed for d is subject to question the calculation, based on the above formula using as the effective diameter a value of half the calculated "free" value of yarn diameter, have been retained in later work.

Knowing the value of the loop angle ϕ, and the minimum value of the yarn strength P , then the strength of each of the two yarns in one structural unit cell will be :

$$Ty = P \times \cos \phi \quad (13)$$

It is clear from equation (13) that the yarn strength in one structural unit cell will depend on the value of ϕ. In unextended fabric, the angle ϕ will depend mainly on the yarn diameter. In the fabric under extension, ϕ decreases as the loop length increases and consequently more force is required to break the yarn. However, the overall strength of a strip of slacker fabric may be much less than the tighter strip due to the change in stitch density.

It follows that the strength of fabric strip of 5cm. width should be :

$$P_f = 10Ty \times Wp.c. \quad (14)$$

The factor of yarn strength utilization or fabric assistance may be expressed in form of the ratio of $\frac{\text{yarn strength in the strip}}{\text{strength of single yarn}}$, which is assumed to reflect the effect of yarn friction and compression resulting from the degree of binding with transverse yarn.

6.1.3.2 Coursewise

The strength of the yarn in one structural unit cell, when it is extended in this direction is assumed to be equal to the strength of one single yarn, thus the strength of the fabric strip will be:

$$P_f = 5 \times Ty \times Cp.c. \qquad (15)$$

Yarn stiffness may also have effect on the fabric strength, but it was neglected particularly when the experiments show that the treatment had no effect on it.

6.2 Load-extension characteristics

It has been shown[31,39,49] that initially, the force required to produce extension of the fabric is relatively low and in a typical load-extension curve, is only a small fraction of the load at break. This part of the curve characterises the initial changes in loop shape by yarn sliding and slippage. Further change in loop shape occurs when the loops are drawn together and the yarn is being straightened out of the sides of the loop, but being bent sharply at the neck and tail of the loop. This is characterised by rapid increase in load and the curve takes almost a linear form. The final part of the load-extension curve characterises the yarn compressive and tensile properties.

Load-extension curves of selected fabric sets extracted from load-extension curves obtained by Instron

Tensile Machine in both walewise and coursewise direction and in both dry- and fully-relaxed state are shown in Figs.47-54. The fabrics in each set are different in loop length.

It has been found, as can be seen from these figs. that there is not much difference between the curve shapes of one-end dry-relaxed fabrics and the curve shapes of one-end fully-relaxed fabrics in both directionsof extension, although the tensile strength and extension at break of the fully-relaxed fabrics are greater than the dry-relaxed fabrics. However, there is obvious difference between the curve shapes of dry-relaxed fabrics made from two ends and the curve shapes of fully-relaxed fabrics when they are extended walewise. This difference is marked by an early and relatively sharp departure of the upper part of the curve from the linear one. This may be related to two causes, first an increase in yarn compressibility not due to treatment only, but also due to doubling, and second, the possibility of a sudden yarn displacement within the structure. It is worth noting that a few fabrics in some other sets show the same phenomenon, but to a lesser degree.

Within each fabric set, the force required to produce initial fabric extension decreases progressively as the loop length increases, and as a result, rapid decrease in fabric modulus occurs. This no doubt due to the

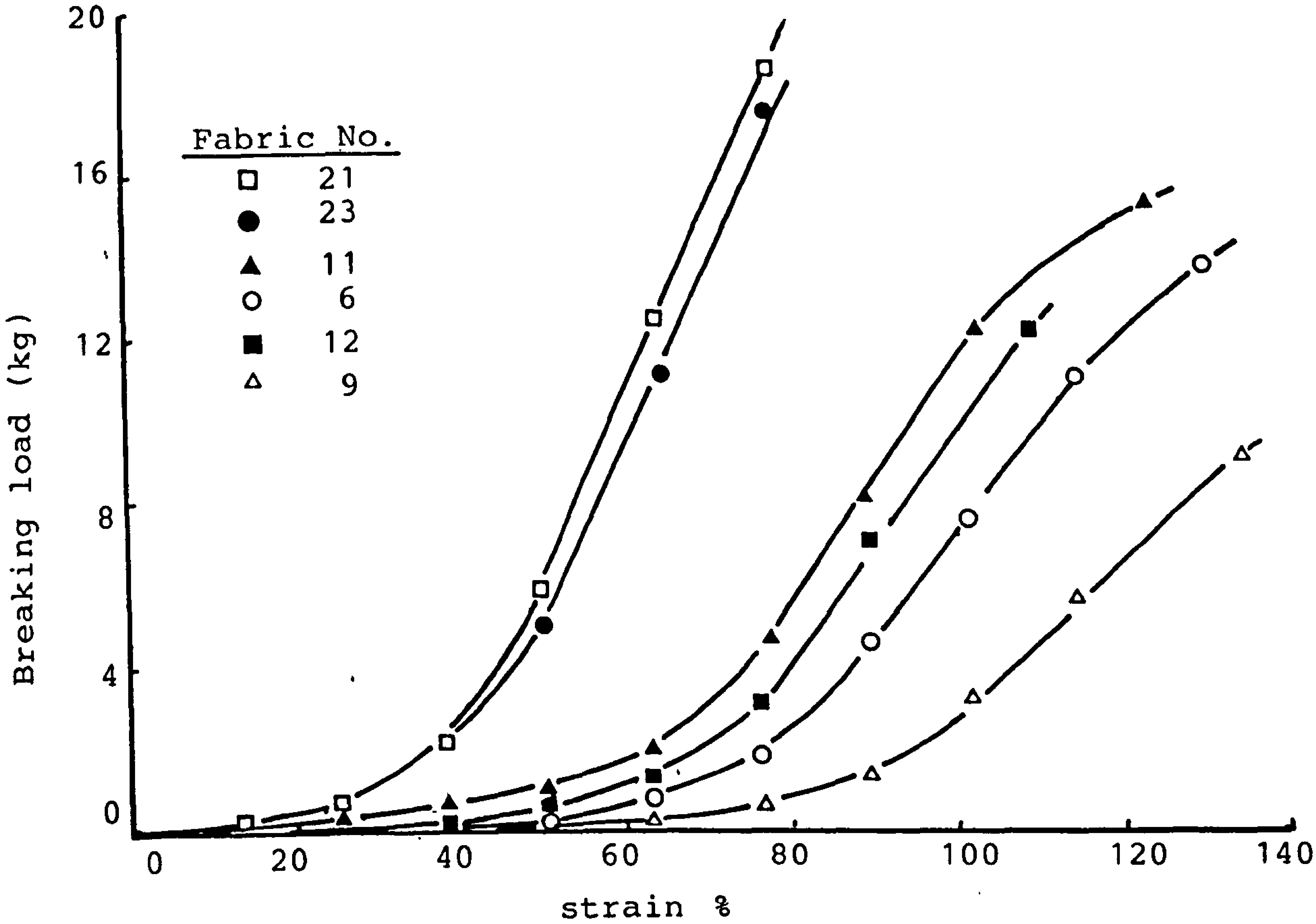


Fig: 47 Load-strain curves of dry-relaxed one-end fabrics, walewise

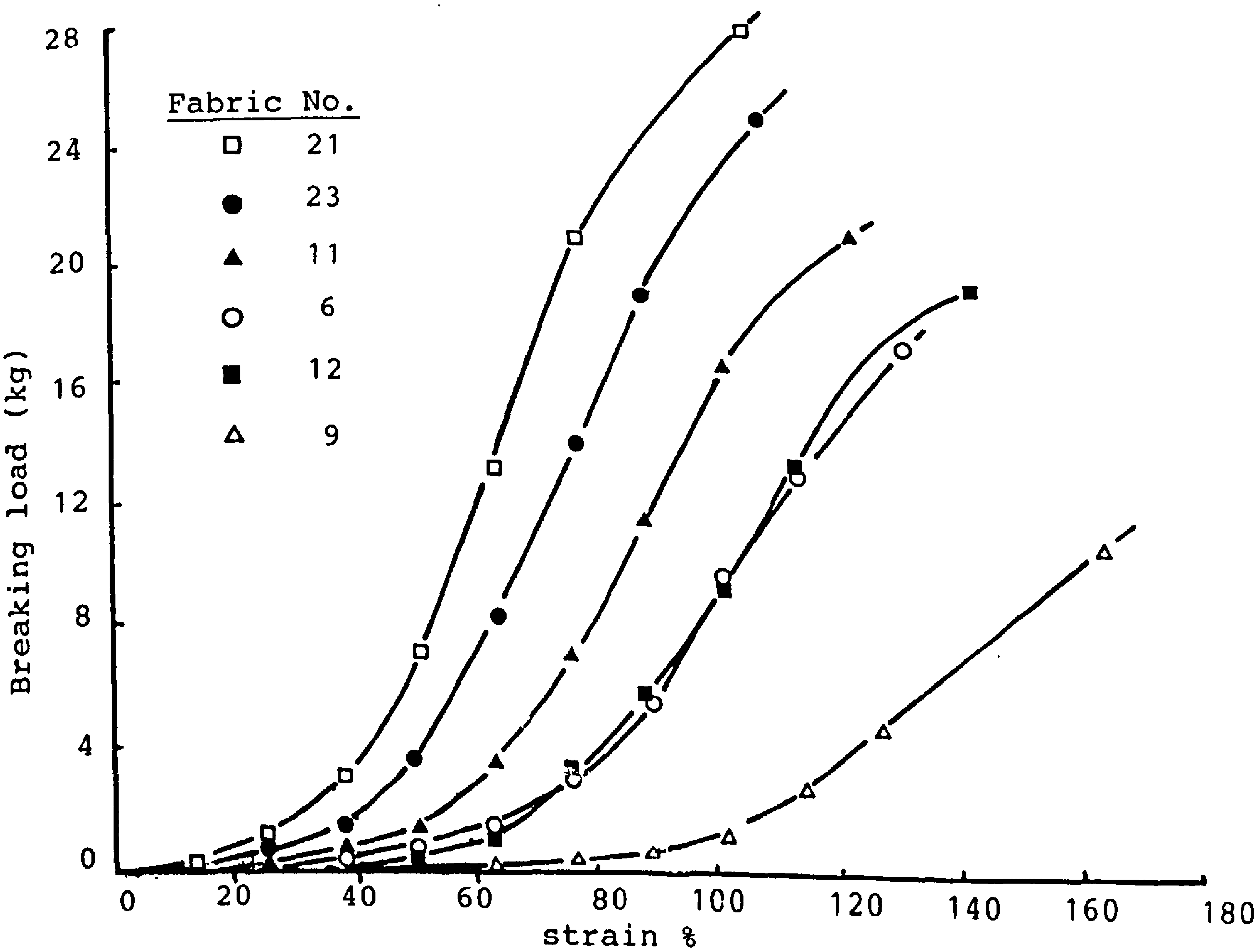


Fig 48: Load-strain curves of fully-relaxed one-end fabrics, walewise

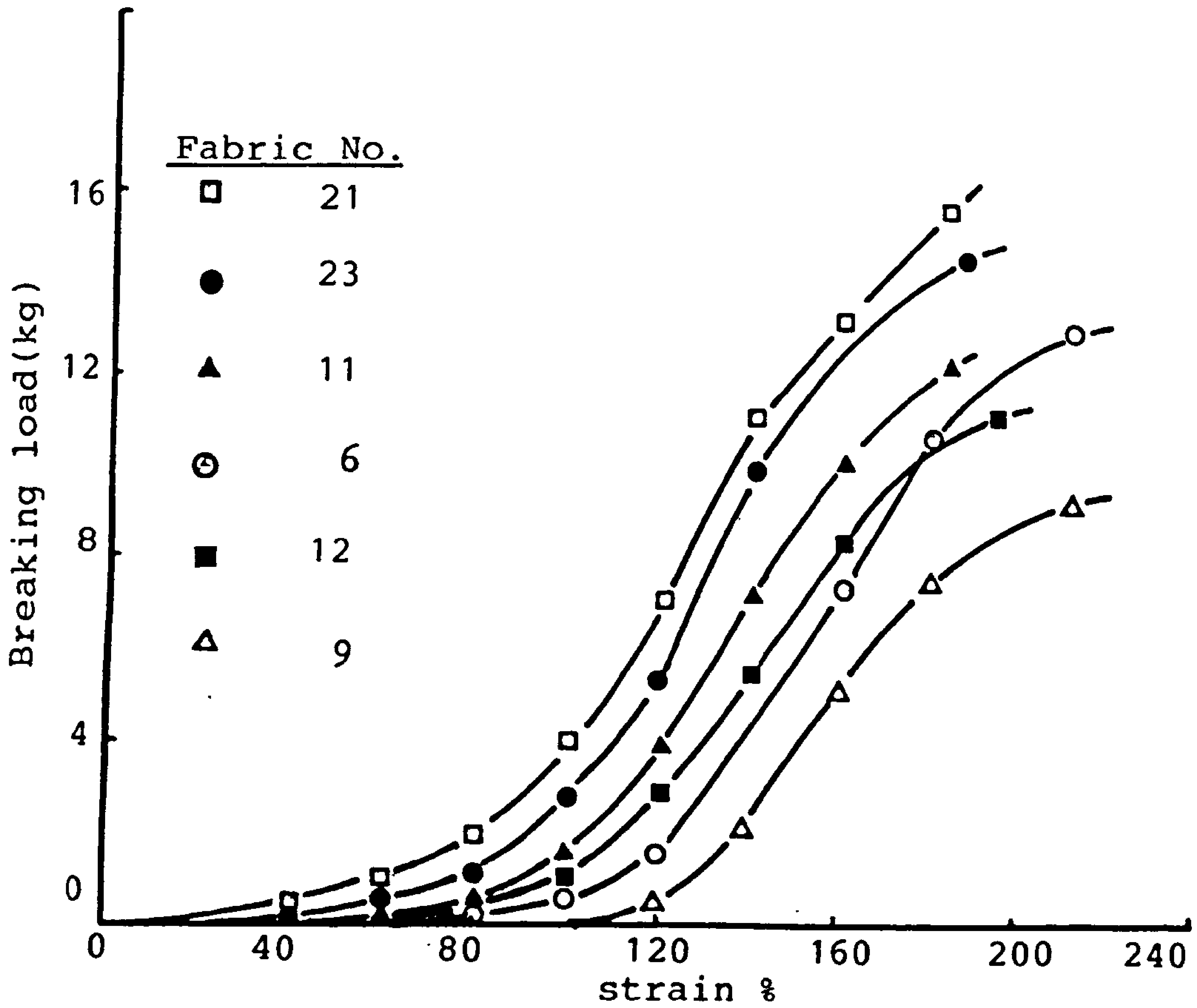


Fig 49: load-strain curves of dry-relaxed one-end fabrics,course-wise.

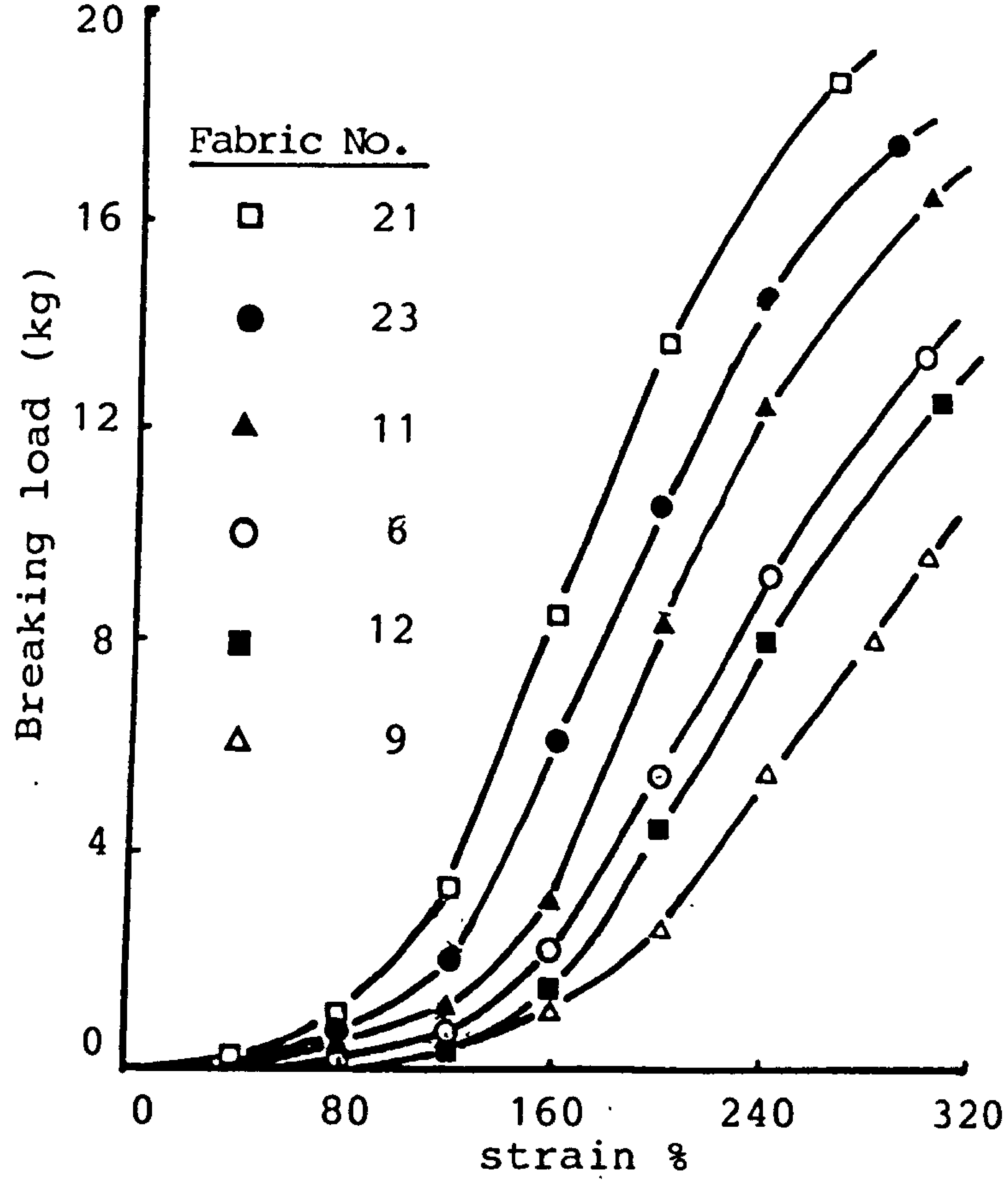


Fig 50 : Load-strain curves of fully-relaxed one-end fabrics, course-wise.

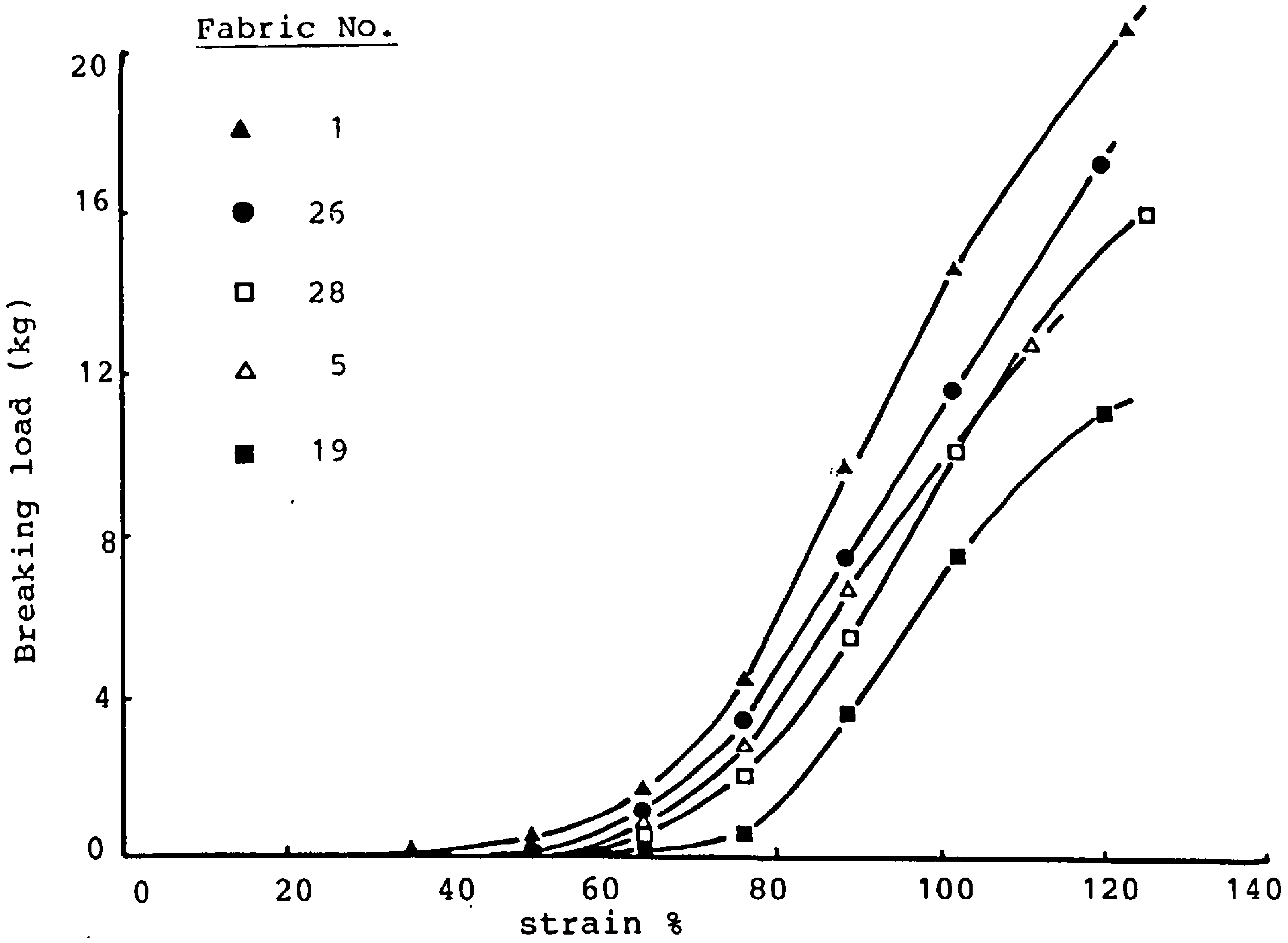


Fig. 51 Load-strain curves of dry-relaxed two-end fabrics,Wale-wise.

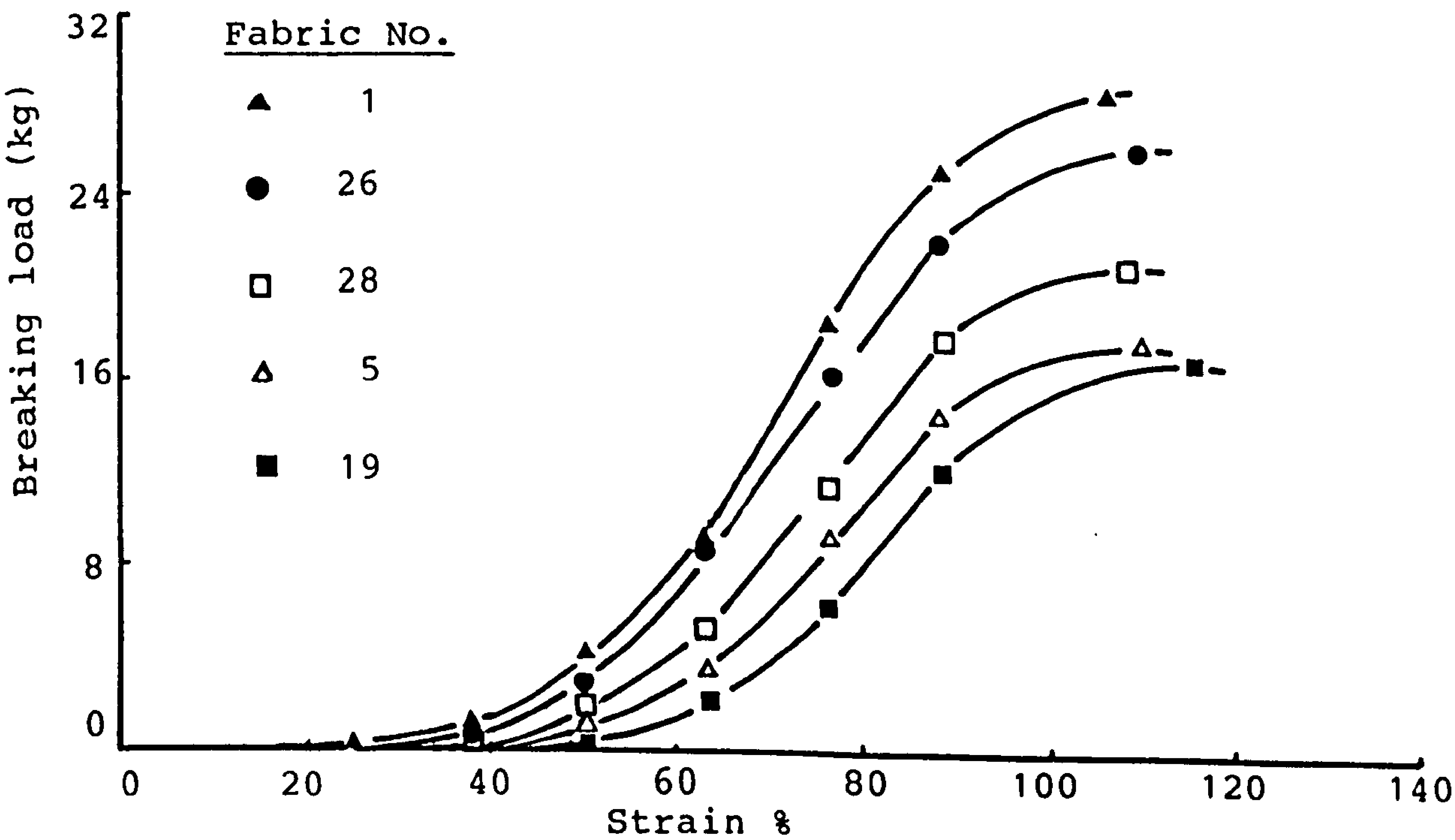


Fig 52 : Load-strain curves of fully-relaxed two-end fabrics, Wale-wise.

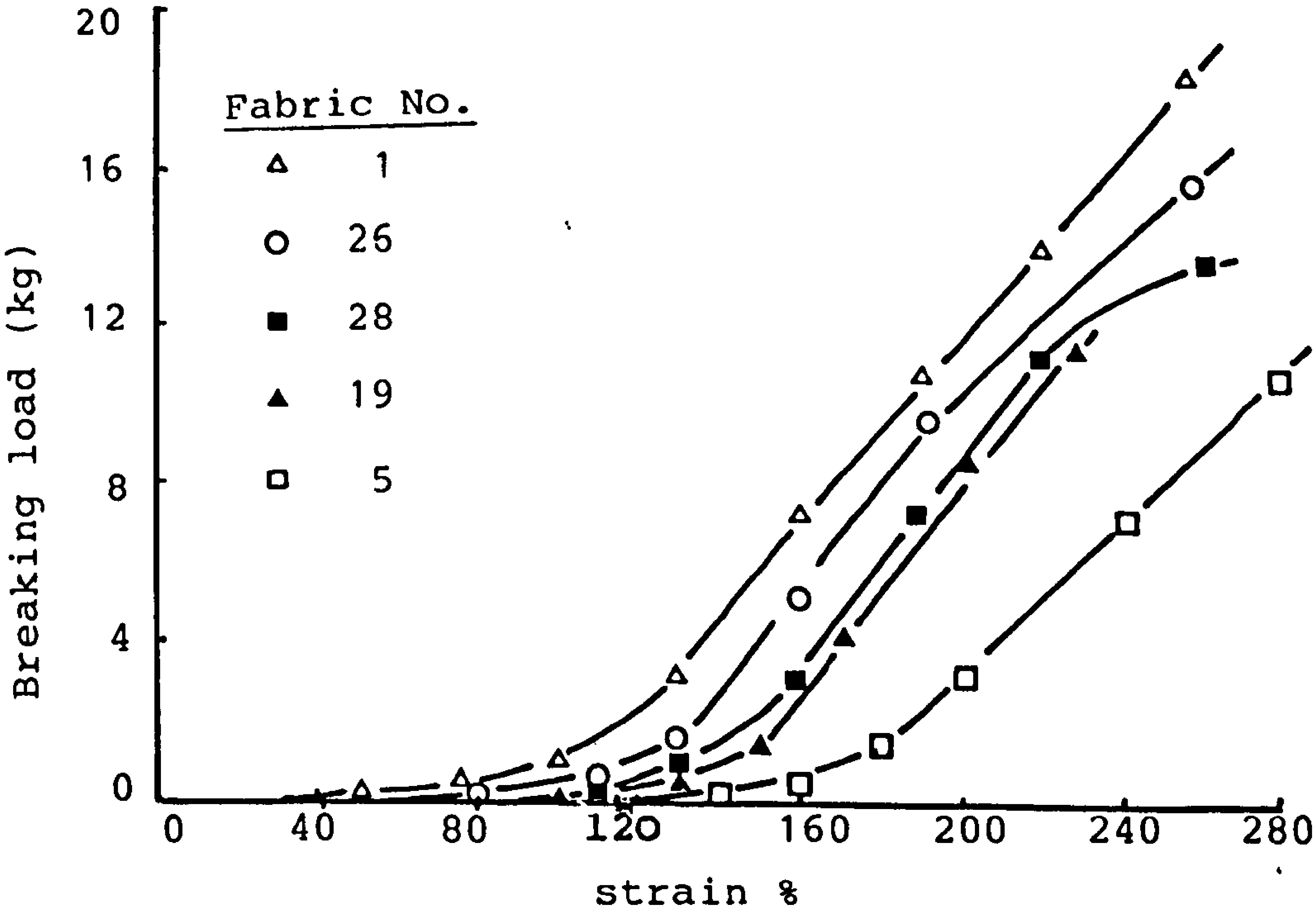


Fig 53: Load strain curves of dry-relaxed two-end fabrics, coursewise

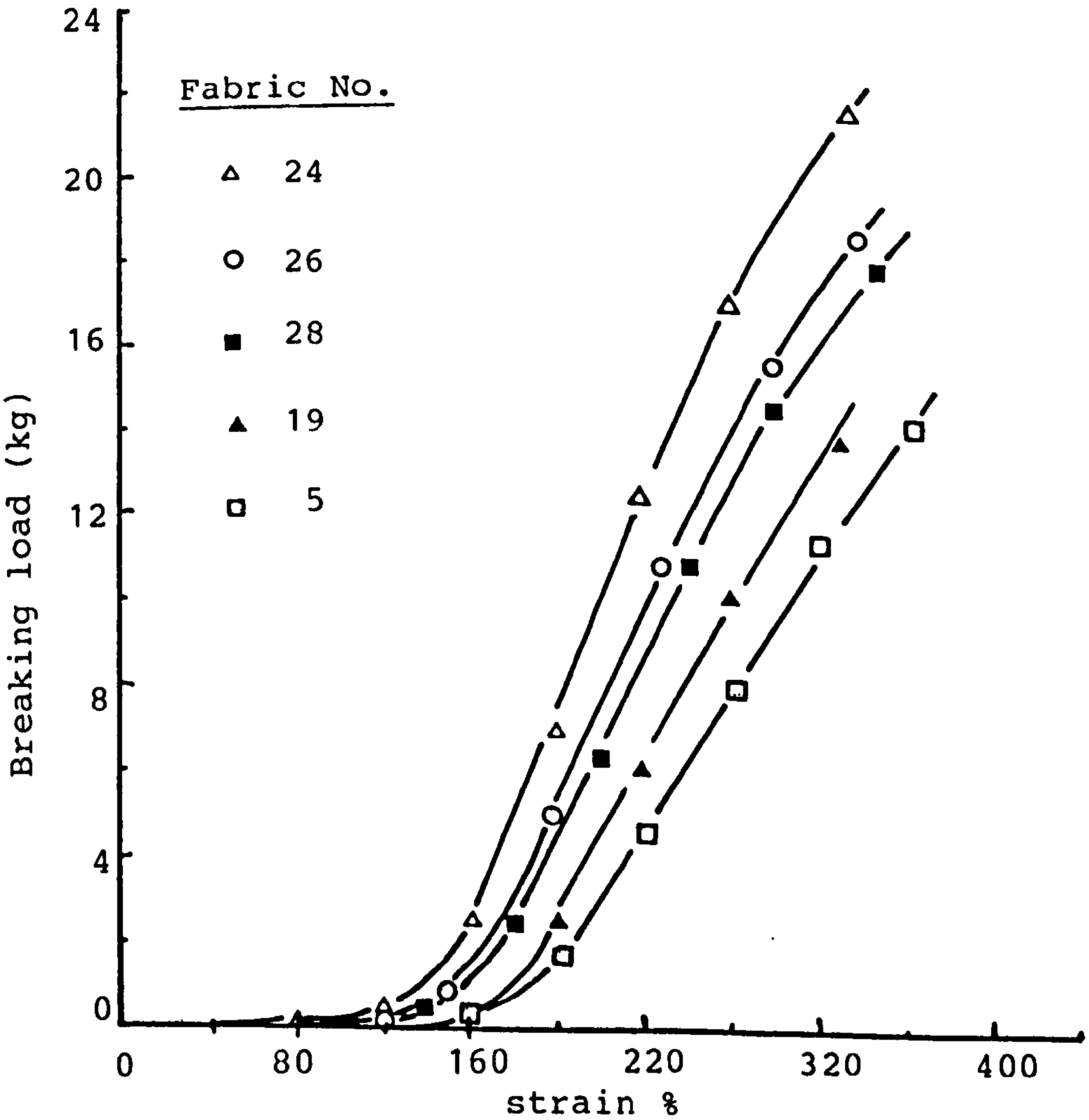


Fig 54: Load-strain curves of fully-relaxed two-end fabrics, coursewise

lower degree of yarn interference and greater space in which the yarn can more easily deform by slippage and sliding to allow the loop to take its initial extended shape.

6.3 Strength and extension of the fabrics

The experimental results of tensile strength and extension at break of all fabrics in both walewise and coursewise directions and the coressponding calculated values are given in Tables 21-28.

The experimental results show that the force required to extend the fabrics to break decreases as the loop length increases, i.e. as the number of ends per unit width in the fabrics decreases. Walewise, the breaking load of the two-end fabrics in both states of relaxation decreases less rapidly than for one-end fabrics. Coursewise, significant differences were not observed. This reflects the change in fabric dimensions resulting from both doubling and treatment. The extension at break increases with the decrease of loop length, but the rate of the increase is higher for fabrics made from one end of yarn than those made from two ends and higher for dry-relaxed fabrics than for fully-relaxed fabrics. Furthermore, the increase in loop length appears to have much less effect on extension at break of the two-end fully-relaxed fabrics either walewise or coursewise (see Tables 27 and 28). The

Table 21: Tensile properties of one-end dry-relaxed fabric, walewise.

Fabric No.	Experimental			Theoretical					
	Breaking load P_o (kg)	Extension at break %	Single end strength T_o (g)	Single end strength T_t (g)	loop angle $\emptyset$	Breaking load P_t (kg)	$\frac{To}{Ty}$	C_{max} (cm)	Extension at break %
21	18.7	78	246	291	7.7	22.1	0.83	0.18	76
23	17.6	77	251	291	7.0	20.4	0.85	0.20	77
11	15.3	123	259	293	5.7	17.3	0.88	0.25	96
12	12.6	109	224	293	4.8	15.8	0.76	0.30	107
6	13.8	130	274	292	4.4	14.6	0.93	0.32	106
7	14.6	138	326	293	4.1	13.2	1.10	0.35	114
13	9.7	120	223	293	4.0	12.6	0.76	0.36	112
14	9.5	116	256	291	3.4	10.8	0.87	0.42	110
15	9.2	116	263	291	3.2	10.2	0.89	0.44	118
9	8.9	136	270	294	3.1	9.7	0.92	0.46	121
10	6.1	140	237	293	2.4	7.9	0.80	0.59	129

Table 22: Tensile properties of one-end fully-relaxed fabric, walewise.

Fabric No.	Experimental			Theoretical					
	Breaking load P_o (kg)	Extension at break %	Single end strength T_o (g)	Single end strength T_t (g)	loop angle Ø	Breaking load P_t (kg)	$\frac{To}{Ty}$	C_{max} (cm)	Extension at break %
21	28.4	105	323	281	6.8	24.8	1.13	0.26	109
23	25.8	117	331	289	6.3	22.6	1.17	0.23	114
11	21.6	123	296	282	5.3	20.6	1.04	0.27	123
6	17.4	132	276	283	4.6	17.8	0.97	0.31	130
12	19.3	143	316	282	4.3	17.2	1.11	0.33	133
7	13.5	143	255	283	3.8	15.0	0.90	0.38	139
13	13.4	140	258	283	3.7	14.7	0.91	0.39	140
14	14.1	163	300	283	3.3	13.3	1.06	0.44	144
15	12.8	161	291	284	3.2	12.5	1.02	0.46	146
9	10.7	165	268	283	2.9	11.3	0.94	0.49	149
10	10.9	162	295	284	2.6	10.5	1.04	0.56	152

Table 23: Tensile properties of two-end dry-relaxed fabric, walewise.

Fabric No.	Experimental			Theoretical					
	Breaking load P_o (kg)	Extension at break %	Single end strength T_o (g)	Single end strength T_t (g)	loop angle $\emptyset$	Breaking load P_t (kg)	$\frac{To}{Ty}$	C_{max} (cm)	Extension at break %
1	20.6	123	271	292	8.1	22.2	0.91	0.35	118
24	19.9	133	283	293	7.5	19.9	0.96	0.38	123
2	18.8	117	285	294	6.6	19.4	0.97	0.44	132
26	18.1	120	283	294	6.5	18.8	0.96	0.44	132
3	16.8	121	280	294	6.0	17.6	0.95	0.47	137
28	16.0	126	276	295	5.6	17.1	0.94	0.51	142
4	14.6	123	271	285	5.2	15.9	0.91	0.55	145
5	12.9	111	248	284	4.7	15.3	0.84	0.61	151
19	11.1	120	232	284	4.6	14.1	0.79	0.62	152
20	13.4	140	281	284	4.2	13.5	0.95	0.68	157

Table 24: Tensile properties of two-end fully-relaxed fabric, walewise.

Fabric No.	Experimental			Theoretical					
	Breaking load P_o (kg)	Extension at break %	Single end strength T_o (g)	Single end strength T_t (g)	loop angle Ø	Breaking load P_t (kg)	$\frac{To}{Ty}$	C_{max} (cm)	Extension at break %
24	30.3	200	360	282	7.1	23.7	1.26	0.40	156
25	28.0	205	350	283	6.7	22.6	1.23	0.43	160
26	26.5	201	348	282	6.3	21.4	1.22	0.46	165
2	25.8	203	358	282	5.8	20.3	1.26	0.49	170
27	22.6	200	323	283	5.7	19.8	1.14	0.50	171
17	22.4	215	330	283	5.6	19.2	1.16	0.51	172
28	21.2	198	321	284	5.3	18.7	1.13	0.54	176
4	17.9	196	299	284	4.9	17.0	1.05	0.59	181
5	17.6	205	304	283	4.4	16.4	1.07	0.65	187
19	17.3	213	309	282	4.3	15.8	1.09	0.67	188
20	14.7	204	294	284	4.0	14.2	1.03	0.72	192

Table 25: Tensile properties of one-end and dry-relaxed fabrics, course wise.

Fabric No.	Experimental			Theoretical			
	Breaking load P_o (kg)	Extension at break %	Single end strength T_o (g)	Breaking load, P_t (kg)	$\frac{To}{Ty}$	W_{max} (cm)	Extension at break %
21	15.7	183	310	14.9	1.05	0.37	208
23	14.6	187	331	13.0	1.12	0.41	209
11	12.2	183	294	12.3	0.99	0.50	233
12	11.2	194	315	10.5	1.06	0.59	247
6	13.5	213	415	9.6	1.40	0.65	256
7	11.1	190	353	9.5	1.19	0.69	258
13	9.5	194	311	9.0	1.05	0.72	260
14	8.7	173	330	7.7	1.11	0.84	273
15	8.6	181	356	7.4	1.20	0.89	275
9	9.9	215	404	7.2	1.36	0.93	279
10	8.2	203	395	6.3	1.33	1.18	290

Table 26: Tensile properties of one-end fully-relaxed fabric, coursewise.

Fabric No.	Experimental			Theoretical			
	Breaking load P_o (kg)	Extension at break %	Single end strength T_o (g)	Breaking load, P_t (kg)	$\frac{To}{Ty}$	W_{max} (cm)	Extension at break %
21	18.8	266	348	15.3	1.22	0.42	282
23	17.4	287	362	13.6	1.27	0.46	277
11	16.5	301	259	13.1	12.6	0.54	308
6	13.6	303	328	11.8	1.15	0.62	320
12	12.7	308	316	11.5	1.11	0.66	326
7	11.7	307	312	10.6	1.10	0.75	337
13	11.6	318	327	10.1	1.15	0.78	339
14	11.5	341	359	9.1	1.26	0.87	347
15	11.3	334	359	8.9	1.26	0.91	350
9	9.7	311	323	8.5	1.14	0.98	355
10	8.6	336	325	7.5	1.14	1.12	363

Table 27: Tensile properties of two-ends dry-relaxed fabric, coursewise.

Fabric No.	Experimental			Theoretical			
	Breaking load P_o (kg)	Extension at break %	Single end strength T_o (g)	Breaking load, P_t (kg)	$\frac{To}{Ty}$	W_{max} (cm)	Extension at break %
1	18.3	257	341	15.7	1.15	0.70	168
24	17.0	248	352	15.7	1.19	0.76	159
2	16.1	261	342	13.9	1.16	0.87	187
26	15.5	250	360	17.7	1.22	0.88	182
3	14.7	266	350	17.4	1.18	0,95	185
28	13.5	263	371	10.6	1.25	1.02	195
4	12.7	276	352	10.6	1.89	1.09	196
5	10.8	282	338	9.5	1.14	1.22	215
19	11.4	228	345	9.8	1.17	1.24	197
20	11.2	286	350	9.5	1.18	1.36	213

Table 28: Tensile strength of two-ends fully-relaxed fabrics, coursewise.

Fabric No.	Experimental			Theoretical			
	Breaking load P_o (kg)	Extension at break %	Single end strength T_o (g)	Breaking load, P_t (kg)	$\frac{To}{Ty}$	W_{max} (cm)	Extension at break %
24	21.6	337	360	17.0	1.26	0.80	288
25	20.6	343	355	16.5	1.25	0.85	295
26	19.1	342	341	15.9	1.20	0.91	302
2	18.9	353	363	14.8	1.28	0.99	309
27	18.6	349	342	14.8	1.20	1.00	310
17	17.8	324	342	14.8	1.20	1.01	312
28	17.5	351	365	13.6	1.28	1.08	318
4	15.3	350	340	12.8	1.20	1.17	325
5	14.2	365	383	11.9	1.35	1.30	335
19	13.7	331	326	11.9	1.14	1.34	336
20	12.9	327	315	11.6	1.11	1.44	343

main reason for this is probably a higher yarn friction within the one-end fabrics than within the two-end fabrics particularly in the fully-relaxed state. Thus the force required to break the fabric will increase with less extension at break. Further discussion about the effect of yarn properties on the fabric tensile properties will follow in the next section.

The calculated tensile strength values both walewise and coursewise for all fabrics are shown in Tables 21-28. Although they are near to, they are higher than the experimental values for dry-relaxed fabrics knitted form one end and two-ends, but lower than the experimental values for fully-relaxed fabrics knitted from one-end and two-ends.

It has been suggested that, single end yarn strength in the fabric, due to binding and transverse yarn, is usually greater than the strength of the single yarn from which the fabric is made. Calculation of the ratio $\frac{\text{strength of single end in fabric } T_o}{\text{single yarn strength } T_y}$ shows this very clearly. This ratio is often referred to as the "fabric assistance"[11] and Kovitski referred to as "coefficient of yarn strength utilization"[86]. It is clear that frictional forces of the yarn and other variable factors on the strength of the yarn in the fabric will be mainly affected by the degree of fabric binding.

The statistical evaluation of yarn strength used in the theoretical calculation of fabric strength shown in the tables above, appeared to be different from one treatment to another. Thus for best agreement it was nesessary to use for dry-relaxed yarn a minimum strength of $P=\bar{P}-3S.D.$, and for fully-relaxed yarn $P=\bar{P}-2S.D.$

Figs. 55-58 show the relationship between the observed and the calculated breaking load with the best fit lines for all fabrics in both states of relaxation and in both walewise and coursewise directions. Although the calculated values of breaking load are not in a very close agreement with the observed values, the correlation coefficients of the relationship between them are highly significant for all fabrics. The lowest correlation coefficients $r = 0.96$ for two-end dry-relaxed fabrics walewise and one-end dry-relaxed fabrics coursewise.

The calculation of loop angle Ø, shows that it decreases with an increase of loop length and this suggests that more force is required to break the yarn in the structural unit cell as the amount of yarn in the cell increases.

The experimental values of the fabric extension at break show, as can be seen from Tables 21-28, an

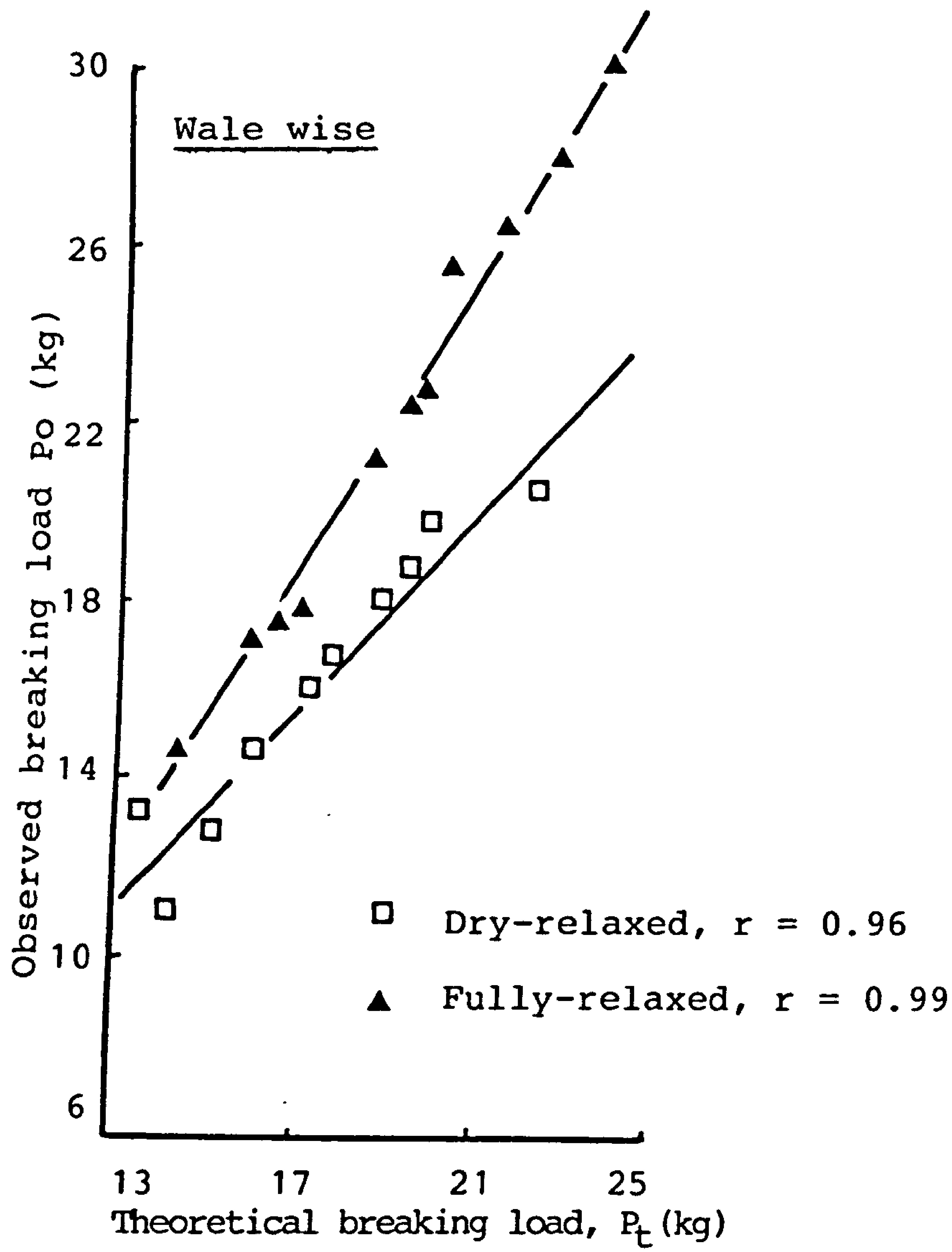


Fig 55: Relation between Po and Pt for dry-and fully- relaxed fabrics made from two-ends.

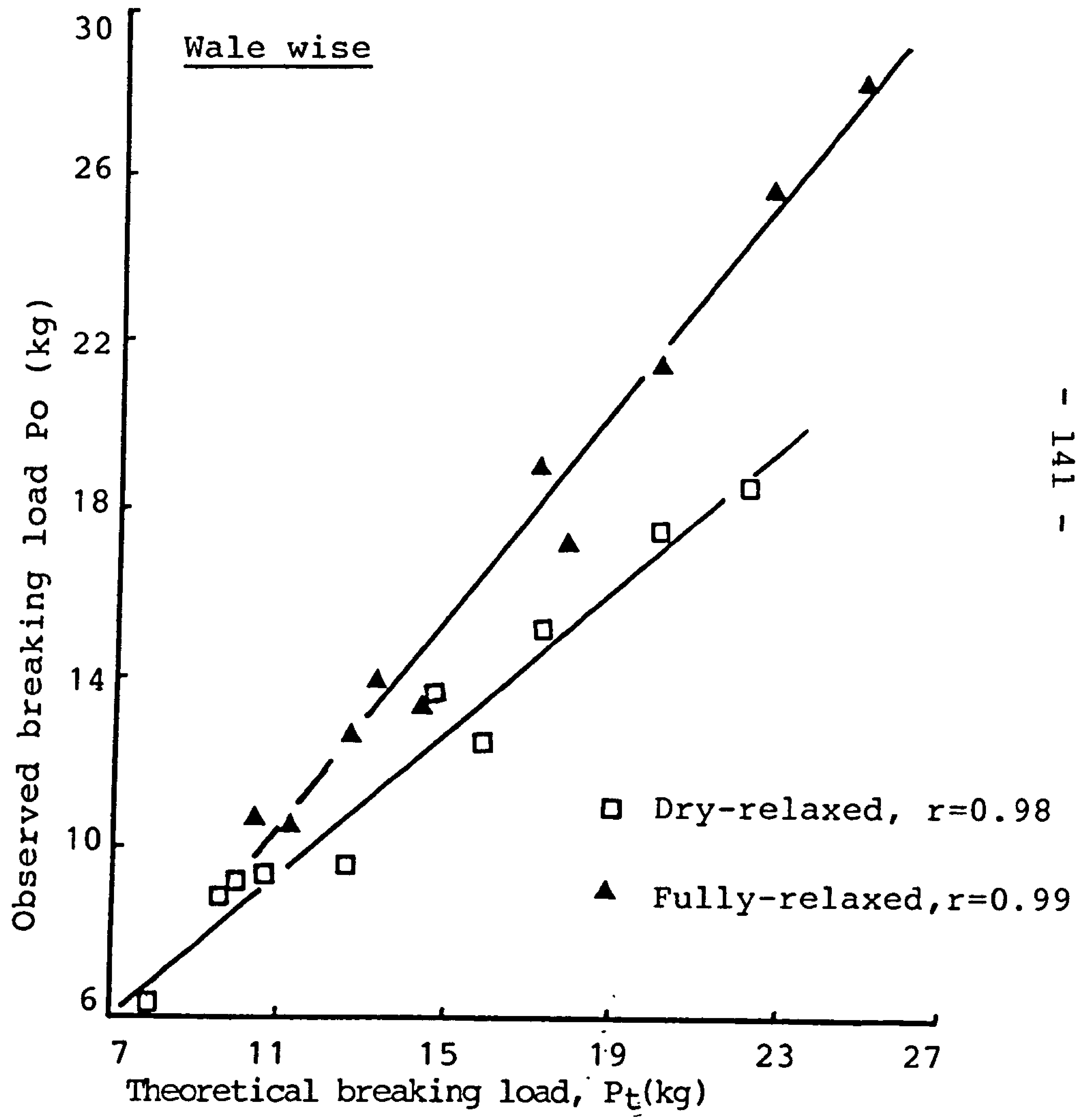


Fig 56 : Relation between Po and Pt for dry- and fully-relaxed fabrics made from one-end.

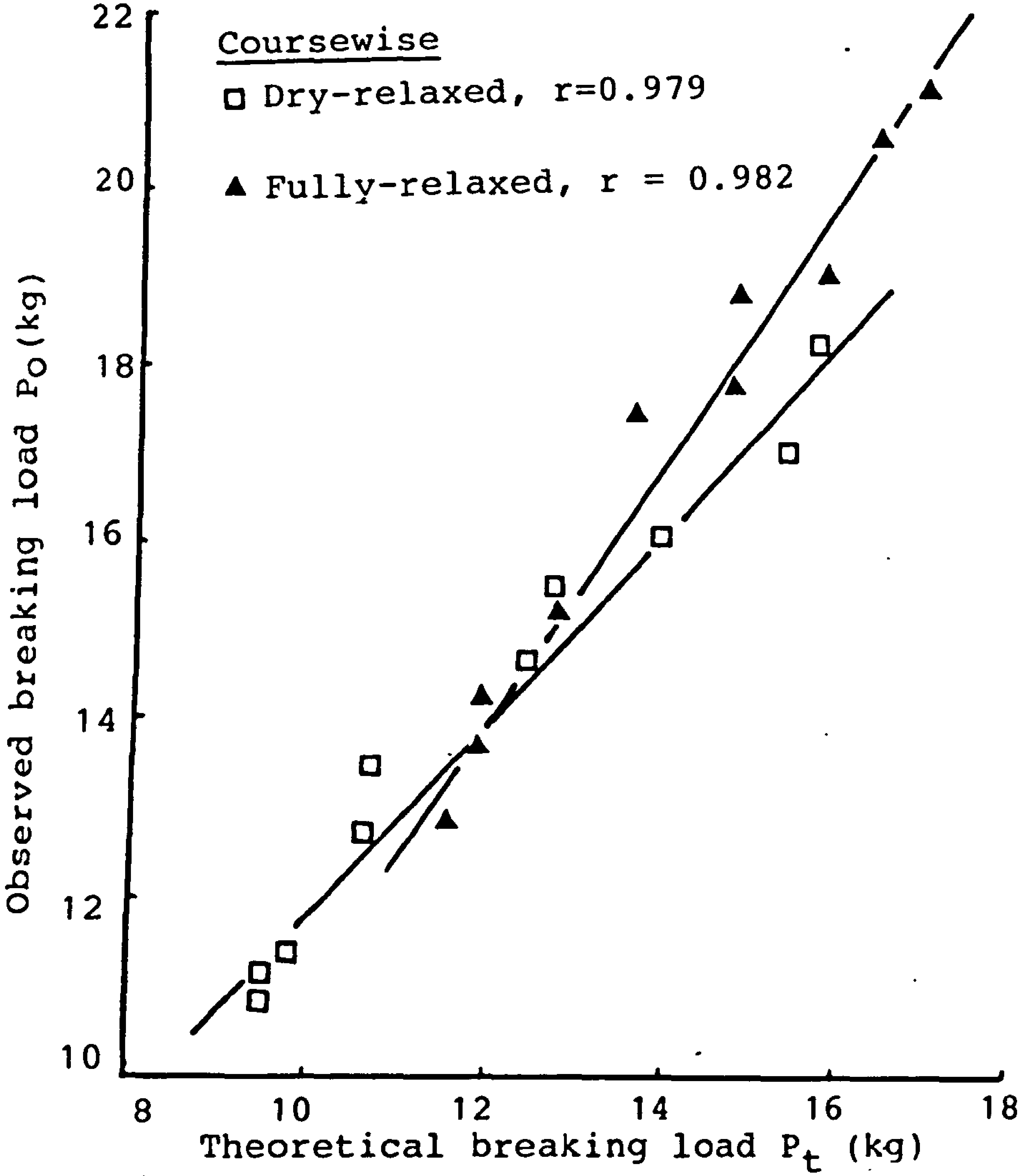


Fig 57 : Relation between Po and Pt for dry- and fully-relaxed fabrics made from two-ends.

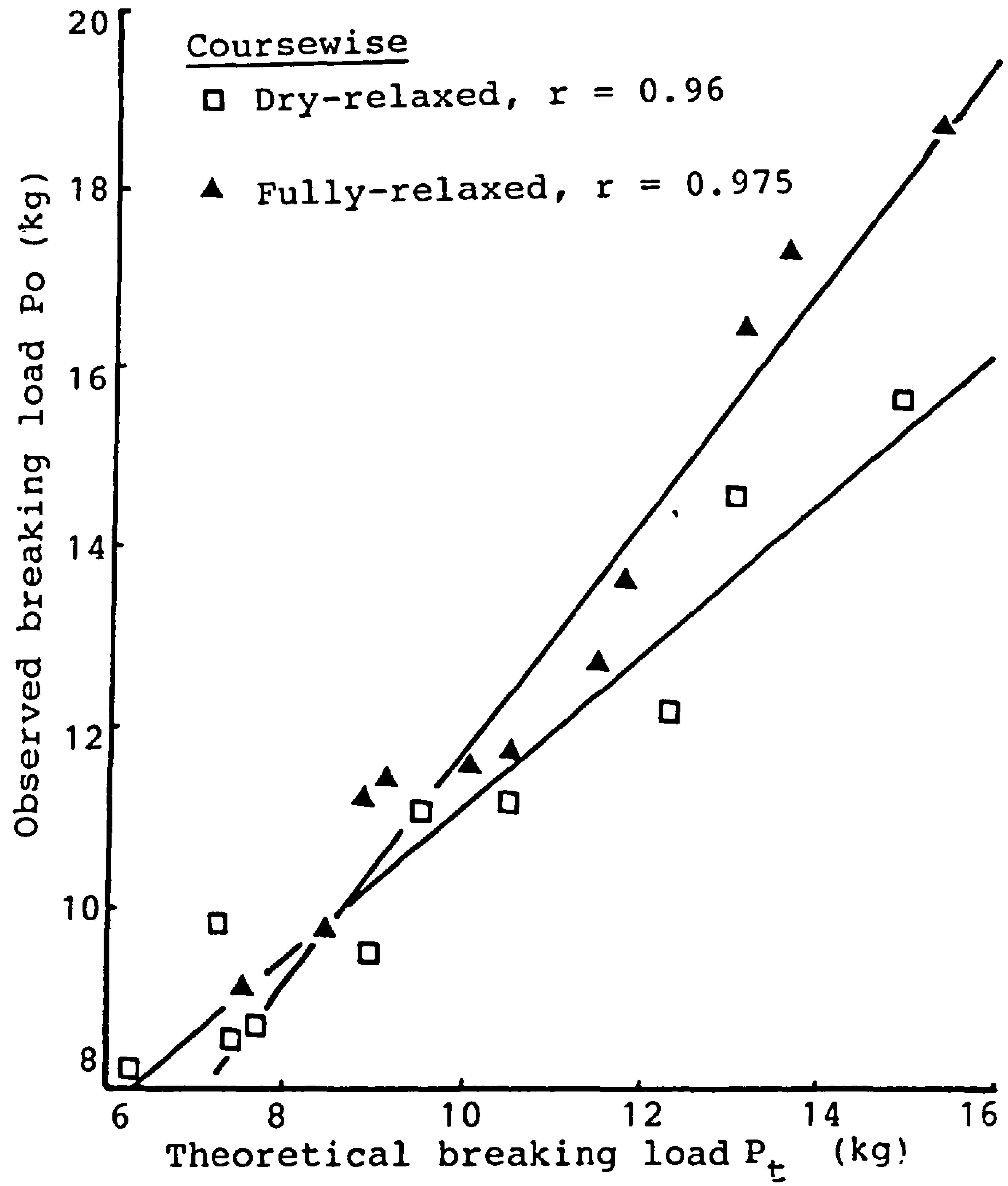


Fig 58 : Relation between Po and Pt for dry and fully-relaxed fabrics made from one-end.

increase with the increase of loop length for all fabrics both walewise and coursewise, except for the fully-relaxed two-end fabric. It can also be seen that there is a greater increase in fabric extension walewise than coursewise for all fabrics in both states of relaxation, although the magnitude of the extension coursewise is almost twice the extension walewise due to geometrical properties and the extension of fully-relaxed fabrics is higher than the extension of dry-relaxed fabrics due to yarn properties. However, the results do not show a consistent change in extension with the increase of loop length. This is no doubt due to non-uniformity of the yarn. As mentioned earlier, the major reason for low increase in extension of the fabrics made from two-ends, particularly when they are in the fully-relaxed state, which requires more force to rupture, is the high friction resulting from both doubling the yarn and the full-relaxation treatment.

The predicted values of fabric extension at break obtained from this expression (3a) for walewise are in fair agreement with the observed extension values of one-end fabric in both dry- and fully-relaxed states. The results for two-end fabrics extended walewise show that the theoretical values of the extension are in poorer agreement with observed extension values, while the difference, between the predicted values obtained from expression (8a) and observed values of fabric extension at break is widening for all other fabrics in both states of relaxation when they are extended coursewise. In addition to the frictional forces which may affect the extension of the two-end fabrics particularly when they are in the fully-relaxed state, the widening gap between the predicted values and observed values, may be related to the following reasons:

1. The side view of the model shown in Fig. 45, from which the expression (6) was derived, is, as assumed before, an approximation to the semi-circle of the fraction b-c and d-e of the loop when it is extended coursewise. The predicted values for one-end fabrics extended coursewise may also be affected to a certain degree by this approximation.

2. In expression (3a) and (8a) which are used to calculate the fabric extension in the two directions, the yarn in the fabrics made from two ends is considered as a single folded yarn with circular cross-section, while it is two separate yarns doubled together during the knitting process. In such a case, the degree of (effective) compression could be higher and the effective diameter would be expected to be somewaht less than $\frac{dy}{2}$.

3. When the numerical values of Kc and Kw in Table 12 are used in the expressions (3a) and (8a) a certain disagreement between the theoretical values and the experimental values of the extension of some fabric sets was evident. Thus, it may be suggested that to predict the fabric extension walewise and coursewise, the mean values of Kc and Kw in Table 11 should preferably be used in the above expressions. It is also possible that the fabric extension in both principal directions may be satisfactorily predicted by using the expressions (3) and (8).

The observed values of fabric extension were plotted against calculated values for all fabrics and the relation is shown in Figs. 59-62. As expected, the correlation coefficient values of this relation for two-end fabrics in both dry- and fully-relaxed state when extended coursewise are very low. Fabrics made from one end extended walewise have a high correlation coefficient with 0.97 for fully-relaxed and 0.87 for dry-relaxed fabrics. The fully-relaxed, one-end fabrics extended coursewise have also high correlation coefficient with 0.87. The high values of correlation coefficient of fully-relaxed fabrics is probably due to the fabric uniformity obtained by the treatment.

All fabrics in both walewise and coursewise direction, show with various degree, that fabric extension is

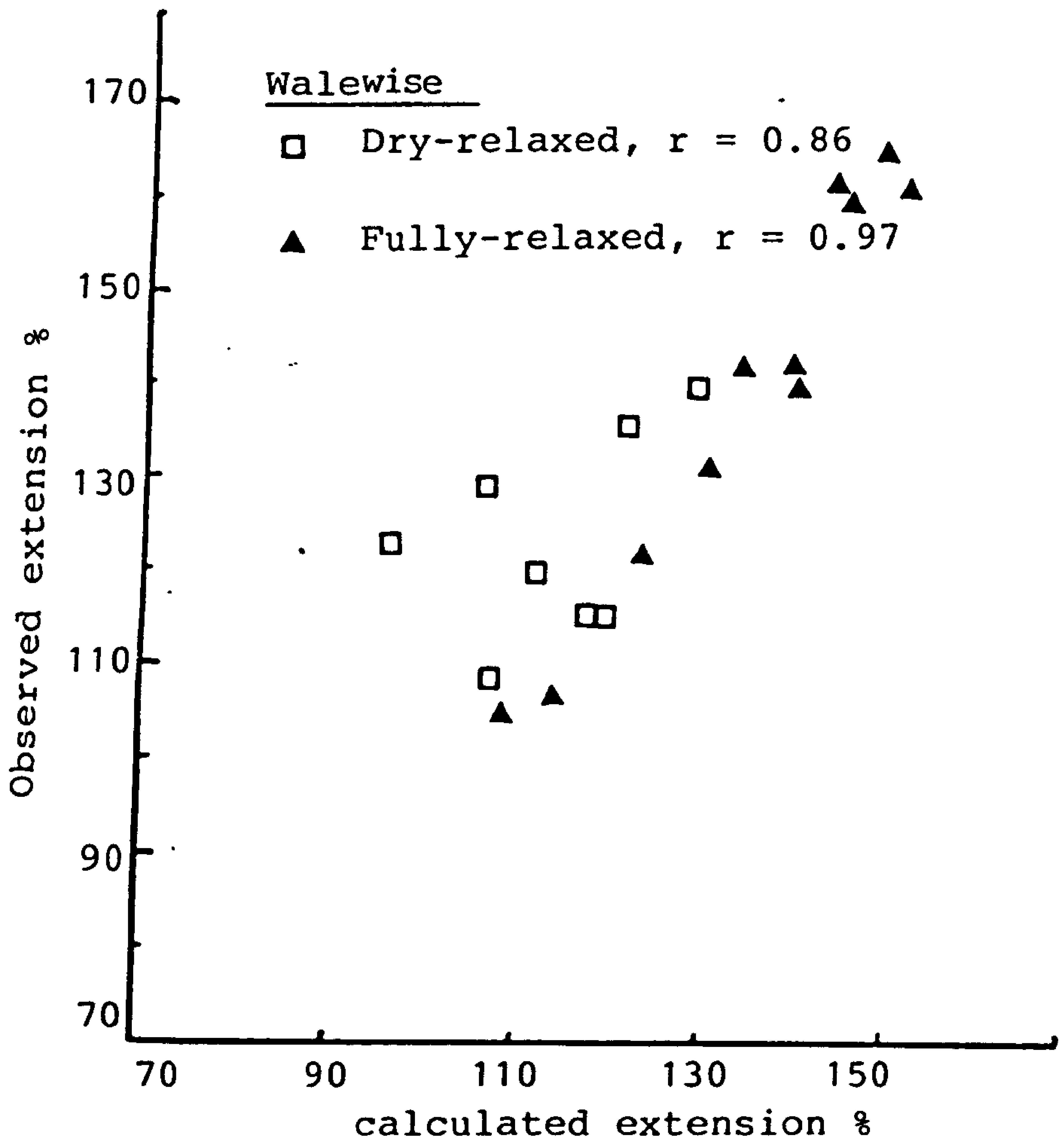


Fig 59 : Relation between observed and calculated extension, one-end fabrics.

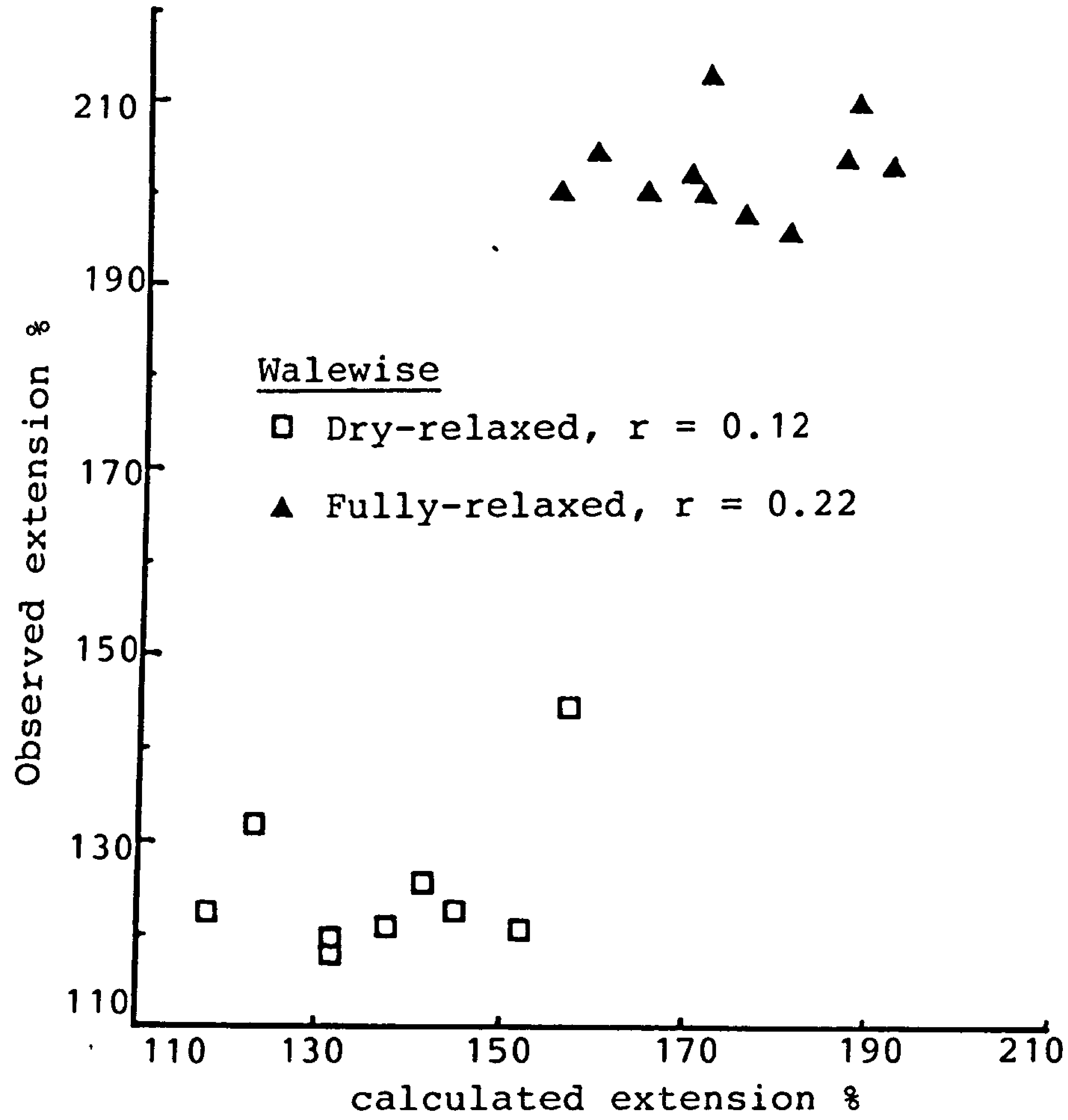


Fig 60 : Relation between observed and calculated extension, two-end fabrics.

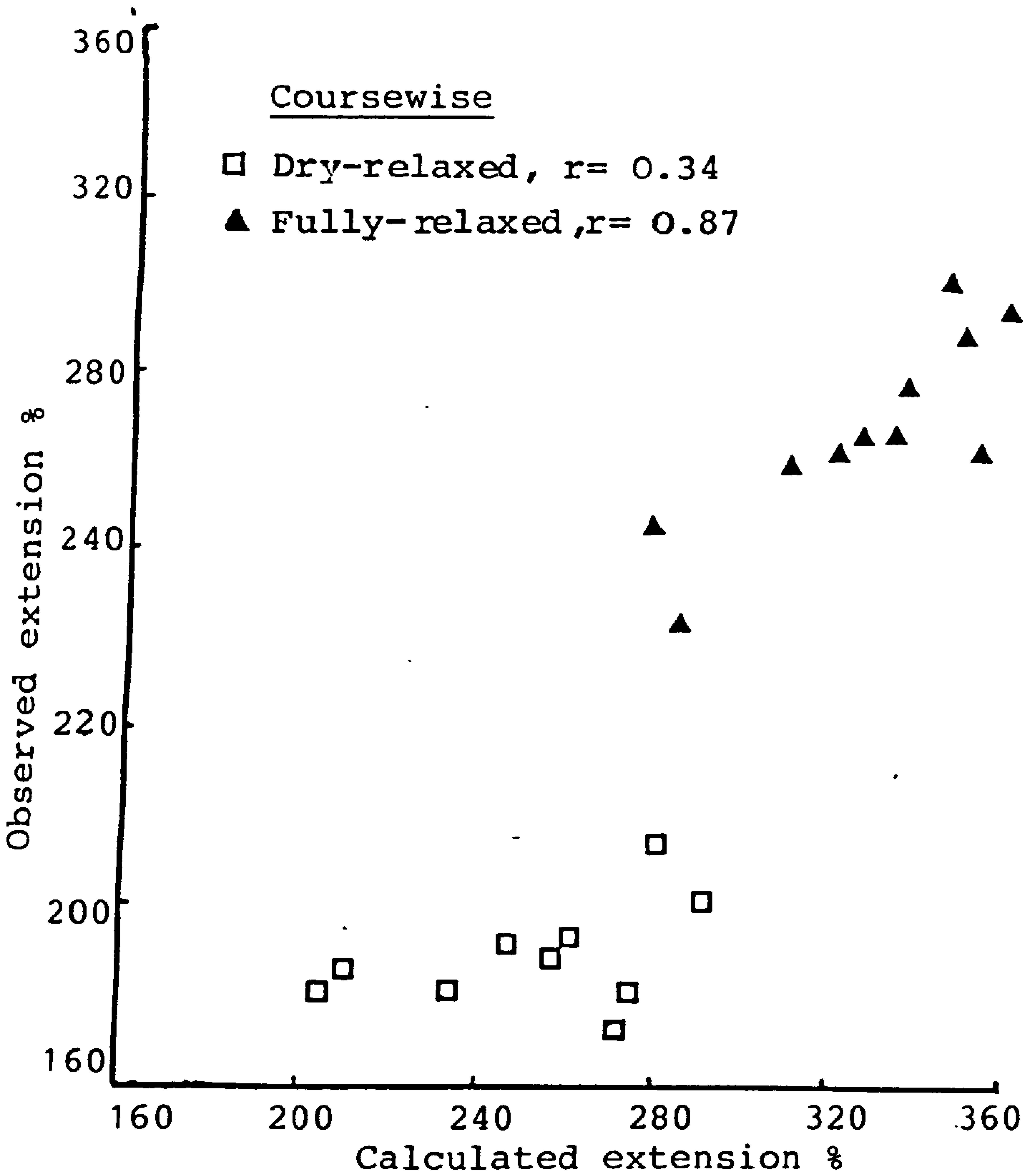


Fig 61: Relation between observed and calculated extension, one-end fabrics.

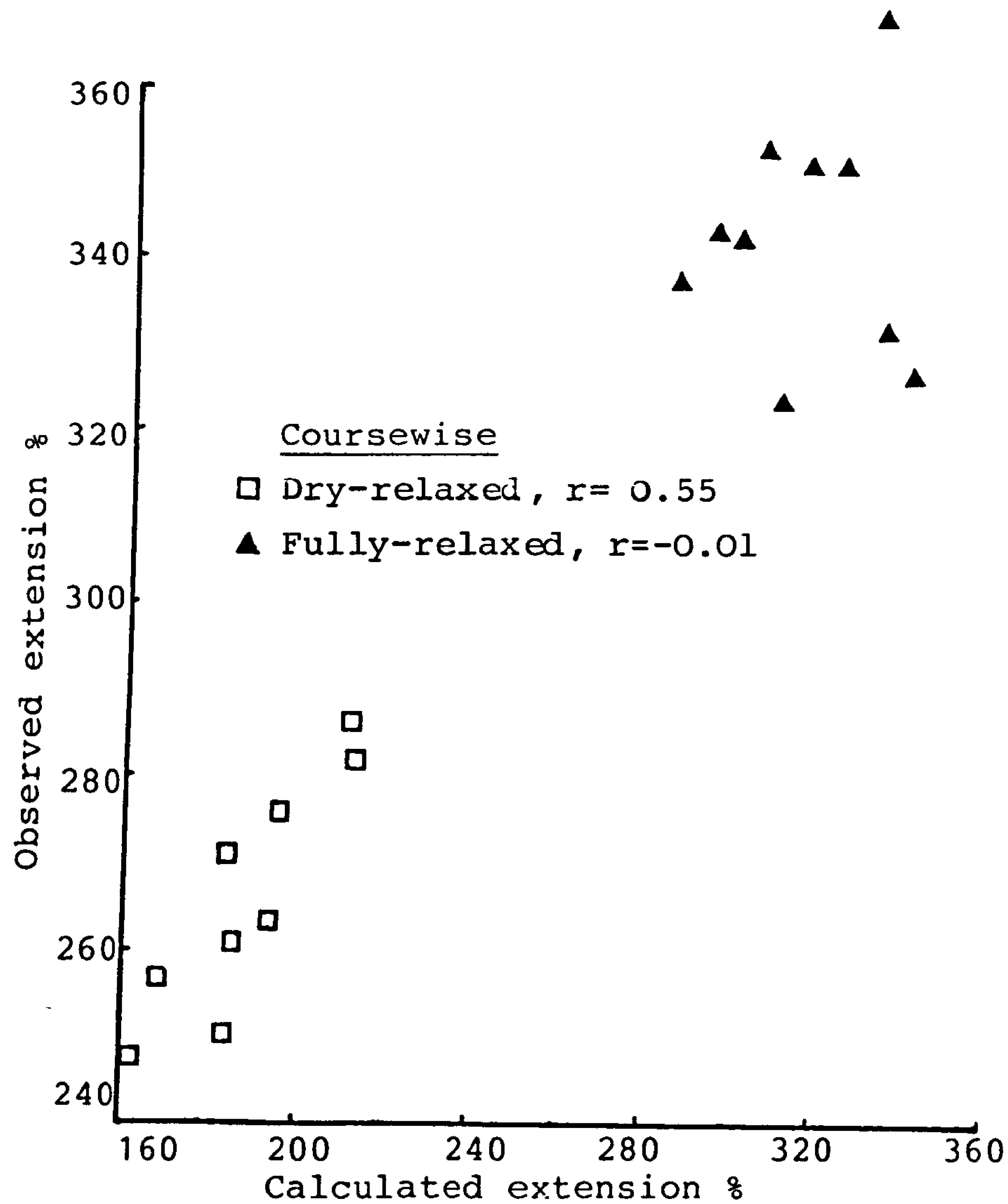


Fig 62 : Relation between observed and calculated extension, two-end fabrics.

dependent on loop length except that dry-and fully-relaxed fabrics knitted from two ends, extended wale-wise show less dependence on loop strength. This suggests that the yarn friction did not decrease proportionally to the increase in loop length.

6.4 The effect of yarn properties on fabric properties

When a 5cm wide strip of fabric is subjected to tensile test walewise, the rupture occurs at the weakest point of the yarn in the strip and the length of this yarn is considered to be equal the L/2 x Cp.c.x gauge length and the number of yarns is equal Wp.c. x 2x5 . Since the fabrics tested have different loop length, i.e., different dimensions,then it is difficult to find precisely what gauge length should be employed to test and to calculate the tensile strength of the yarn which may be used in the calculation of the fabric strength. The yarn was retested at 1cm gauge length and the results show that the tensile strength of dry-relaxed yarn increased from 423g in previous test with gauge length 10cm to 590g and the tensile strength of fully-relaxed yarn increased from 358g to 465g. Standard deviations of both yarns have also increased. Thus, a gauge length of 10cm may be regarded as the appropriate length to evaluate the tensile strength of the yarn which has been used in the previous calculation.*

* It might be more appropriate to use the loop strength of the yarn but this would make little difference to the results (see p. 60).

When the yarn friction was measured for dry- and fully-relaxed yarns, the results showed a remarkable increase in coefficient of friction resulting from the treatment (see Chapter 4, section 4.7). This increase appears to have a great effect on the tensile properties of fully-relaxed fabrics particularly the fabrics made from two ends. This is evident from the results in Tables 21-28 where it can be noted that the tensile strength of one-end yarn in the fully-relaxed fabrics is greater than the tensile strength of one-end yarn in the dry-relaxed fabrics while the results in Table 6 (see chapter 4, section 4.5) show that the tensile strength of the single dry-relaxed yarn is greater than the tensile strength of fully-relaxed yarn.

The effect of treatment on the yarn extensibility (see Chapter 4, Table 6), is also reflected in the results of fabric extension. As can be seen from the Tables 21-28, the extension of fully-relaxed fabrics is much greater than the extension of dry-relaxed fabrics.

Yarn rigidity, by contrast, is the same for both dry- and fully-relaxed yarns. However, it is expected that, rigidity, of one-end yarn will be different from the rigidity of two-end yarn.

It is difficult to assess the effect of yarn rigidity on the tensile properties of the fabrics, but it is felt that the "fabric assistance" factor may combine the friction, bending resistance and yarn compression which are all affected mainly by the binding or transverse yarn.

CHAPTER 7

ELASTIC RECOVERY PROPERTIES

Elastic recovery is one of the most important properties of the knitted fabrics. Good elastic recovery provides comfort in wear with good dimensional stability of the fabrics.

In actual wear, the knitted garments need to be stretched in order to follow easily the movement of some parts of the body such as knee, elbow and back, or to follow comfortably the shape of the other parts of the body, but the extent of this stretching will not be above 50%. Thus, the fabric extension levels used in this work between 10% and 50% are satisfactory for the purpose of studying the elastic recovery of plain-knitted wool fabrics.

The degree of re-gaining the geometrical restraint of the extended fabric depends on its stored energy resulting from the external force applied to that fabric. The stored energy in the fabric takes the form of yarn resistance to tensile, bending and to some extent torsional forces. However, once the external force is removed and the structure, under its internal energy, tends to recover its dimension of geometrical shape, frictional forces such as inter-loop, inter-yarn and inter-fibre friction (internal friction)will resist this recovery. The time factor as well as some other factors (moisture, temperature,etc) at this stage have an important effect on the recovery. The considerable effect of these frictional forces on tensile properties of the fabrics has been discussed in the previous chapter .

The elastic recovery properties of the fabrics used in this work are arranged in loop length order and presented in Tables 29-36. As usually happens, the values of the initial elastic recovery % (I.E.R.) are lower than the values of total elastic recovery % (T.E.R.) at any strain level in the first and fourth cycles, they are particularly lower at high strain levels. The results in these tables also show that both the initial and total elastic recovery and the load in the fourth cycle are lower than in the first cycle. This indicates that the elastic recovery diminished with the amount of stretch due to the fact that any material is losing part of its internal energy when it is subjected to a cyclic extension and at high extension some plastic deformation (non-recoverable extension of the material) could have occurred.

It will be noted from the Tables 29-36 and Figs. 63 and 64, where the load is plotted against strain in both directions of the fourth cycle for selected dry-relaxed fabrics only, the load required to extend the fabric to any strain level decreased rapidly with the increase of loop length. Figs 63 and 64 also shows that at high strain

Table 29 : Elastic properties of dry-relaxed fabric knitted from one-end, Walewise.

Fabric Code No.	Strain %	1st Cycle load (g)	1st Cycle I.E.R. (%)	1st Cycle T.E.R. (%)	4th Cycle load (g)	4th Cycle I.E.R. (%)	4th Cycle T.E.R. (%)
23	10	35	87.2	89.2	51	87.2	89.7
	20	195	81.1	83.8	175	79.7	82.4
	30	480	80.8	83.3	430	80.7	82.4
	40	1060	78.3	80.5	960	75.3	79.8
	50	2120	71.9	78.0	1900	69.8	73.1
11	10	38	92.3	92.9	33	92.3	94.9
	20	84	86.1	86.6	76	83.5	87.3
	30	144	83.2	86.6	130	81.5	85.7
	40	340	81.1	85.5	300	78.6	83.0
	50	940	84.6	87.8	780	77.8	82.6
12	10	31	87.2	92.3	28	87.2	89.7
	20	60	86.1	89.9	53	86.1	89.9
	30	108	84.9	87.4	98	83.2	86.6
	40	212	81.3	84.5	185	74.2	81.3
	50	380	76.7	84.7	335	73.6	81.6
6	10	20	97.4	100.0	18	94.9	100.0
	20	43	89.9	96.2	39	86.1	92.4
	30	80	84.9	89.9	74	84.0	87.4
	40	154	84.3	88.7	138	83.0	86.2
	50	425	79.7	87.5	370	78.6	85.9

Table 29: continued/

Fabric Code No.	Strain %	1st Cycle load (g)	1st Cycle I.E.R. (%)	1st Cycle T.E.R. (%)	4th Cycle load (g)	4th Cycle I.E.R. (%)	4th Cycle T.E.R. (%)
13	10	15	87.2	89.7	14	87.2	89.7
	20	27	81.0	87.3	25	81.0	86.0
	30	40	80.5	86.4	36	78.8	84.7
	40	82	79.9	86.7	74	78.6	84.3
	50	171	83.4	86.9	152	82.4	85.4
8	10	13	89.7	97.4	12	87.2	94.9
	20	23	82.3	88.6	21	78.5	87.3
	30	37	82.3	88.2	34	78.1	85.7
	40	62	80.5	88.0	56	78.6	85.5
	50	100	79.9	86.9	88	76.4	82.4
9	10	10	87.2	94.9	9	84.6	92.3
	20	14	87.3	92.4	13	81.0	84.8
	30	25	79.7	82.2	23	75.4	80.5
	40	34	76.1	83.6	30	75.5	81.7
	50	76	74.4	83.4	68	72.4	81.4
10	10	6	82.1	89.1	5	76.9	82.1
	20	11	82.3	87.3	9	79.7	83.5
	30	13	72.0	83.9	11	71.2	78.9
	40	15	66.0	78.6	14	62.9	76.1
	50	24	64.8	76.3	21	62.8	75.4

Table 30 : Elastic recovery properties of fully-relaxed fabrics made from one-end, Walewise.

Fabric Code No.	Strain %	1st Cycle load (g)	1st Cycle I.E.R. (%)	1st Cycle T.E.R. (%)	4th Cycle load (g)	4th Cycle I.E.R. (%)	4th Cycle T.E.R. (%)
23	10	68	89.7	92.3	64	87.1	92.3
	20	180	82.2	83.6	165	81.1	82.0
	30	500	84.9	89.3	455	83.1	87.6
	40	850	79.0	82.6	750	76.8	81.2
	50	2200	75.6	79.4	1880	74.0	76.7
11	10	44	94.9	97.4	40	94.9	97.4
	20	126	89.9	94.9	115	88.6	91.1
	30	215	85.4	89.7	190	80.3	87.1
	40	455	84.6	88.4	410	80.1	86.5
	50	970	83.9	88.1	860	74.1	83.9
6	10	32	100.0	100.0	30	97.4	97.4
	20	84	93.7	94.9	77	92.4	93.7
	30	152	93.2	94.9	140	91.5	93.2
	40	280	84.7	87.7	250	83.4	85.9
	50	640	82.4	84.5	540	77.8	81.4
7	10	20	92.3	94.9	19	89.7	92.3
	20	45	88.6	92.4	41	87.3	89.8
	30	89	88.2	91.5	70	86.5	89.9
	40	140	87.4	89.9	128	86.1	88.0
	50	240	82.4	85.4	205	76.3	80.4

Table 30: Continued/

Fabric Code No.	Strain %	1st Cycle load (g)	1st Cycle I.E.R. (%)	1st Cycle T.E.R. (%)	4th Cycle load (g)	4th Cycle I.E.R. (%)	4th Cycle T.E.R. (%)
8	10	15	89.7	92.3	14	84.6	87.1
	20	31	84.8	88.6	29	84.8	87.3
	30	65	84.0	88.2	57	84.0	87.0
	40	120	84.9	88.7	105	82.3	86.7
	50	160	80.9	85.9	136	78.9	83.4
15	10	15	97.4	100.0	13	94.9	97.4
	20	37	88.6	92.4	32	84.8	88.6
	30	63	87.4	89.1	55	83.2	85.7
	40	98	85.5	87.4	85	81.1	84.3
	50	138	84.4	86.9	120	78.4	83.9
9	10	14	84.6	87.2	13	84.6	87.2
	20	28	84.8	87.3	24	82.2	84.8
	30	70	84.8	86.6	53	82.4	84.0
	40	82	84.2	86.2	70	78.6	82.4
	50	128	81.9	84.4	104	77.4	80.9
10	10	11	84.6	87.1	10	84.6	84.6
	20	25	82.7	84.8	22	79.7	82.2
	30	49	83.1	84.8	43	79.8	81.5
	40	105	82.3	84.1	94	79.2	80.5
	50	122	80.0	83.0	100	75.0	79.5

Table 31: Elastic recovery of dry-relaxed fabrics made from two ends, Walewise.

Fabric Code No.	Strain %	1st Cycle load (g)	1st Cycle I.E.R. (%)	1st Cycle T.E.R. (%)	4th Cycle load (g)	4th Cycle I.E.R. (%)	4th Cycle T.E.R. (%)
1	10	30	87.2	92.3	28	82.1	87.2
	20	64	83.5	88.6	54	79.8	83.5
	30	152	81.5	84.9	132	80.0	81.5
	40	260	78.6	84.3	230	73.6	79.2
	50	450	77.9	82.9	380	69.3	79.3
25	10	26	94.9	97.4	23	92.3	94.9
	20	68	86.1	88.6	60	79.7	84.8
	30	124	81.5	86.6	110	79.0	82.4
	40	195	74.8	81.3	165	74.2	78.7
	50	375	79.8	85.1	325	76.4	81.0
2	10	24	87.2	94.9	22	82.1	92.3
	20	54	79.7	87.3	46	74.7	82.3
	30	105	76.5	86.6	87	75.6	83.2
	40	135	76.1	79.2	110	67.9	74.2
	50	214	75.4	78.9	175	67.8	72.8
3	10	14	87.1	94.8	12	82.1	92.3
	20	35	78.5	84.8	29	73.4	81.0
	30	63	75.6	81.5	51	69.7	77.3
	40	120	75.5	81.1	96	69.1	76.7
	50	184	75.3	80.9	152	68.3	76.4

Table 31: Contd./

Fabric Code No.	Strain %	1st Cycle load (g)	1st Cycle I.E.R. (%)	1st Cycle T.E.R. (%)	4th Cycle load (g)	4th Cycle I.E.R. (%)	4th Cycle T.E.R. (%)
28	10	28	87.2	89.7	25	84.6	87.2
	20	62	79.7	87.3	54	77.2	86.0
	30	120	79.8	87.4	105	77.3	85.7
	40	204	79.9	86.4	180	77.9	84.9
	50	295	79.3	83.4	255	77.4	80.4
4	10	14	97.4	100.0	11	92.3	97.4
	20	36	86.1	89.9	27	78.5	83.5
	30	54	77.3	86.6	45	75.6	80.7
	40	52	80.5	85.5	46	76.7	81.8
	50	84.0	80.4	86.9	71	77.8	84.4
5	10	16	87.2	92.3	12	84.6	89.7
	20	30	79.7	86.1	25	78.5	83.5
	30	48	74.8	82.3	41	73.1	80.5
	40	88	78.0	86.8	77	77.4	84.2
	50	130	75.9	84.4	110	73.9	79.4
20	10	13	94.9	100.0	12	84.6	100.0
	20	29	75.9	86.1	26	74.7	78.5
	30	65	77.3	84.8	57	75.6	83.2
	40	92	76.1	84.9	82	74.8	83.0
	50	178	74.9	83.4	152	73.9	79.0

Table 32: Elastic recovery properties of fully-relaed fabrics made from two-ends, walewise.

Fabric Code No.	Strain %	1st Cycle			4th Cycle		
		load (g)	I.E.R. (%)	T.E.R. (%)	load (g)	I.E.R. (%)	T.E.R. (%)
24	10	40	92.3	94.9	34	89.7	92.3
	20	92	88.6	91.1	85	86.1	88.6
	30	164	86.5	88.5	148	84.8	86.5
	40	275	85.1	86.4	235	80.4	81.7
	50	400	83.5	85.7	345	79.4	80.4
1	10	30	89.7	92.3	28	87.4	89.2
	20	84	88.6	89.8	76	86.1	87.3
	30	142	86.4	88.1	126	84.7	86.4
	40	230	81.2	82.4	195	75.3	77.9
	50	330	78.8	81.4	280	76.8	78.3
2	10	26	89.5	92.1	23	86.8	89.5
	20	57	87.3	88.6	50	84.8	86.1
	30	106	87.3	89.1	96	84.0	85.7
	40	194	85.5	88.0	120	83.0	85.5
	50	260	74.7	78.9	215	69.7	73.8
3	10	24	82.1	87.2	22	79.5	84.6
	20	57	83.5	84.8	48	82.2	83.5
	30	94	83.1	84.0	84	80.6	82.3
	40	166	83.6	84.9	146	80.5	81.7
	50	215	83.4	84.4	180	80.4	81.4

Table 32 : cont./

Fabric Code No.	Strain %	1st Cycle load (g)	1st Cycle I.E.R. (%)	1st Cycle T.E.R. (%)	4th Cycle load (g)	4th Cycle I.E.R. (%)	4th Cycle T.E.R. (%)
18	10	19	87.1	89.7	17	87.1	89.7
	20	50	86.1	88.6	45	84.8	87.3
	30	86	84.8	86.5	79	84.0	85.7
	40	152	85.5	87.4	132	83.6	86.1
	50	205	85.4	86.4	172	81.4	83.4
5	10	20	92.3	94.8	18	89.7	92.3
	20	51	83.5	86.1	45	81.0	83.5
	30	79	83.2	84.8	67	79.8	81.5
	40	113	79.8	83.6	93	76.1	78.6
	50	160	79.8	81.9	132	75.8	78.4
19	10	16	86.8	89.5	15	84.2	86.8
	20	37	84.8	86.1	34	83.5	84.8
	30	67	84.8	86.6	61	83.2	84.8
	40	100	84.2	85.5	87	79.9	81.7
	50	156	82.4	84.4	130	79.9	81.4
20	10	14	100.0	100.0	13	97.4	100.0
	20	30	82.3	83.5	27	79.7	82.3
	30	53	82.3	84.0	48	79.8	81.5
	40	87	83.0	84.9	76	80.5	81.7
	50	130	81.9	83.4	110	77.4	79.8

Table 33 : Elastic properties of dry-relaxed fabrics knitted from one-end, coursewise.

Fabric Code No.	Strain %	1st Cycle			4th Cycle		
		load (g)	I.E.R. (%)	T.E.R. (%)	load (g)	I.E.R. (%)	T.E.R. (%)
23	10	35	92.3	94.9	33	92.3	94.9
	20	95	89.9	93.7	92	88.6	92.4
	30	150	84.9	90.7	148	84.0	89.1
	40	235	84.6	87.1	210	80.1	85.9
	50	305	84.6	87.2	280	83.6	85.7
11	10	28	94.9	94.9	26	94.9	94.9
	20	63	87.3	92.4	58	86.1	89.9
	30	110	84.9	88.2	102	82.3	86.6
	40	143	80.5	85.5	130	81.7	84.3
	50	210	85.4	86.4	185	87.4	83.9
12	10	16	97.0	100.0	15	94.9	97.4
	20	38	91.1	100.0	35	89.9	94.9
	30	72	88.1	92.4	67	86.4	90.6
	40	106	87.4	88.7	97	83.6	87.4
	50	134	85.9	88.7	120	84.9	86.4
6	10	13	89.7	97.4	12	87.2	92.3
	20	35	86.1	92.4	32	86.1	91.1
	30	45	85.5	90.6	41	84.7	89.8
	40	81	84.9	89.9	74	83.6	88.6
	50	103	85.4	89.4	92	84.4	87.4

Table 33: Contd./

Fabric Code No.	Strain %	1st Cycle load (g)	1st Cycle I.E.R. (%)	1st Cycle T.E.R. (%)	4th Cycle load (g)	4th Cycle I.E.R. (%)	4th Cycle T.E.R. (%)
13	10	12	100.0	100.0	12	100.0	100.0
	20	27	87.3	91.1	25	86.1	89.9
	30	45	84.0	88.2	41	83.2	87.4
	40	74	82.4	88.1	67	81.8	85.5
	50	84	82.4	84.9	75	80.4	83.4
8	10	8	94.9	97.4	7	94.9	97.4
	20	17	83.5	88.6	16	81.0	86.1
	30	31	83.2	87.4	28	81.5	86.5
	40	51	84.2	86.7	46	81.1	85.5
	50	59	80.9	86.9	52	79.9	84.4
9	10	7	100.0	100.0	6	100.0	100.0
	20	15	87.3	93.7	14	86.1	91.1
	30	29	87.3	93.2	25	84.0	88.2
	40	36	83.6	88.1	32	80.5	85.5
	50	56	85.4	88.4	49	79.9	85.4
10	10	3	100.0	100.0	3	100.0	100.0
	20	9	86.1	89.9	8	79.7	82.3
	30	14	80.6	83.1	14	80.6	82.3
	40	31	83.6	85.5	28	81.1	83.0
	50	34	82.4	83.4	30	79.9	82.0

Table 34: Elastic recovery properties of fully-relaxed fabrics made from one-end, coursewise.

Fabric Code No.	Strain %	1st Cycle load (g)	1st Cycle I.E.R. (%)	1st Cycle T.E.R. (%)	4th Cycle load (g)	4th Cycle I.E.R. (%)	4th Cycle T.E.R. (%)
23	10	36	100.0	100.0	32	100.0	100.0
	20	84	94.9	97.5	80	93.7	96.2
	30	136	94.1	96.5	126	93.3	95.0
	40	195	90.0	91.3	175	86.6	88.6
	50	270	87.1	88.2	230	84.6	85.6
11	10	26	100.0	100.0	24	100.0	100.0
	20	60	97.5	98.7	56	94.9	97.5
	30	100	95.0	96.6	90	94.1	95.8
	40	140	93.7	95.0	130	89.3	93.7
	50	190	88.2	90.8	170	88.2	90.3
6	10	16	100.0	100.0	15	100.0	100.0
	20	39	100.0	100.0	36	97.5	100.0
	30	72	95.8	97.4	66	93.3	94.9
	40	100	91.6	93.5	90	90.9	92.9
	50	126	91.0	93.0	114	89.4	91.5
7	10	11	94.8	97.4	10	94.8	97.4
	20	24	88.6	91.1	22	88.6	91.1
	30	42	86.5	90.7	38	85.7	88.2
	40	71	89.3	93.1	65	89.8	91.8
	50	86	91.4	92.9	80	88.4	91.0

Table 34 : cont./

Fabric Code No.	Strain %	1st Cycle load (g)	1st Cycle I.E.R. (%)	1st Cycle T.E.R. (%)	4th Cycle load (g)	4th Cycle I.E.R. (%)	4th Cycle T.E.R. (%)
8	10	9	97.4	100.0	8	92.3	97.4
	20	20	86.1	89.9	18	84.8	87.3
	30	33	85.7	89.9	29	84.0	86.5
	40	50	84.9	89.3	44	83.6	86.1
	50	60	84.9	87.4	52	82.9	85.9
15	10	15	97.4	100.0	14	94.9	100.0
	20	32	88.6	91.1	29	84.8	88.6
	30	51	88.2	90.7	46	86.4	88.1
	40	85	88.0	89.9	75	86.2	88.1
	50	130	85.9	89.4	116	82.9	88.4
9	10	8	87.2	89.4	7	82.1	87.2
	20	14	84.8	88.6	13	82.3	87.3
	30	26	84.9	86.6	24	82.3	85.7
	40	44	84.9	86.7	39	82.3	85.5
	50	57	84.9	87.4	48	81.9	85.4
10	10	7	89.7	92.3	6	84.6	87.2
	20	16	81.0	84.8	15	79.7	83.5
	30	22	80.6	82.3	19	79.8	81.5
	40	30	87.4	88.7	27	86.2	88.1
	50	48	85.4	86.9	45	82.9	84.4

Table 35: Elastic recovery properties of dry-relaxed fabric made from two-ends, coursewise

Fabric Code No.	Strain %	1st Cycle load (g)	1st Cycle I.E.R. (%)	1st Cycle T.E.R. (%)	4th Cycle load (g)	4th Cycle I.E.R. (%)	4th Cycle T.E.R. (%)
1	10	13	94.9	100.0	12	89.7	100.0
	20	38	86.1	91.1	34	84.8	88.8
	30	67	84.0	89.9	61	83.0	88.2
	40	106	83.0	88.6	98	82.4	86.7
	50	200	84.4	88.9	175	82.9	85.4
25	10	14	94.9	97.9	13	89.7	92.3
	20	33	90.0	91.1	30	88.6	90.0
	30	54	84.9	87.4	50	82.4	87.4
	40	76	84.2	85.5	68	79.9	84.3
	50	112	84.9	87.9	102	82.9	86.4
2	10	12	89.7	97.4	11	87.2	94.9
	20	26	84.8	89.9	23	79.7	83.5
	30	45	83.2	88.2	40	79.0	83.2
	40	68	82.4	87.4	58	78.6	83.0
	50	87	80.9	86.9	70	78.3	80.9
3	10	9	87.2	97.4	8	82.1	92.3
	20	20	79.7	84.8	17	75.9	82.3
	30	32	76.5	80.6	27	73.9	79.0
	40	50	77.9	81.1	41	72.3	79.2
	50	63	82.9	85.4	52	75.4	81.4

Table 35 : Cont./

Fabric Code No.	Strain %	1st Cycle load (g)	1st Cycle I.E.R. (%)	1st Cycle T.E.R. (%)	4th Cycle load (g)	4th Cycle I.E.R. (%)	4th Cycle T.E.R. (%)
28	10	13	94.9	100.0	12	92.9	100.0
	20	28	87.3	97.5	26	88.6	94.9
	30	49	85.7	90.8	45	81.5	89.9
	40	70	84.3	89.3	61	81.1	87.4
	50	98	87.4	88.9	87	85.9	87.9
4	10	7	94.9	94.9	6	87.2	89.7
	20	14	88.6	93.7	13	83.5	88.6
	30	24	84.9	89.9	20	79.0	84.0
	40	35	83.6	89.9	30	78.6	83.0
	50	45	81.9	88.4	37	75.4	82.9
5	10	4	94.9	100.0	4	92.3	94.9
	20	14	94.9	96.2	12	92.4	93.7
	30	20	91.5	97.4	18	91.5	94.0
	40	27	86.2	90.6	24	83.6	88.6
	50	31	81.9	88.9	27	81.4	86.9
20	10	8	94.9	100.0	7	94.9	100.0
	20	17	77.2	89.9	15	75.9	83.5
	30	29	77.1	87.3	27	74.8	80.7
	40	37	79.8	86.8	33	79.2	85.5
	50	45	85.4	88.9	40	85.4	88.9

Table 36 : Elastic recovery properties of fully-relaxed fabrics made from two-ends, coursewise.

Fabric Code No.	Strain %	1st Cycle load (g)	1st Cycle I.E.R. (%)	1st Cycle T.E.R. (%)	4th Cycle load (g)	4th Cycle I.E.R. (%)	4th Cycle T.E.R. (%)
24	10	25	92.3	100.0	23	92.4	100.0
	20	52	91.1	94.9	49	89.9	92.4
	30	90	91.6	93.2	82	39.9	91.6
	40	128	89.9	91.1	116	88.0	89.3
	50	172	89.4	90.4	152	87.9	88.9
1	10	20	100.0	100.0	19	100.0	100.0
	20	45	96.2	97.5	42	94.9	96.2
	30	70	92.3	94.1	64	89.0	90.7
	40	96	91.2	92.4	87	89.3	90.5
	50	144	91.4	92.4	128	89.4	90.9
2	10	18	89.7	92.3	16	89.7	92.3
	20	36	89.8	91.1	33	88.6	89.8
	30	60	86.5	88.2	57	84.9	86.5
	40	98	86.7	88.6	88	86.1	88.0
	50	124	85.4	87.9	106	82.9	85.4
3	10	16	92.3	94.9	14	89.7	92.3
	20	35	89.9	92.4	30	87.3	89.9
	30	60	88.2	89.1	54	86.6	87.4
	40	82	86.8	88.7	76	85.5	87.4
	50	122	86.4	88.9	104	82.4	86.6

Table 36 : Cont./

Fabric Code No.	Strain %	1st Cycle load (g)	1st Cycle I.E.R. (%)	1st Cycle T.E.R. (%)	4th Cycle load (g)	4th Cycle I.E.R. (%)	4th Cycle T.E.R. (%)
18	10	11	89.7	92.3	11	87.1	89.7
	20	26	87.3	88.6	24	86.1	87.3
	30	42	87.3	88.2	37	85.7	86.6
	40	66	87.4	88.6	60	85.5	86.6
	50	90	87.4	88.4	78	84.4	85.4
5	10	13	94.9	97.4	11	92.3	94.9
	20	26	84.8	87.3	23	83.5	86.1
	30	41	84.0	86.6	36	83.2	84.9
	40	60	82.3	85.5	52	81.7	83.0
	50	83	81.9	83.9	68	78.3	80.9
19	10	11	94.9	97.4	10	92.3	94.9
	20	23	91.1	93.7	21	91.1	93.7
	30	38	87.4	89.9	34	86.6	89.1
	40	52	86.2	88.6	46	82.4	87.4
	50	74	86.4	87.9	65	83.9	86.9
20	10	9	97.4	100.0	9	94.7	100.0
	20	19	87.3	88.6	7	86.1	87.3
	30	34	84.9	87.4	31	84.0	85.7
	40	48	86.1	89.3	44	85.5	88.0
	50	66	83.5	85.0	56	80.9	82.4

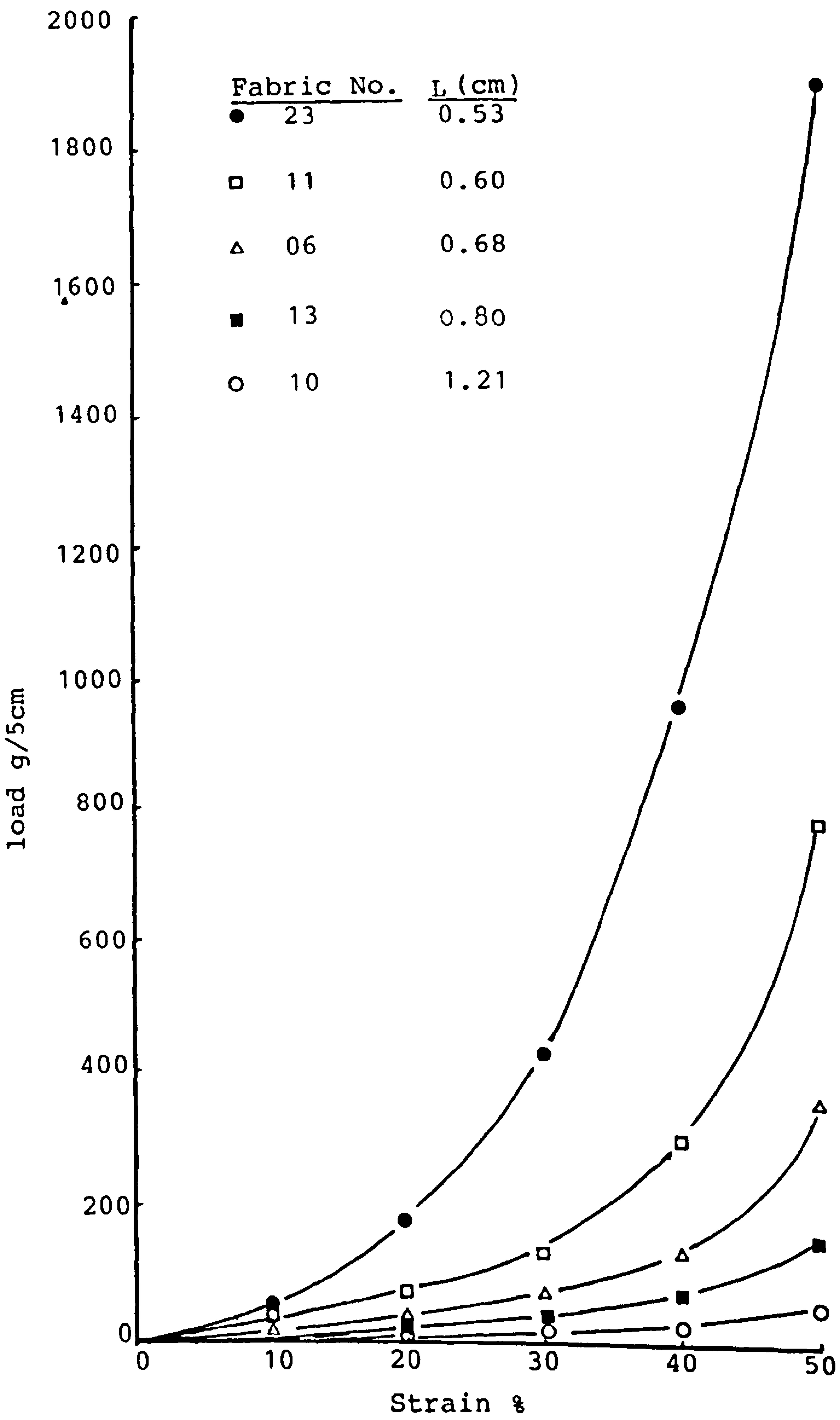


Fig 63 : Load against strain for one-end dry-relaxed fabrics in fourth cycle, walewise.

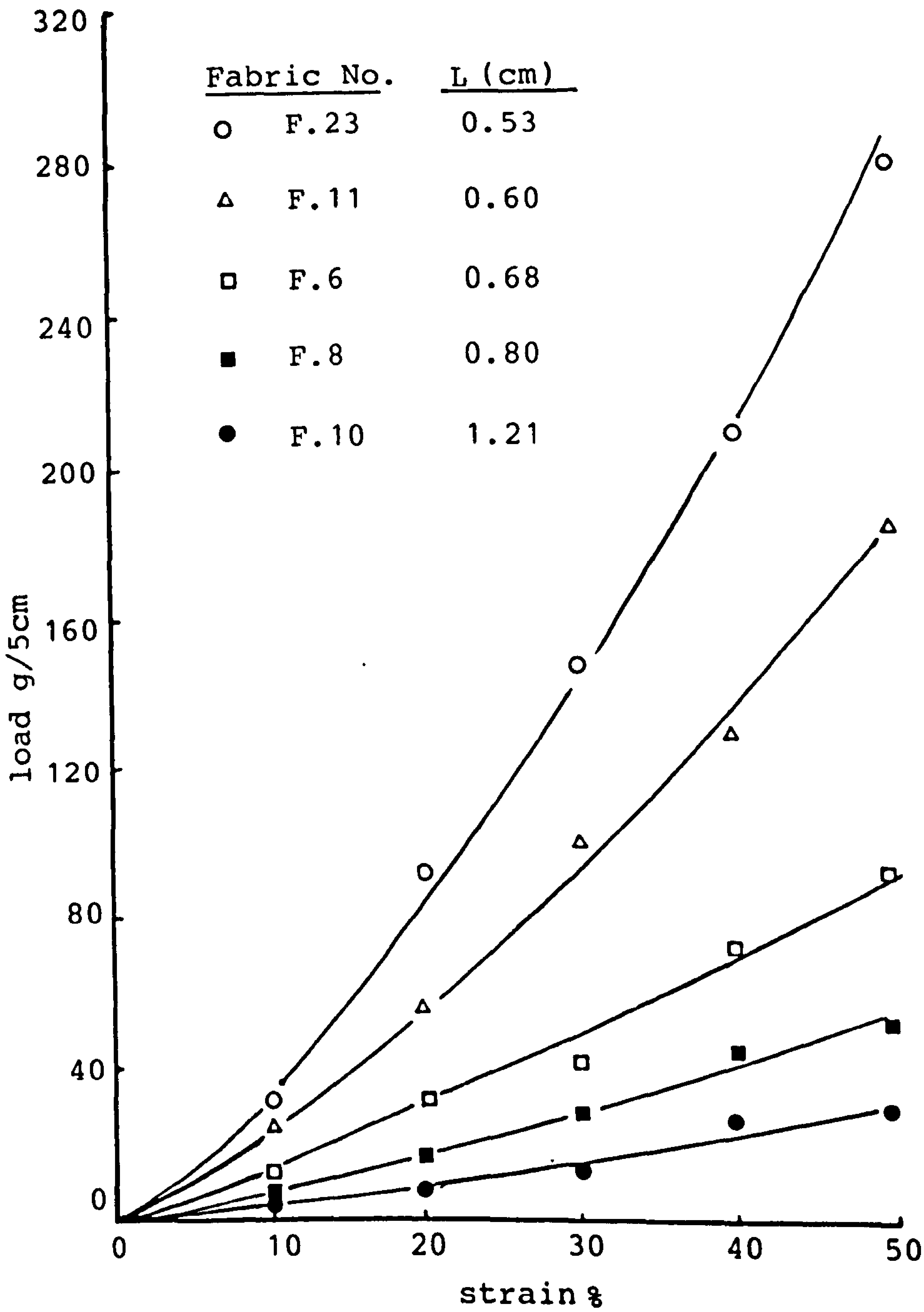


Fig 64 : Load against strain for one-end dry-relaxed fabrics in fourth cycle, coursewise.

level, the load in the walewise direction is very much higher than twice the load in the coursewise direction while at low strain level it is only marginally higher. This gives quite a different picture from the load-extension curves in the previous chapter. It is obvious that the load-strain curves presented in Figs. 63 and 64 correspond to the first part of the load-extension curves in Chapter 6, i.e., the characterisation of the first stage in the changes of loop shape. Therefore it is normal, that the load-strain curves in Fig. 63 for wale-wise extension do not take the linear form, but the curves in Fig. 64 for course-wise extension almost do.

Similarly to what has been shown in Chapter 6, the results in Tables 29-36 show that the load for all levels of strain increases as the treatment progresses and as the number of ends in the fabric increases.

It has been found that in plotting the elastic recovery against strain in the fourth cycle, the curve shape of the initial elastic recovery against strain at any loop length almost follows or is parallel to the curve shape of total elastic recovery against strain. In addition, the total elastic recovery has a more practical importance than the initial elastic recovery. On the basis of this the total elastic recovery is plotted against strain and loop length for all fabrics in both state of relaxation and direction and this is shown in Figs. 65-80. The plots of total elastic recovery against strain (Figs. 65-72) for all fabrics show that the total elastic recovery generally decreases with the increase of strain. Also, the values of total elastic recovery of all fabrics at low strain are higher in the course-wise direction than in the walewise direction and at high strain level they are only marginally higher. This would suggest that due to the repeated loading and unloading the permanent non-recoverable extension (plastic deformation) increases with the increase in strain. It would also suggest that the amount of friction resulting from this process is responsible for the higher values of total elastic recovery coursewise.

It can be seen from the geometry of the extended fabric shown in Figs. 44 and 45 in Chapter 6 that, to reach the loop-to-loop friction coursewise, much higher extension is needed while walewise this friction begins to affect the recovery even at a very low level of strain.

Marvin [87] suggested that the greater the amount of crimp in the yarn the more powerful the recovery in fabric form, but the results he obtained showed that crimp rigidity has little influence on total elastic recovery. A comparison of Figs. 65 and 66 with Figs. 67 and 68, and of Figs. 69 and 70 with Figs. 71 and 72 shows that the total recovery of fully relaxed fabrics walewise and coursewise is only moderately higher than the total

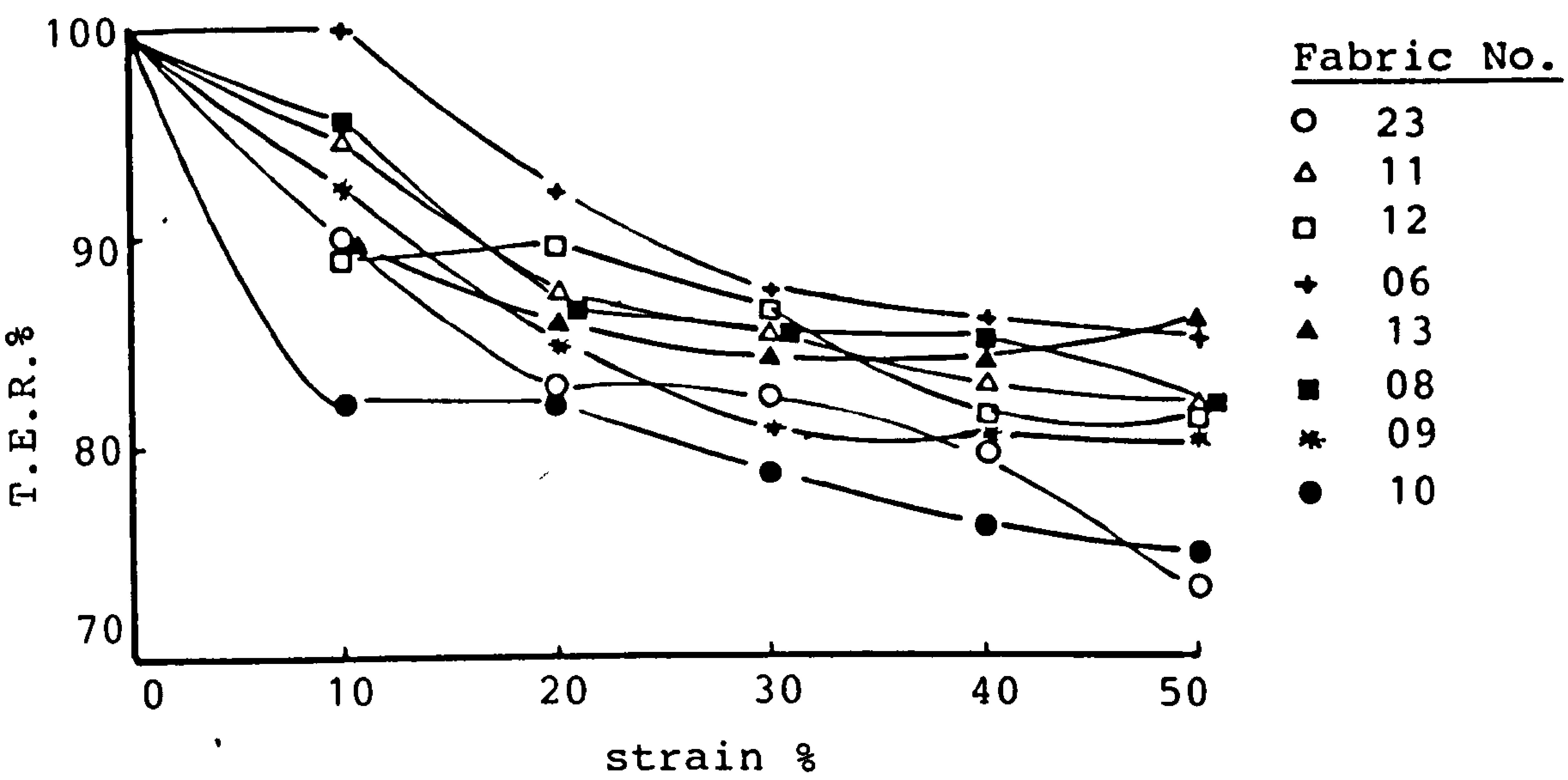


Fig65: Plot of T.E.R. against strain for dry -relaxed fabrics, one-end, fourth cycle, walewise.

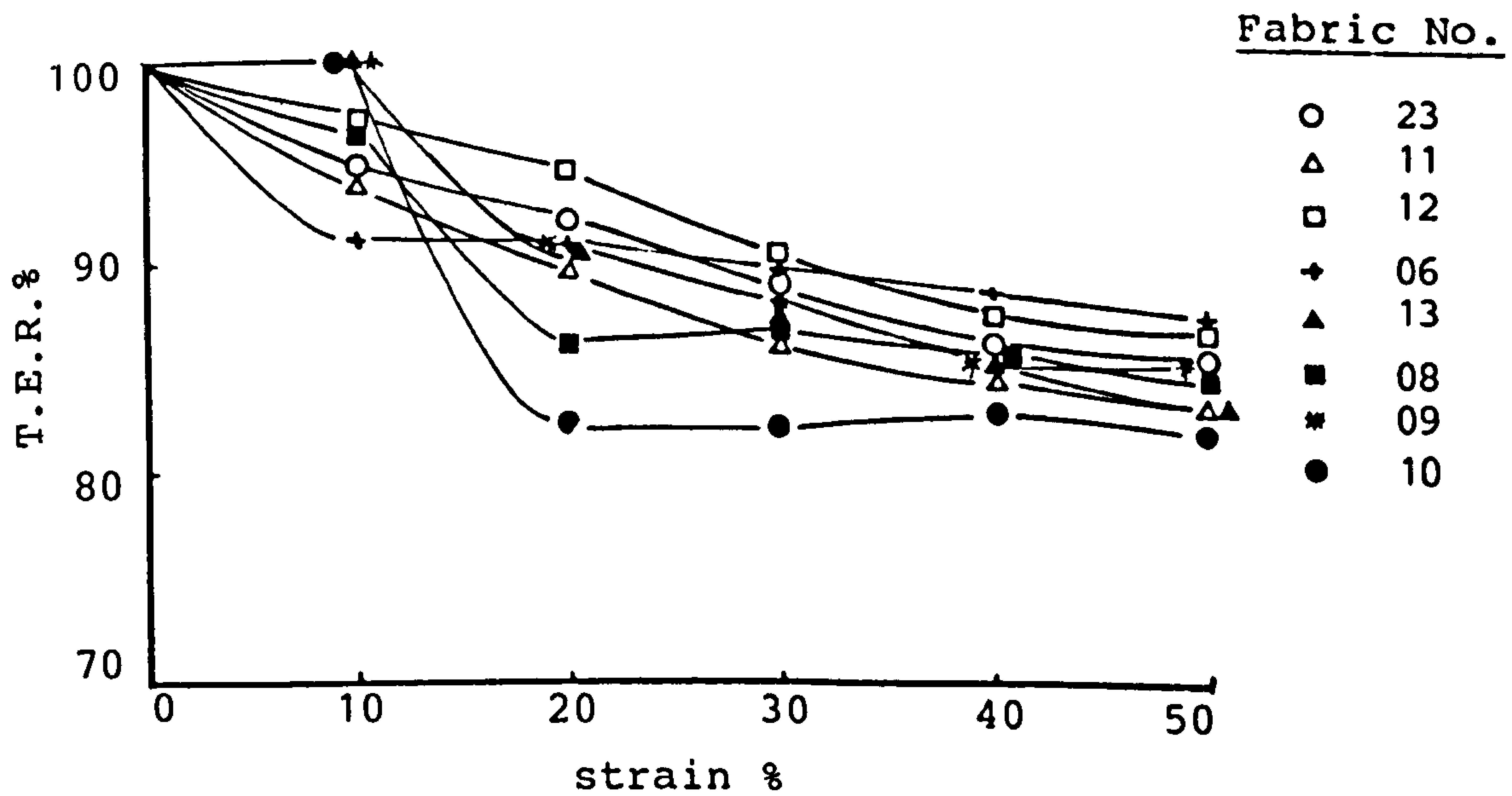


Fig 66: Plot of T.E.R. against strain for dry-relaxed fabrics, one-end, fourth cycle, coursewise.

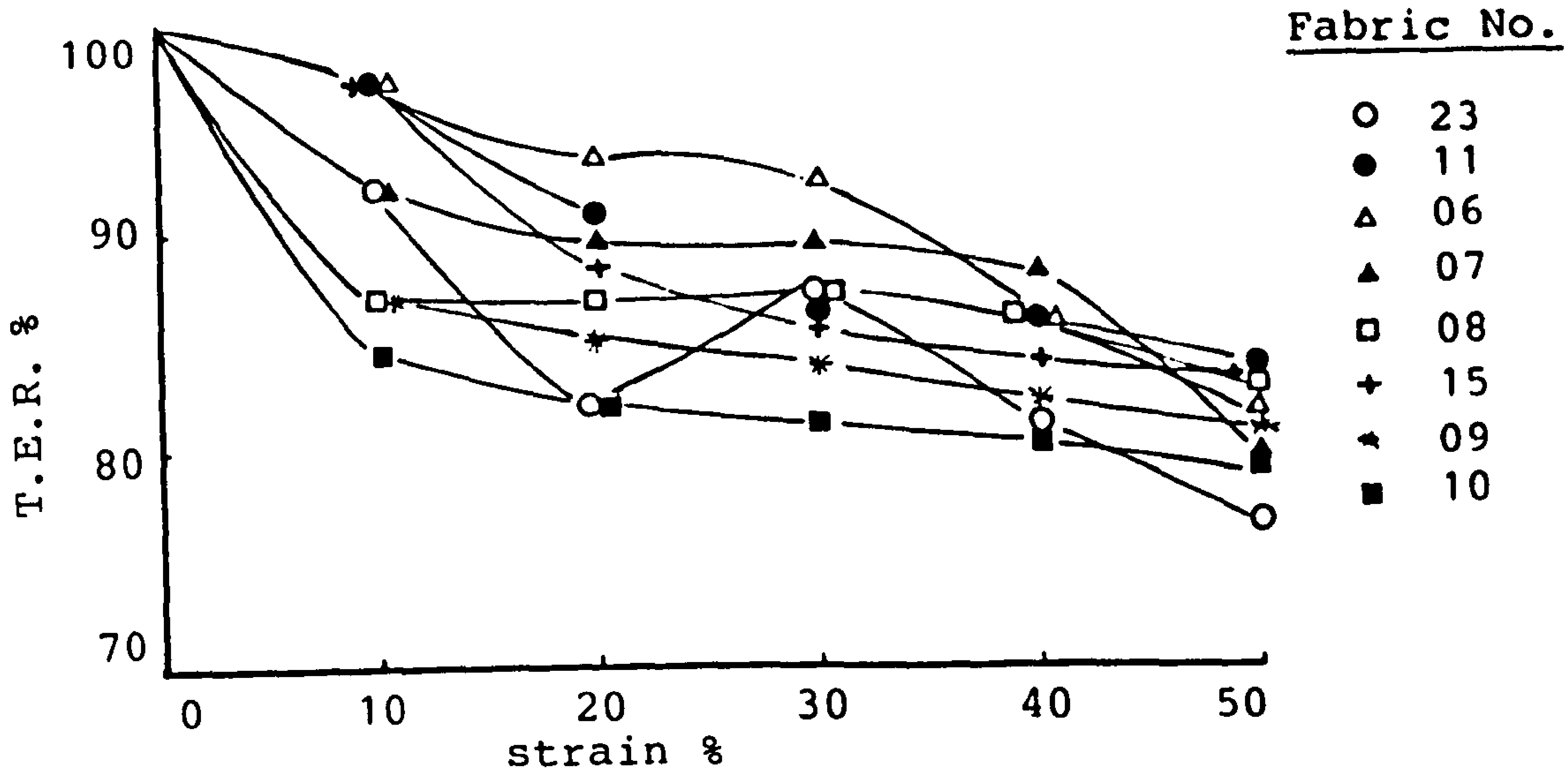


Fig 67: Plot of T.E.R. against strain for fully-relaxed fabrics one-end, fourth cycle, walewise.

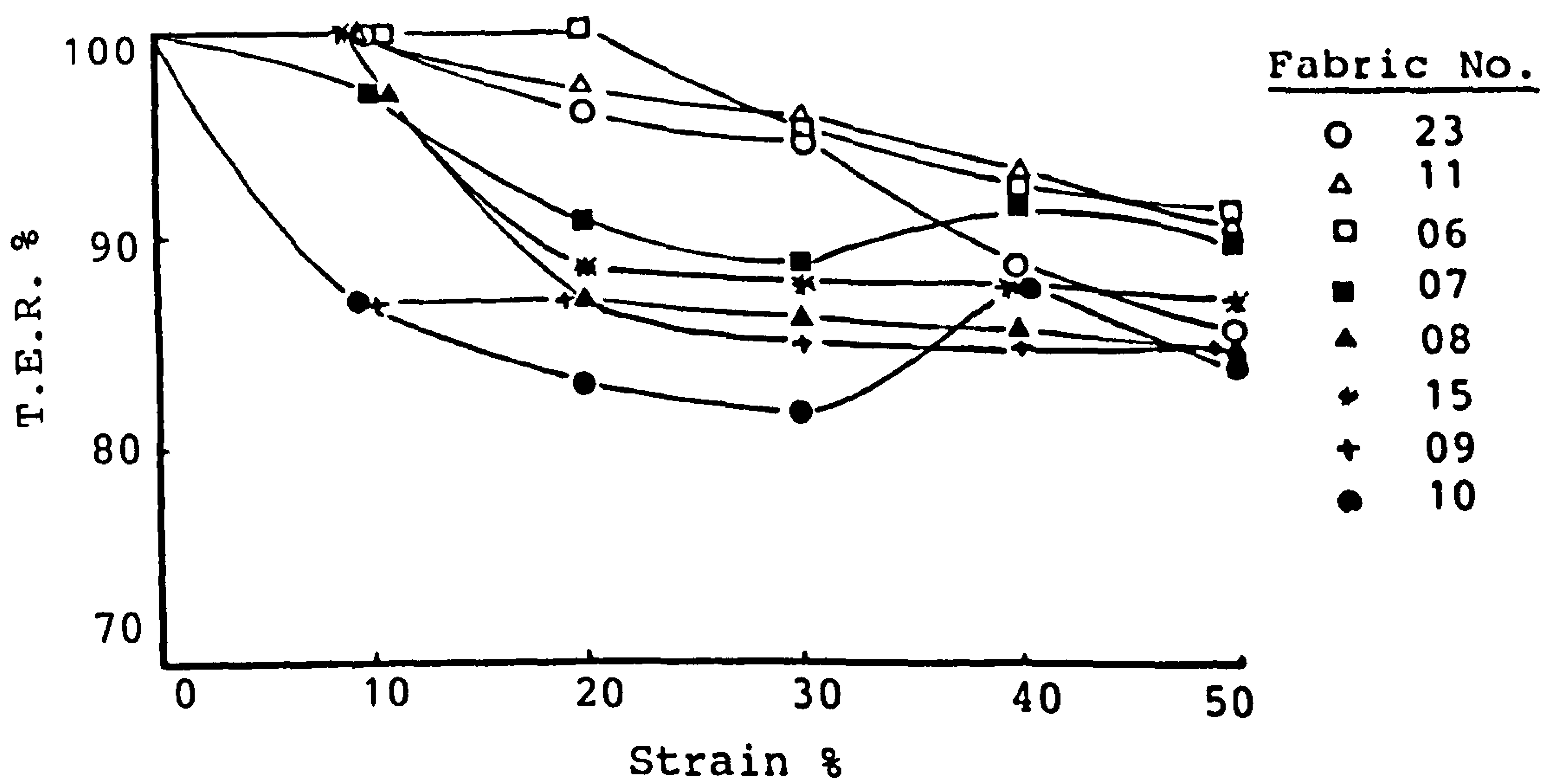


Fig 68 : Plot of T.E.R. against strain for fully-relaxed fabrics, one-end, fourth cycle, coursewise.

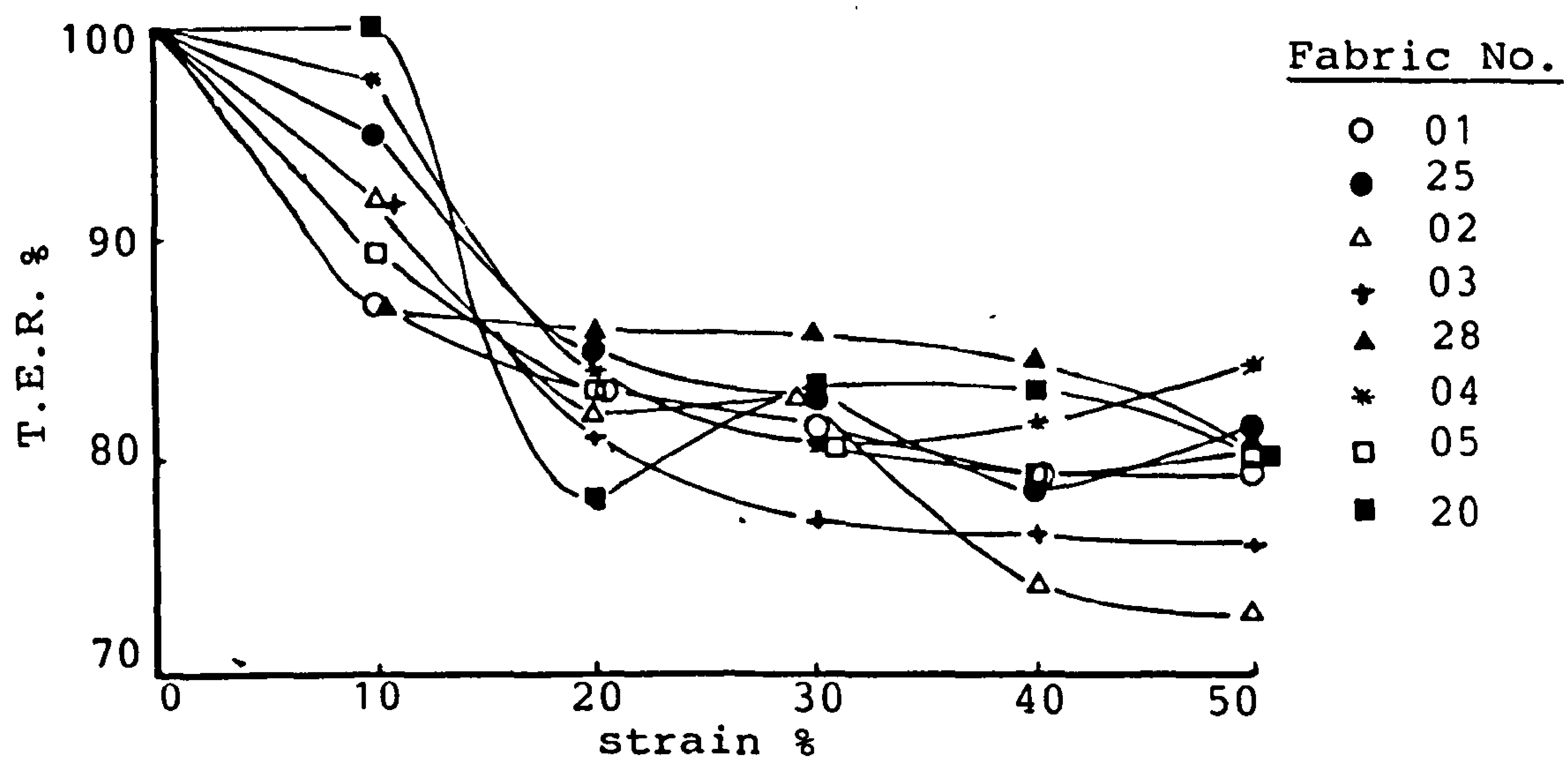


Fig 69 : Plot of T.E.R. against strain for dry-relaxed fabrics , two-ends, fourth cycle,walewise.

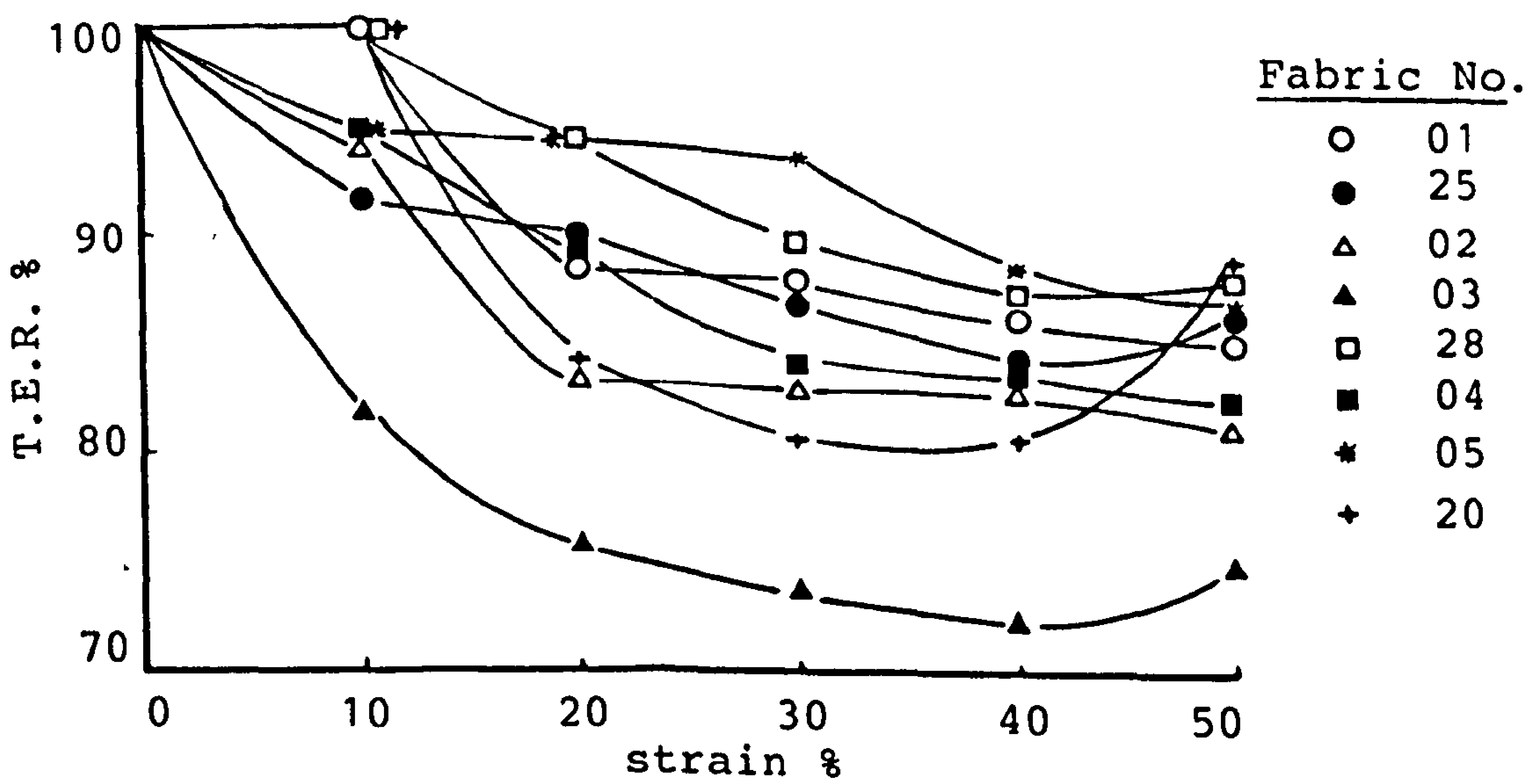


Fig 70 : Plot of T.E.R. against strain for dry-relaxed fabrics , two-ends, fourth cycle,coursewise.

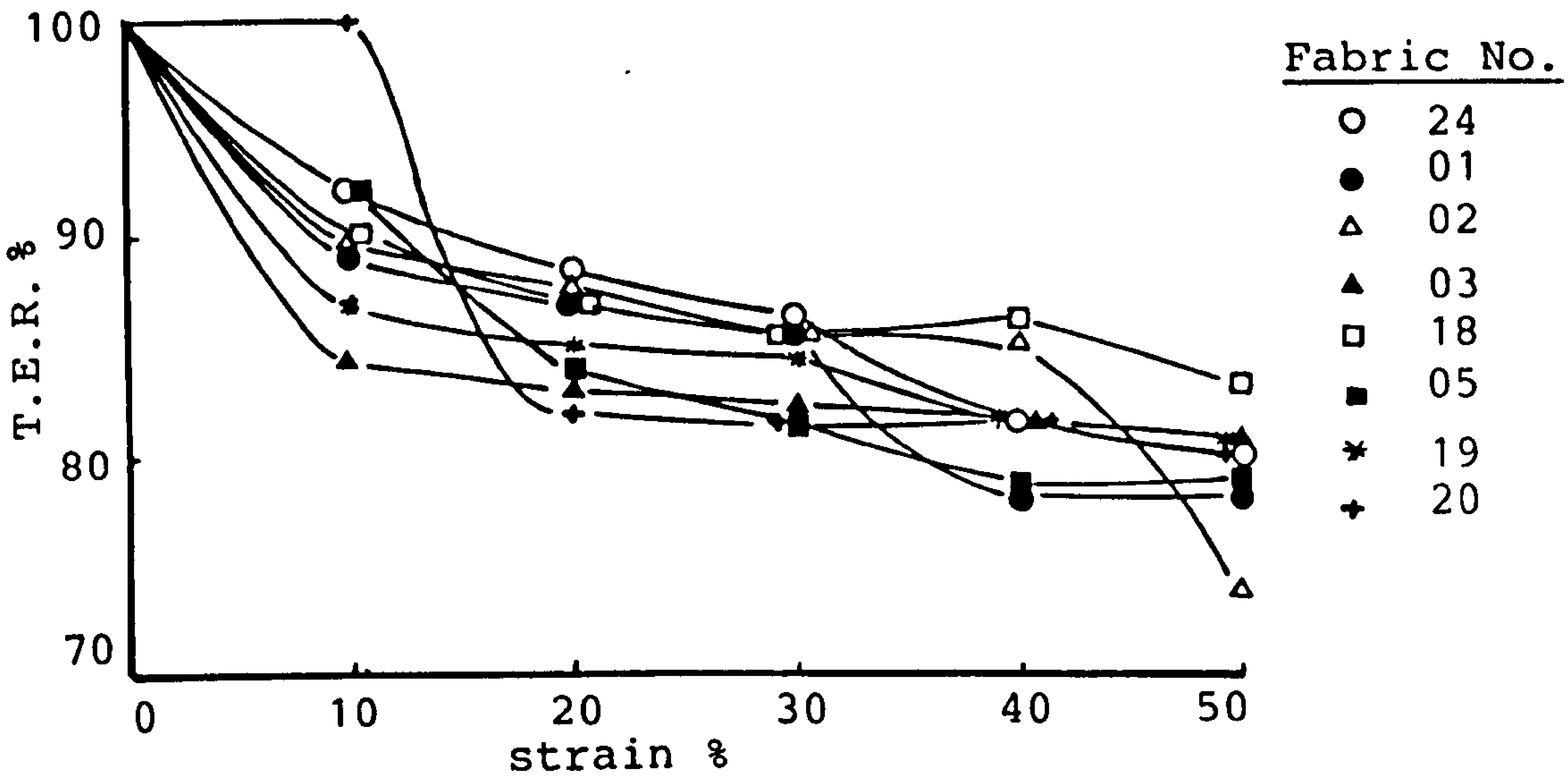


Fig 71 : Plot of T.E.R. against strain for fully-relaxed fabrics, two-ends, fourth cycle, walewise.

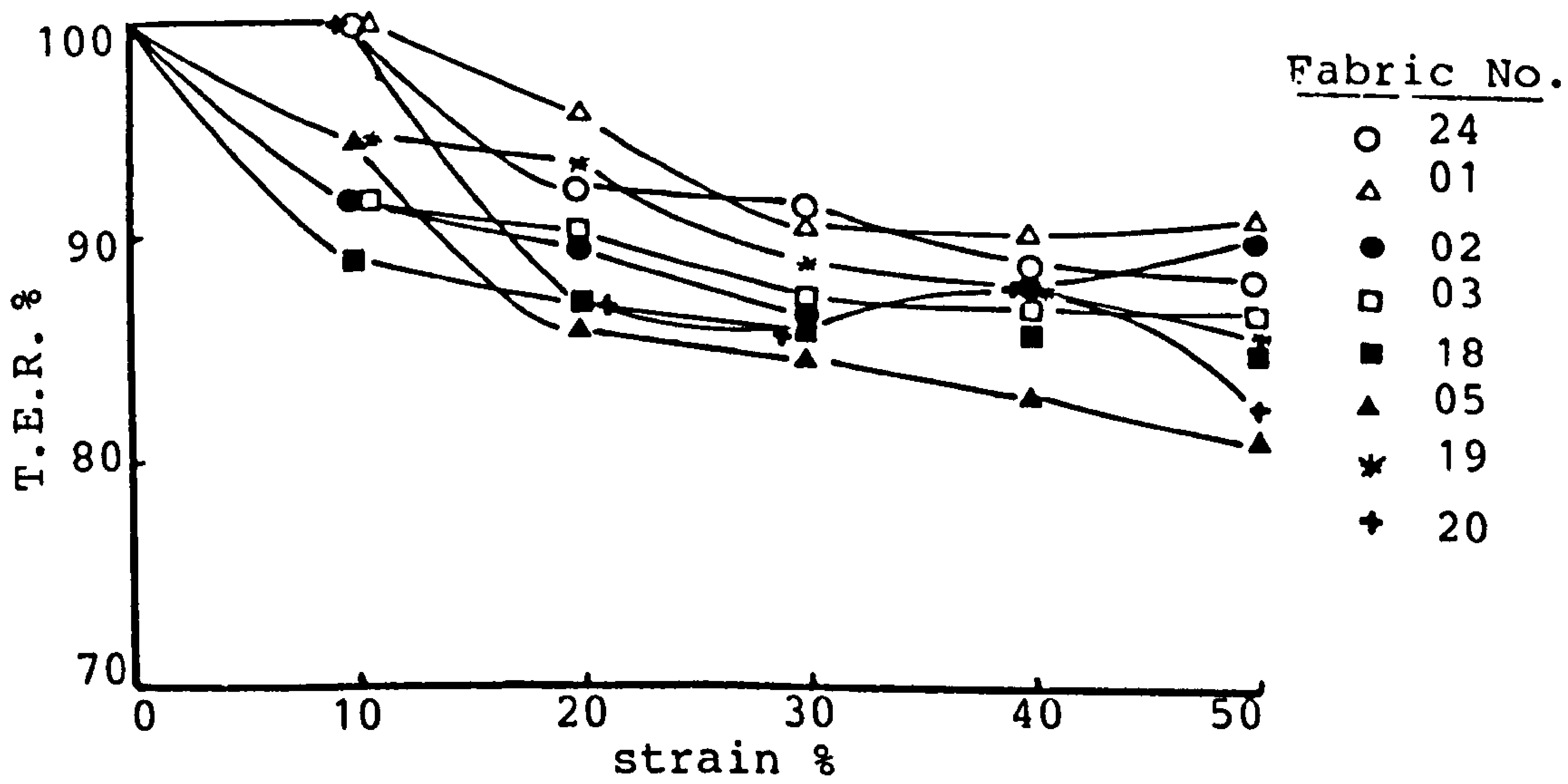


Fig 72 : Plot of T.E.R. against strain for fully-relaxed fabrics, two-ends, fourth cycle, coursewise.

recovery of dry-relaxed fabrics (except for some odd results of individual fabrics such as fabric 3 and 10) and this is in agreement with Marvin's findings. Possibly, the influence of crimp rigidity will be greater at higher strain level, beyond the 50%, as is evident in Figs. 34 and 36 of Ugbolue's work[70], although it has been found that the yarn-to-yarn friction is greater when it is fully-relaxed than when it is dry-relaxed. However, the treatment may reduce the overall frictional restraints in the fabric resulting from the yarn processing and fabric manufacturing and this may also contribute to the improvement of fabric elastic recovery.

In comparison of the Figs. 65-68 for one-end fabrics with the Figs. 69-72 for two-ends fabric in both states of relaxation and for both directions, the total elastic recovery of the latter fabrics is generally lower than the former fabrics again, with the exception of some individual fabrics. It is also lower at high strain level rather than at low strain level. This would give more evidence about the importance of friction as the major factor influencing the fabric elastic recovery.

It would appear that within the limit of the strain 10%-50%, the yarn properties, except the friction and, to a lesser extent the flexural rigidity, have less influence on the elastic recovery than the geometrical and structural properties of the fabric. However the yarn property involvement in determining the elastic recovery of the fabric within this limit may be increased with the increase of fabric tightness.

Fletcher and Roberts [88] in their work on recovery of plain-knitted cotton fabrics found that the elastic recovery is related linearly to cover factor (L/d) and that, the "immediate elastic recovery" initial elastic recovery) is decreased with cover factor while the "delayed elastic recovery" (total recovery) is increased with cover factor apparently for both dry- and fully-relaxed fabrics(laundered and unlaundered fabrics).

Plots of total elastic recovery at three different strain levels, 10%, 30% and 50% against loop length for all fabric groups are shown in Figs. 73-80. As can be seen from these Figs., the form of the relationship between recovery and loop length is rarely, if ever,linear as suggested by Fletcher and Roberts and both the strain level and the treatment have a considerable effect on the form of this relationship for one-end and two-end fabrics both walewise and coursewise. Even in the three cases when there appeared to be linear correlation (Figs. 74,79 and 80) the correlation was generally poor and in all other cases, the total elastic recovery is non -linearly related to the loop length.

When the results of other workers were examined, it is found that the non -linear relationship is a common

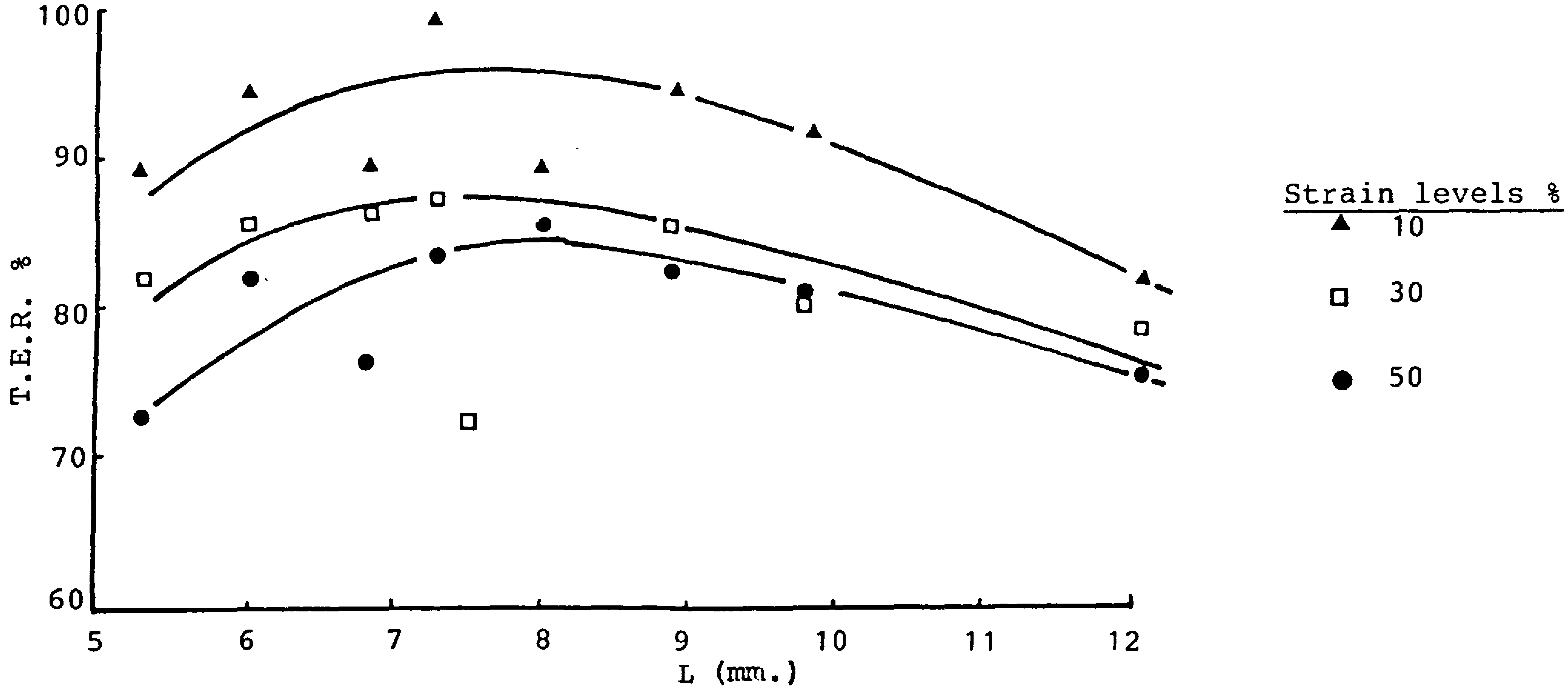


Fig 73 : Plot of T.E.R. against loop length at 10%, 30% and 50% strain levels for one-end dry-relaxed fabrics, fourth cycle, coursewise.

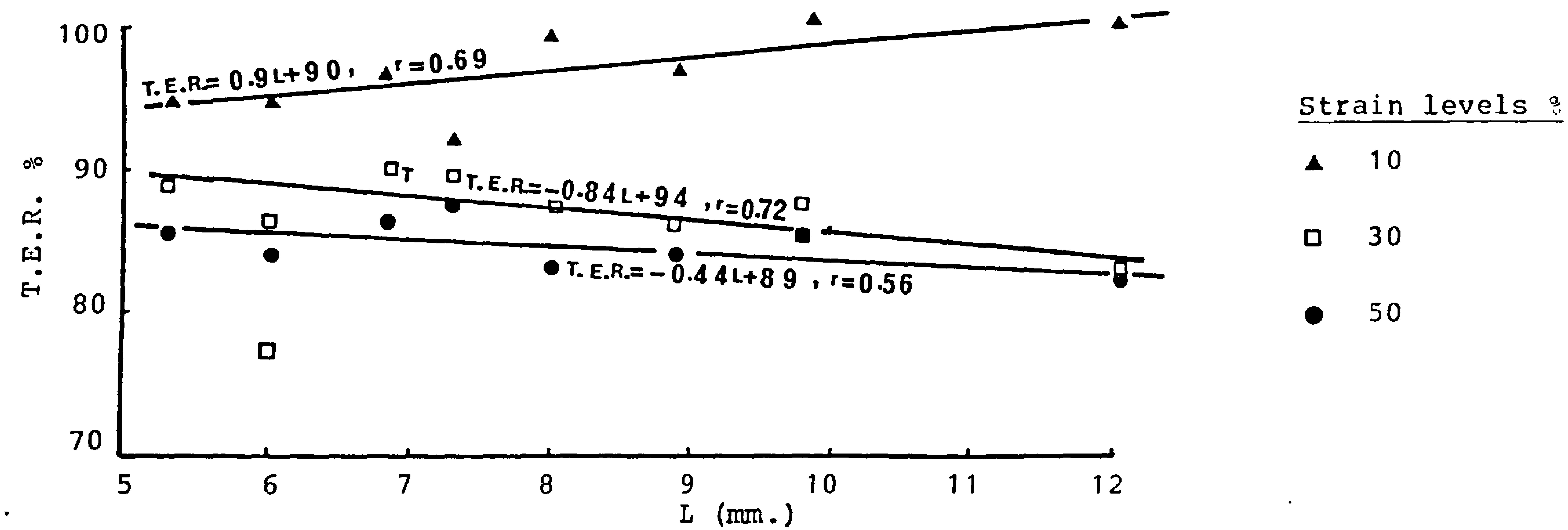


Fig 74: Plot of T.E.R. against loop length at 10%, 30% and 50% strain levelsfor one-end dry-relaxed fabrics, fourth cycle, coursewise.

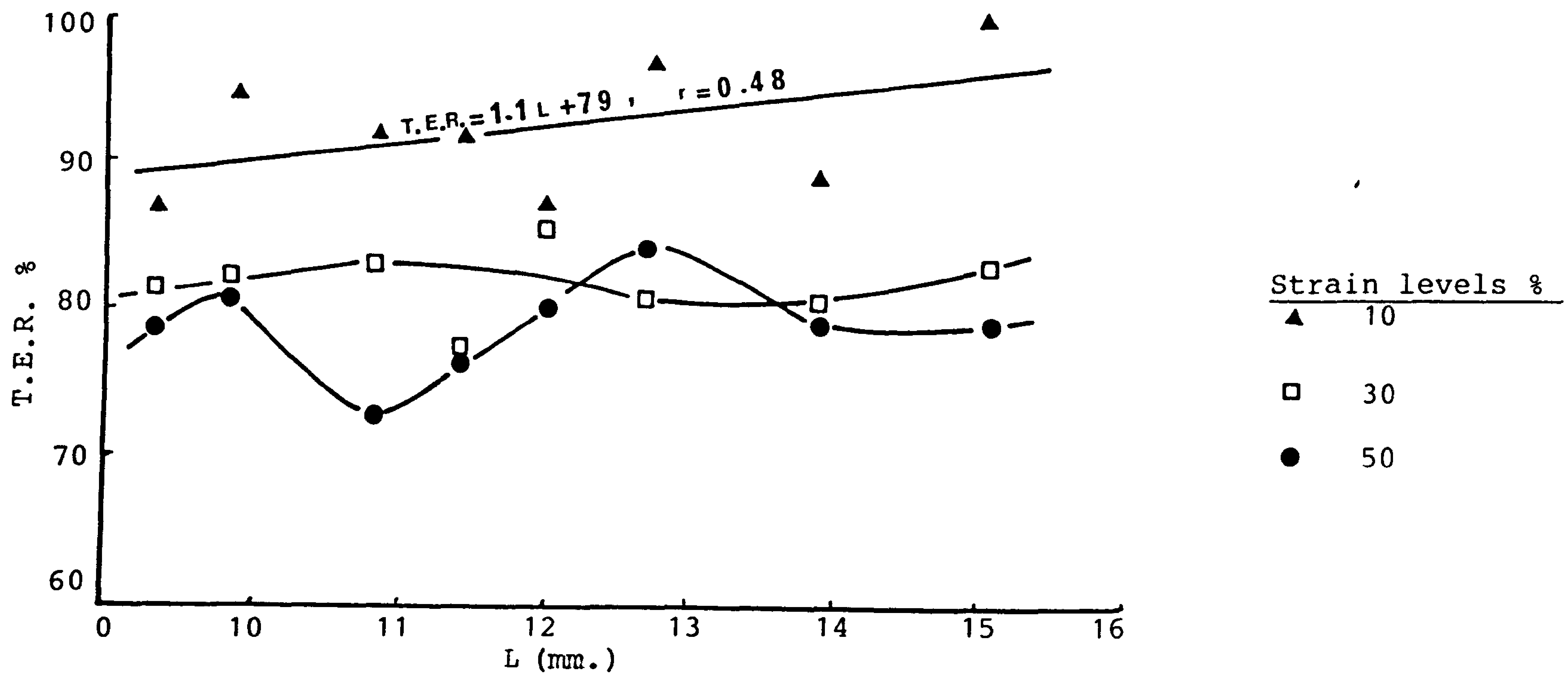


Fig 75: Plot of T.E.R. against loop length at 10%, 30% and 50% strain levels for two-ends dry-relaxed fabrics, fourth cycle, walewise.

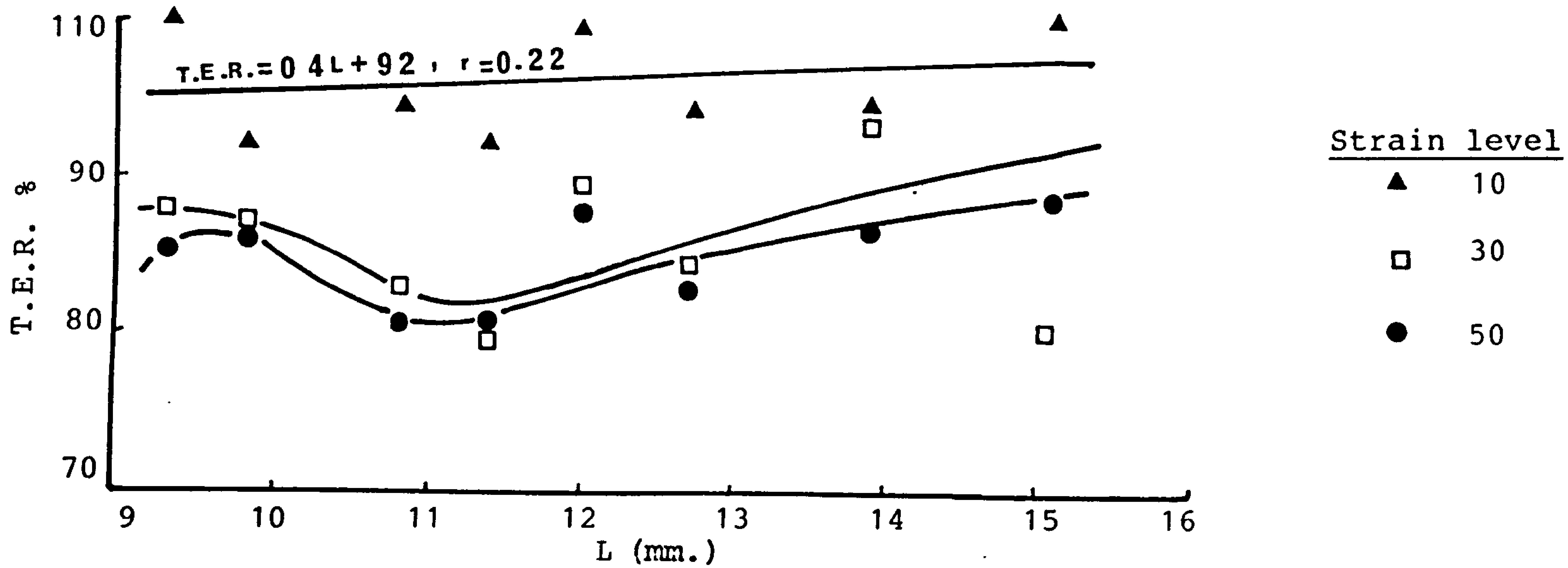


Fig 76 : Plot of T.E.R. against loop length at 10%, 30% and 50% strain levels for two-ends, dry-relaxed fabrics fourth cycle, coursewise.

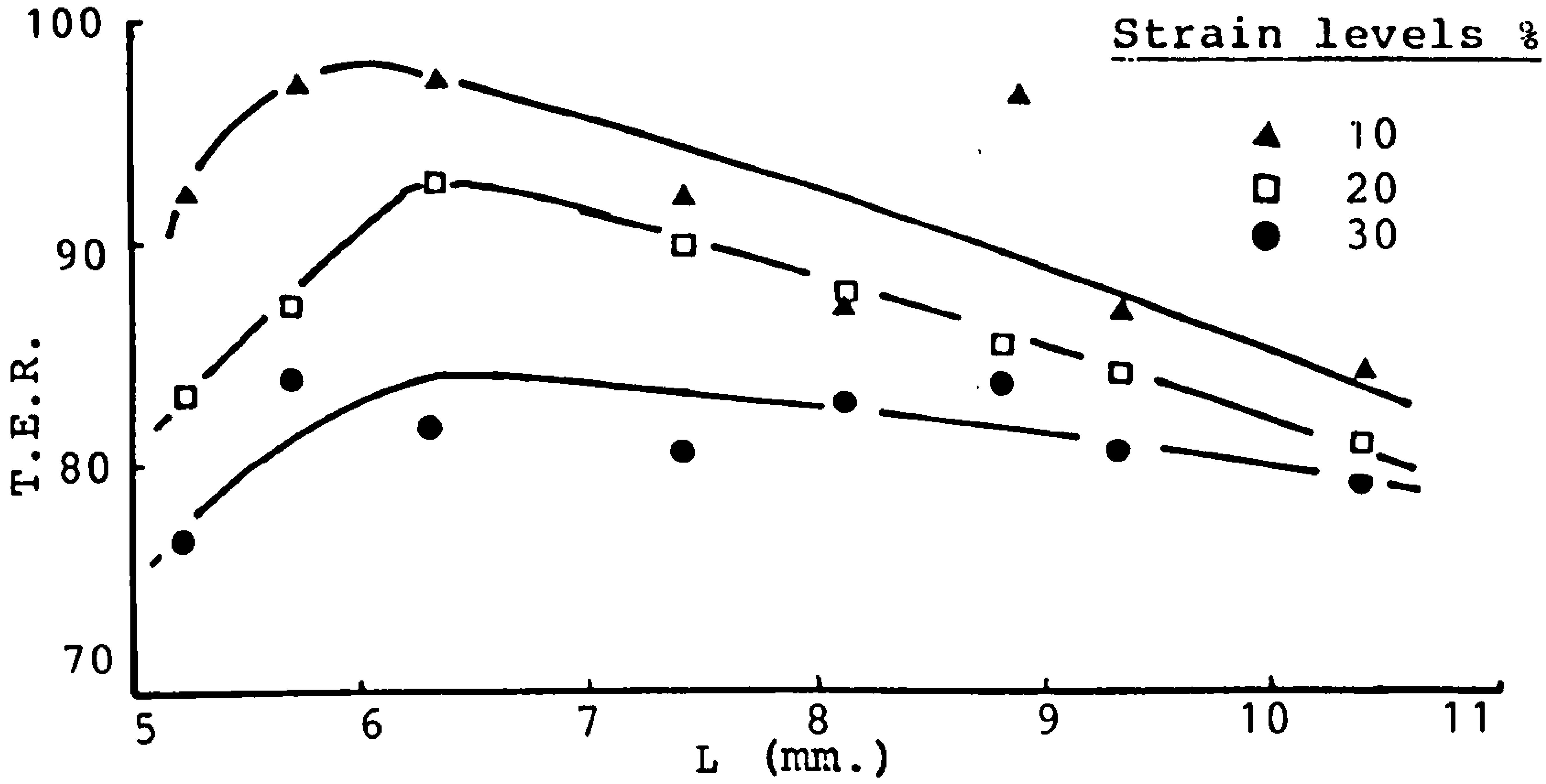


Fig 77 : Plot T.E.R. against loop length at 10%, 30% and 50% strain levels for one-end fully-relaxed fabrics, fourth cycle, walewise.

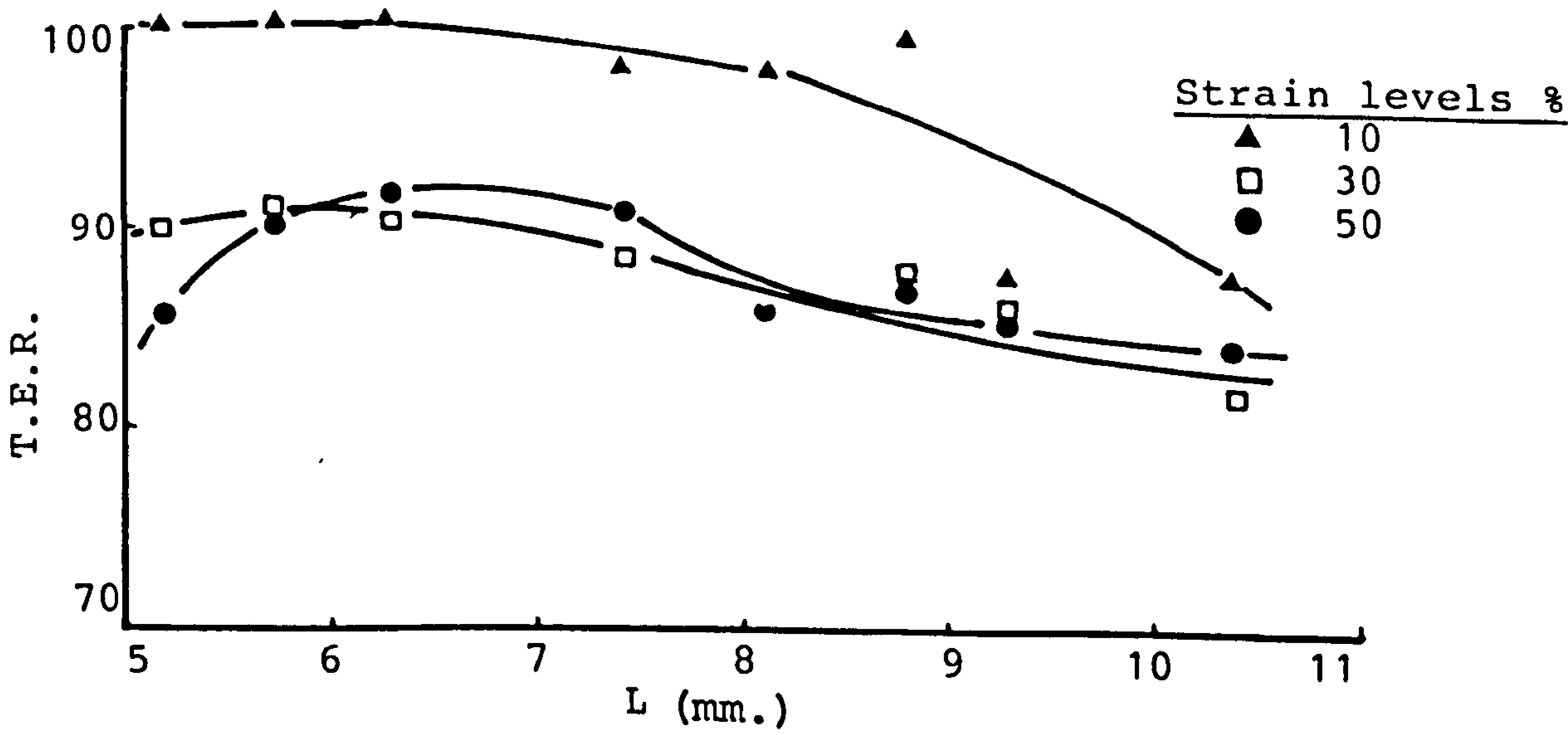


Fig 78 : Plot of T.E.R. against loop length at 10% 30% and 50% strain, levels for one-end fully-relaxed fabrics, fourth cycle, coursewise.

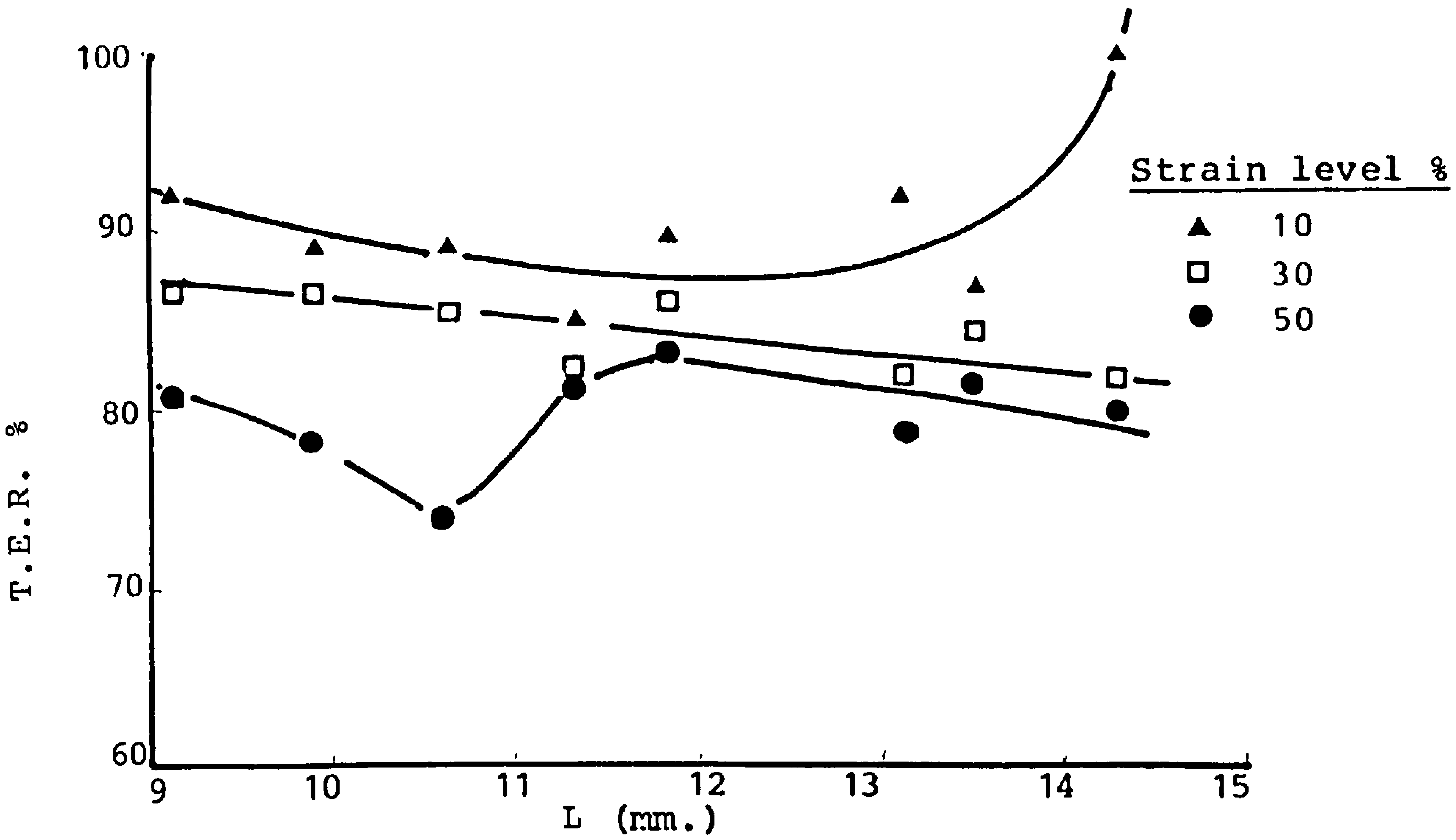


Fig 79: Plot of T.E.R. against loop length at 10%, 30% and 50% strain levels for two-end fully-relaxed fabrics, fourth cycle, walewise.

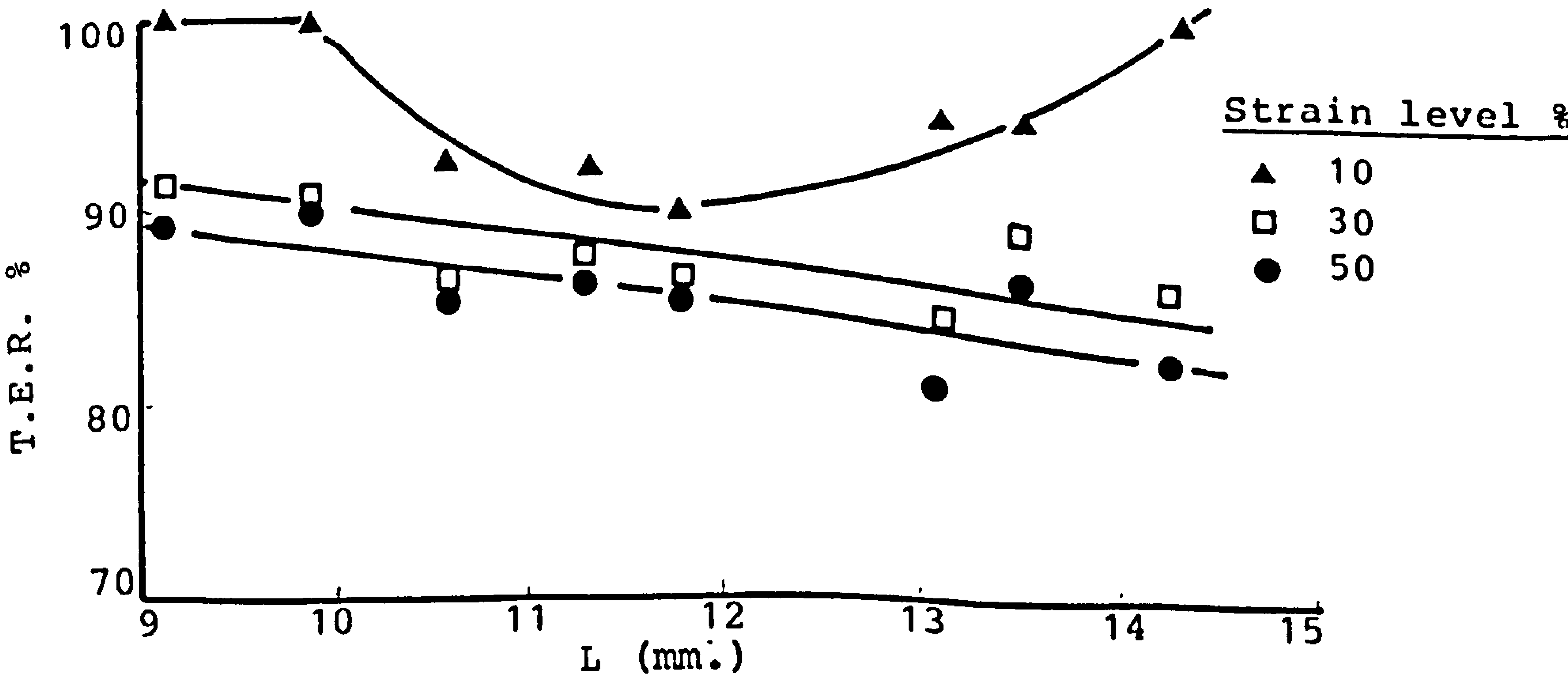


Fig 80: Plot of T.E.R. against loop length at 10%, 30% and 50% strain levels for two end fully-relaxed fabrics, fourth cycle, coursewise.

phenomenon. Some results in Ugbolue's[70] work were extracted and re-arranged and the values of total elastic recovery walewise were plotted against loop length for dry-relaxed fabrics at 25%, 40% and 60% strain level and the graph illustrated this relationship is shown in Fig.81. As can be seen from this Fig., the total elastic recovery at 25% strain level is hardly related to loop length, although it increases somewhat, and at 40% and 60% strain levels this relationship is non -linear. This in fair agreement with the general trends shown in Fig.75 for two-end dry-relaxed fabrics walewise, altuough the strain levels are different.

In the one instance where the relationship between the total elastic recovery and the loop length for dry-relaxed fabrics shows reasonable linear correlation at all strain levels((Fig. 74), at 10% strain level the total elastic recovery increases with the loop length while at 30% and 40% strain levels it somewhat decreases. This may be explained by the fact that the extending forces at low level of strain are small in magnitude and as the fabric becomes slacker it is easier for loops to regain their original shape due to the reduction in frictional forces within the fabric. This is also, as can be seen from Figs. 79 and 80, the case for the two-end, dry-relaxed fabrics in the two directions, but here the correlation coefficient is not significant.

An interesting feature of the relationship between total elastic recovery and loop length is that the lines or the curves at 30% and 50% strain levels are almost parallel and of identical form. One exception is that, in Fig. 79, the recovery at 30% strain is linearly related to the loop length while at 50% the relationship is non-linear.

There is a definite similarity between the curve shapes in Fig. 73 for one-end, dry-relaxed fabrics and the curve shapes in Fig. 77 for one-end fully-relaxed fabrics at all strain levels in the walewise direction. In these two Figs. the total elastic recovery first increases with loop length and then starts to decrease without reaching the values of the fabric having the shortest loop length. At 30% and 50% strain similar trends can be seen in Fig. 78 for one-end fully-relaxed fabric coursewise. This would suggest that in the very tight fabrics the yarn in the loop is highly bent and compressed to the extent that makes the yarn movement very limited and this will result in transferring the deformation, even under the force required to extend the fabric to 10%, from the fabric to the yarn which may lead to a linkage break. Fabrics with average loop length(cover factor 10.8-13.5 for dry-relaxed one-end fabrics, walewise and cover factor 11.7-13.6 for one-end fully-relaxed also walewise) have the best elastic recovery. This may be explained in terms of yarn bending properties.

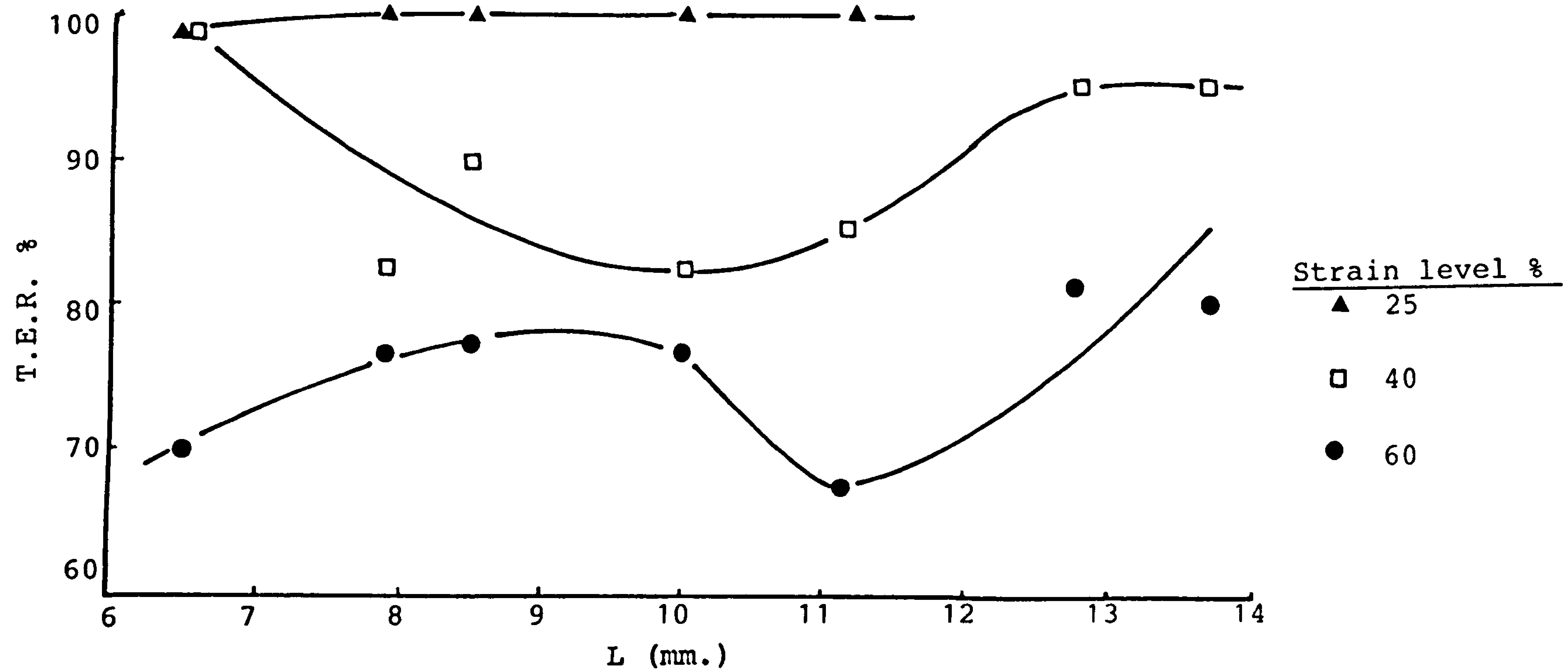


Fig.81: Plot of T.E.R. against loop length at 25%, 40% and 60% strain levels for dry-relaxed fabric fourth cycle, waleswise.

Unlike its poor tensile properties, as it has been shown in Chapter 4, the fully-relaxed yarn has good bending recovery. A slight decrease in loop curvature due to the increase in loop length makes it possible, when the fabric is extended, to impose further bending of yarn and to recover better once the force is removed. As the fabric becomes slacker, the yarn gains greater space for movement so when the force is applied to the fabric, the yarn moves much more easily. After removing the force despite the fact that the frictional force is lower in slack fabric it is able to interrupt the recovery movement because the bending resistance is also smaller.

The mechanism which governs the relationship of total elastic recovery of one-end fabric in both states of relaxation and in both directions, seems to be interrupted by doubling the yarns. The curves in Figs. 75 and in 79 at 50% strain level would suggest that yarn transposition may be the reason behind their non smoothness. However, the overall features of the relationship of total elastic recovery with loop length for two-end fabrics shown in Figs. 75-76, is that in the dry-relaxed state the elastic recovery generally increases with the increase in loop length both walewise and coursewise, while in the fully-relaxed state (Figs. 79 and 80) the recovery generally decreases with the increase of loop length at 30% and 50% levels of strain. It is difficult to identify and to explain the mechanism behind this trend, but doubling the yarn, the bending properties and the effect of the treatment are the major factors responsible for such trend.

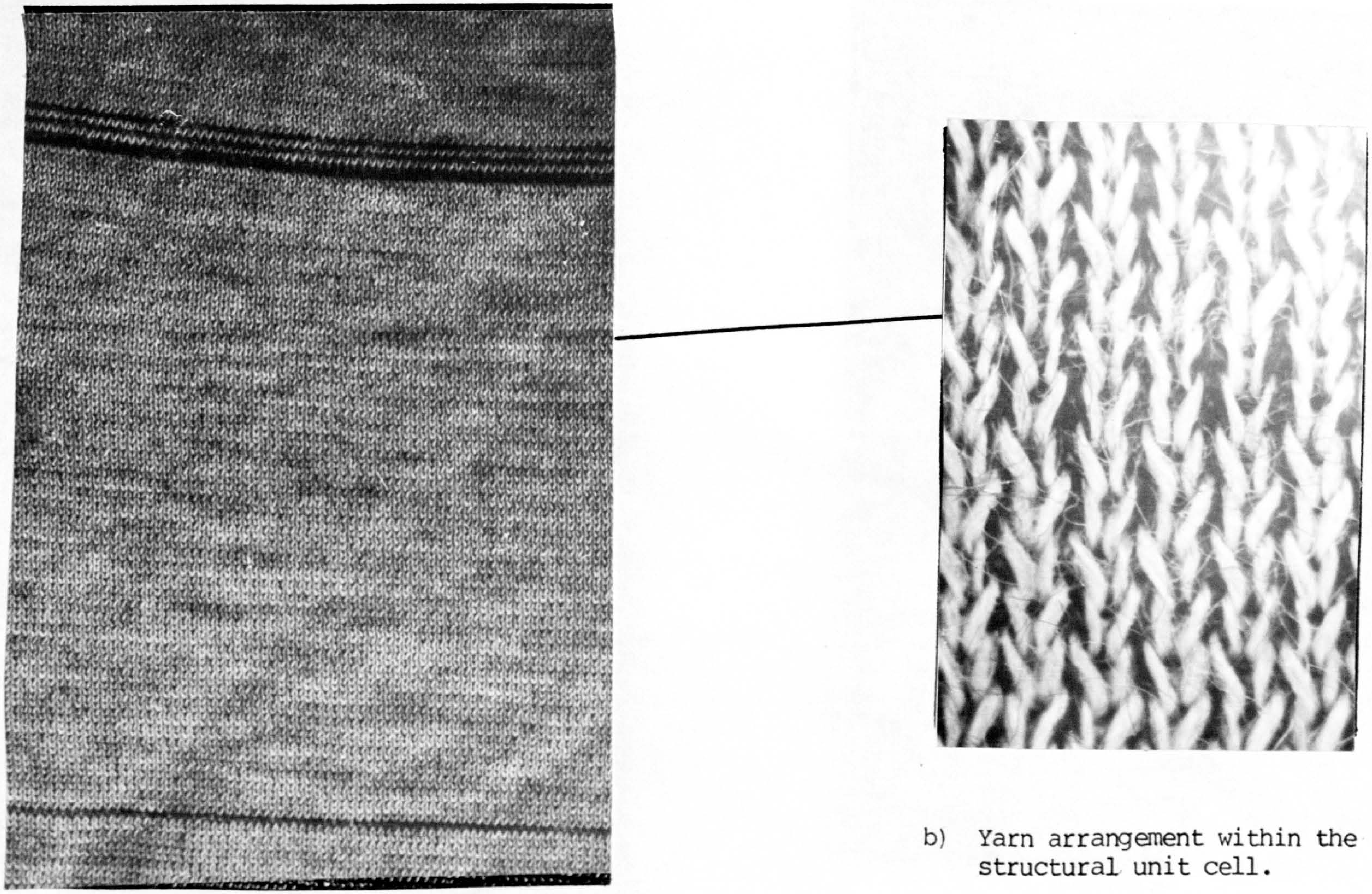
The effect of yarn doubling on elastic recovery as well as on other properties of the fabric will be discussed in the following chapter .

CHAPTER 8

THE EFFECT OF YARN DOUBLING ON THE GEOMETRICAL AND MECHANICAL PROPERTIES OF THE FABRIC

The use of more than one end of yarn in knitting is mainly to improve the regularity and appearance of the fabric. However, such use appeared, as shown previously to affect most properties of the knitted fabrics.

To start with, the two ends of yarn free of twist with linear density equal to a single yarn have different geometrical and probably mechanical properties simply because they are different in structure. This is not the only reason why the fabrics knitted from two ends of yarn have different properties from the fabrics knitted from single yarn. The yarn positions relative to each other within the structural unit cell and within the fabrics knitted from two ends which are determined during the knitting processes as well as during the relaxation treatments are the major reason. It is almost impossible to establish any experimental evidence about the yarn position within the structural unit cell and within the fabric knitted from yarns of the same colour. Therefore two worsted yarns 2/28s (31.6 x 2 tex), slightly thinner than the original yarn used in this work, and of two different colours were used to knit three samples of fabrics with different loop lengths on V-Bed manual machine. One fabric was knitted with loop length, L = 8.2mm., the second fabric with a loop length, L = 9.4 m m. and the third one with a loop length, L = 10.2 m m. The fabric sample with the short loop length, L = 8.2 m m. is shown in Fig. 82a, the sample with medium loop length, L = 9.4m m. is shown in Fig. 83 and the sample with longer loop length, L = 10.2 m m. is shown in Fig. 84. As can be seen from Fig. 82, the face of the fabric sample is almost entirely dominated by the white coloured yarn, and the black coloured yarn is shown only in three courses of the fabric out of 120 courses. In Fig. 83 the black coloured yarn appears in 32 courses out of 116 courses and in Fig. 84 the black coloured yarn appears in 16 courses out of 100 courses. Thus in the first fabric sample which has the shortest loop length 2.5% of the fabric face is black, in the second fabric with medium loop length 28% of the fabric face is black coloured and the third fabric sample with the longest loop length, 16% of the fabric face is black coloured. This indicates that the frequency of black coloured appearance during the knitting in the fabric having medium loop length is greater than both fabric with short loop length and fabric with long loop length. It is difficult to know why and when this alternation of yarn occurred during the knitting process but it is certain that, the systematic appearance of the coloured yarn is related to the amount of yarn in the structural unit cell.



a) Yarn alternation in the fabric knitted with loop length, L = 8.2 m m.

b) Yarn arrangement within the structural unit cell.

Fig 82: (a) Yarn alternation in the fabric knitted with loop length, L = 8.2 m m.
(b) Yarn arrangement within the structural unit cell.

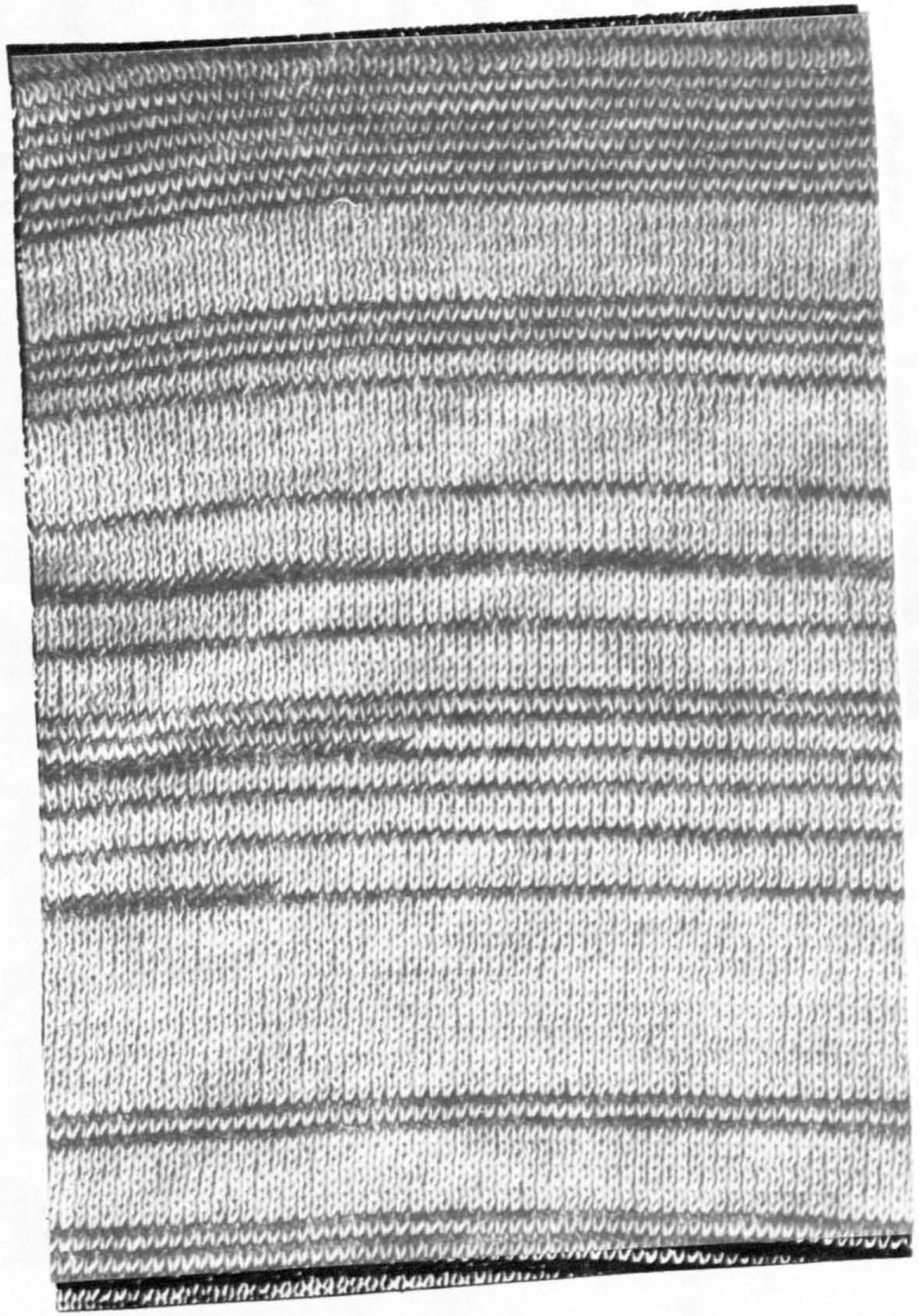


Fig. 83 Yarn alternation in the fabric knitted with loop length, L = 9.4 m m.

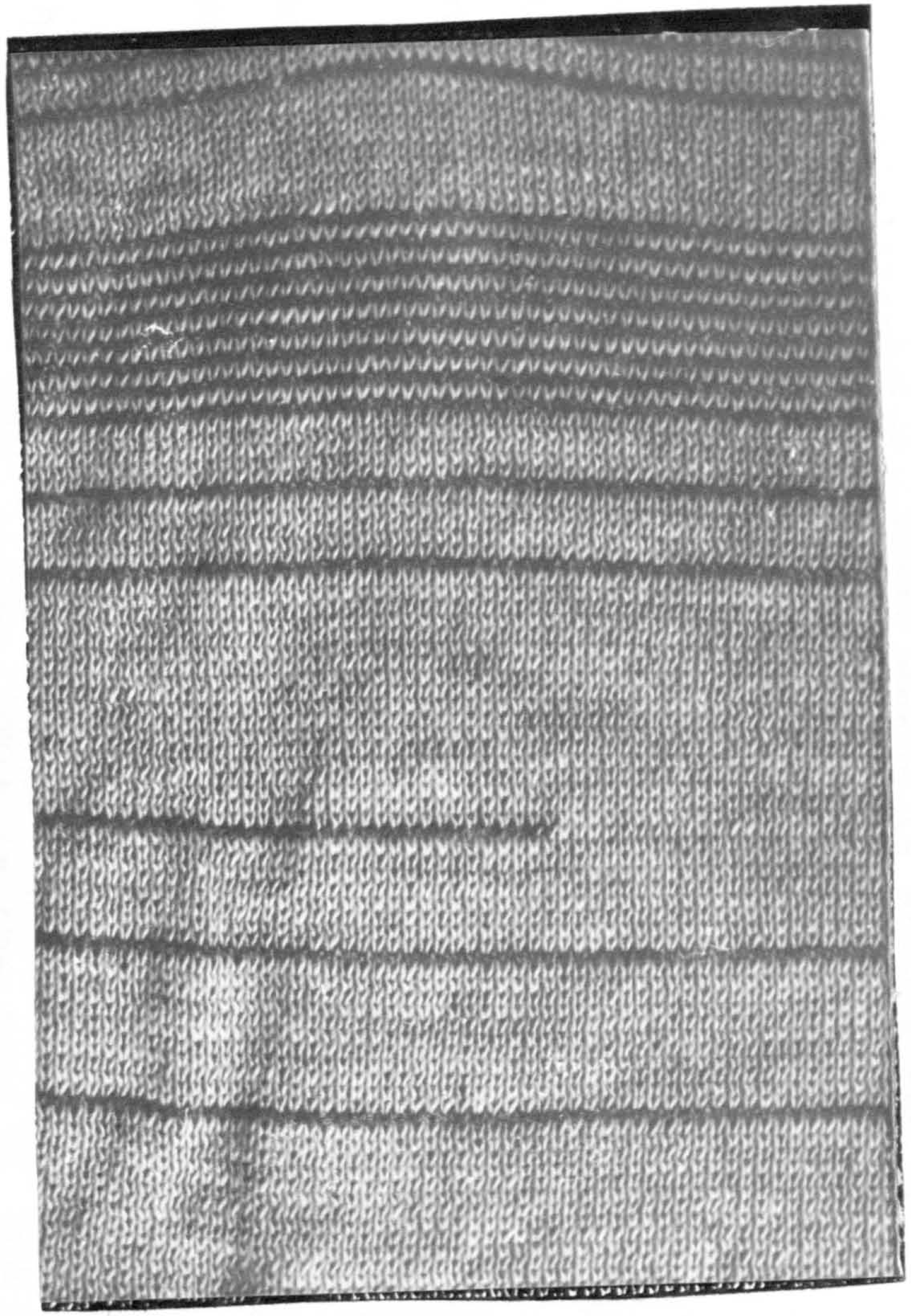


Fig. 84 Yarn alternation in the fabric knitted with loop length, L = 10.2 m m.

The alternation of the yarns in such a way doubtfully has any effect on the fabric properties as far as the two ends used are similar, but it may reflect the yarn positions relative to each other in the repeating structural unit cell which in its turn may affect considerably the geometrical and mechanical properties of the fabric.

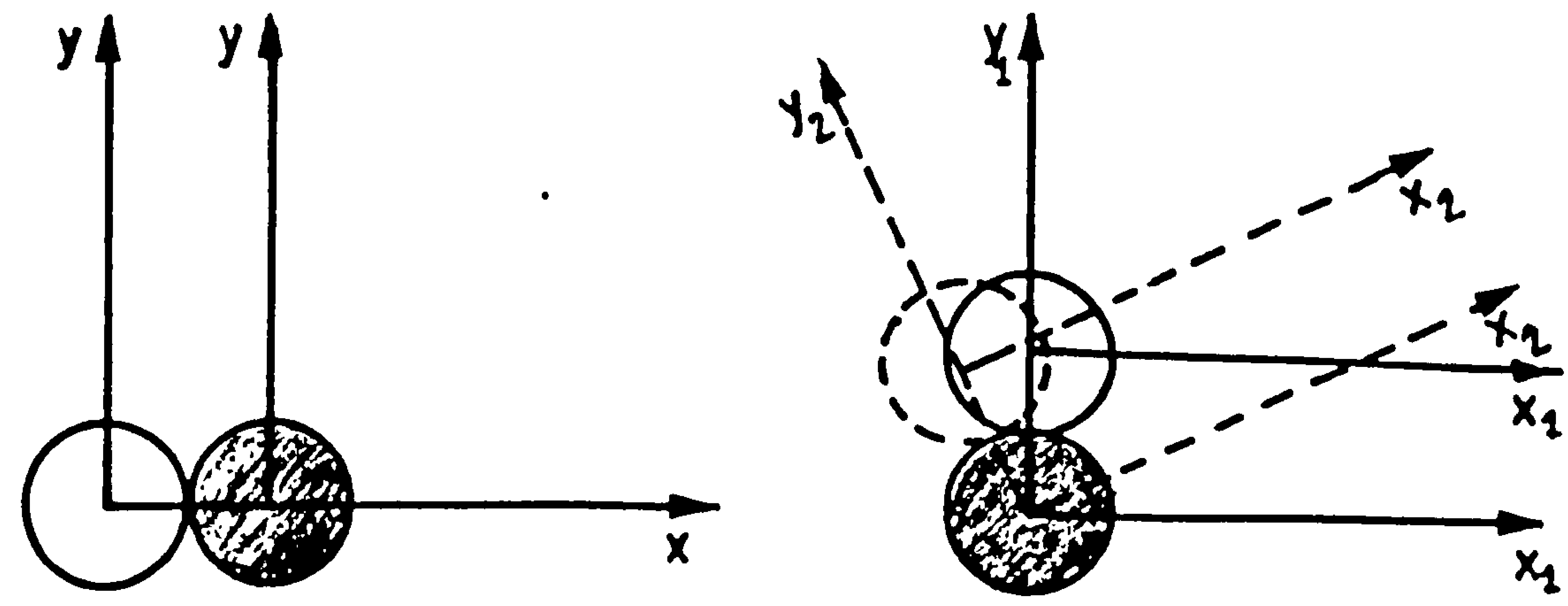
The yarn arrangement within the structural unit cell may take any intermediate form between those shown in Fig.85a and b, where X lies in the fabric plane and Y is normal to it.

Closer microscopic examination of the fabric shows that the yarns arrangement in the structural unit cell takes both forms of Fig. 85, that is the form a, and b, but with various degree of yarn distribution of one form at the expense of another form depending on the loop length. It is found that on the face of each fabric sample there are loops where the yarn arrangement takes the form (a) in their straight parts and in or near the points of interlacing the yarns overlap taking the form (b) and then they either remain in this position in the curved part or return to the former one. In most other loops, the arrangement takes the form (b) which explains the domination of the fabric face by one colour and the former process may be repeated in reverse. This may be seen in Fig. 82 b, where the fabric is magnified five times.

The examination shows that the fabric with the shortest loop length contains 63 out of 192 loops in an area 2.5 x 2.5cm, that is 33% of the total loops are either fully exposed(Fig.85a)or partially exposed(Fig.85b,x_2 y_2). In the fabric with medium loop length, such loops form only 31 out of 154 loops, that is 20% of total and in the fabric with longest loop length 36 loops out of 117, that is 30% of the total of the same fabric area.

It is impossible to know when and why the alternation of the yarn and their arrangement within the structural unit cell occurred, but what is obvious is that they are the reason behind the change in geometrical and mechanical properties of the fabrics.

On the geometrical properties, the effect of yarn doubling is evident when the Fig. 26 is compared with the



a. Yarn arrangement in X-axis. b. Yarn arrangement in Y-axis.

Fig 85: Schematic illustration of the yarn arrangement within the structural unit cell of the two-end knitted fabrics.

Fig. 25 in Chapter 5. The shape factor of two-end fabrics in Fig. 26 is nearly independent from cover factor (K) and on average it is lower than the shape factor of one-end fabrics in Fig. 25 which shows some dependence on cover factor (K). This indicates that loop shape of two-end is slightly different from the loop shape of one-end fabric and that maybe the regularity of two-end fabrics is greater than the regularity of one-end fabrics in both states of relaxation.

When a single yarn of double the diameter is used, the thickness of the fabric which is knitted from that yarn is supposed to be doubled, but it seems this is not the case with the fabric knitted from two-ends mainly because the yarn arrangement within the structural unit cell and secondly due to the change in the compressive and bending properties of the yarn resulting from doubling. This is evident by comparing the results in Table 16 for the two-end fabrics with the result in Table 15 for one-end fabricsin Chapter 5. These results show that the thickness of two-end fabrics never reached twice the thickness of one-end fabrics.

In a similar manner, the results of fabric air permeability were also affected (compare results in Table 17 with the results in Table 18 in Chapter 8).

The abrasion properties are much more greatly affected by the yarn arrangement within the structural unit cell just discussed. While the percentage weight loss of the fabrics made from single yarn increases linearly with the loop length, the relationship between the percentage weight loss with loop length of the fabric made from two ends is non-linear, the percentage weight loss first increases then it decreases and starts to increase again. This may be explained by the mechanism of yarn arrangement within the structural unit cell of the fabrics knitted with different loop length, i.e. the area of contact between the abradant and the fabrics having short loop length is greater than the area of contact between the abradant and the fabrics having medium loop length. This area of contact begins to increase with a further increase in loop length. The relationship between the % weight loss and the loop length shown in Fig. 42 for dry-relaxed fabrics and 43 for fully-relaxed fabricsin Chapter 5 are clearly reflecting the pattern of yarn arrangement within the structural unit cell.

The effect of yarn arrangement on the fabric tensile properties is evident from the results in Tables 21-23 in Chapter 6. First, the tensile strength per single thread in two-end fabrics is greater than the strength per thread in one-end fabrics. This is due to an increase in inter-yarn friction resulting from doubling, and may be related to the fact that the break of a single thread does not lead immediately to fabric rupture and this was observed during the tensile tests. Second, the extension of the two-end fabrics is also greater than the extension of the one-end fabrics which is probably due to the yarn slipping and re-arrangement, and to a greater compressibility of two-end fabrics than one-end fabrics.

The most obvious effect of yarn doubling is on the calculated values of fabric strength and extension. As stated before, the two ends of yarn were considered as a single yarn with a circular cross section double in diameter, while they are in fact occupying the areas shown in Fig. 85 and in addition to that, sudden displacement in the yarn from the position shown in Fig. 85b within the structural unit cell may occur particularly at high extension. Thus, the theoretical values of both the strength and the extension of the fabric appeared to be far from close agreement with the experimental values.

The results show that the doubling and the arrangement of the yarn within the structural unit cell affects the above properties more than the elastic properties of the fabric. This is evident form Figs. 65-72, where the total elastic recovery of a selected fabric made from one end of yarn coursewise and walewise is only marginally higher than the total elastic recovery of a selected fabric made from two ends. However, the effect of yarn doubling is greater when the total elastic recovery is plotted against loop length. While the pattern of the curves of one-end fabric are relatively easy to explain, the curves of two-end fabric are more complex and in the walewise direction the curves of each strain level are considerably different from each other (see Fig. 75

and 79) and this can only be related to yarn arrangements in the two-end fabrics. It is worth noting that some of the curves of these fabrics (see Figs. 75 and 76 at strain levels 30% and 50% and Fig. 79 at strain level 50%) do reflect the pattern of yarn arrangement in the structural unit cell of fabric having short, medium and long loop length.

The effect of yarn doubling on the elastic recovery properties of the knitted fabrics may be disscussed by further examination of Fig. 86. Fig. 86a, b, and c shows the same area of the fabric with loop length 10.2 mm when it is in normal state, when it is subjected to the force stretching it walewise up to 50% and when force is removed.

Fig. 86 gives evidence that certain yarn displacement occurs during stretching. This is shown by the domination of one colour of yarn at the expense of the other colour. In Fig. 86b, the row of black yarn becomes blacker and the rows of white yarn become whiter in comparison to the same rows in Fig. 86a and c. This means that the yarns of one colour cover up the yarns of the other colour during stretching due to changes in yarns position relative to each other i.e. the yarns in almost all the structural unit cells of the fabric take the positions shown in Fig. 85b.

The examination of the same structural unit cell inside the square 1 and 2 of the Fig. 86a, b and c provides more detail of the effect of yarn doubling because the position of the yarns relative to each other in the cells shown inside each of these squares is clearer than the others, i.e. the yarns in the largest part of the cell take the position shown in Fig. 85a which was discussed earlier in this Chapter.

Comparing the yarn positions in the structural unit cell inside the square 1 in Fig. 86a with that inside the square 1 in Fig. 86b, the white yarn increased its covering up of the black one. Comparing the same cell inside the square 1 in Fig. 86a with that inside the square 1 in Fig. 86c, a slight difference in the yarns position does exist, and this more clearly evident by comparing the cell inside the square 2 in Fig. 86a with the same cell in Fig. 86b and Fig. 86c. This suggests that the yarns which were displaced during the stretching do not return to their original position which may affect the elastic performance of the fabric and provide an experimental explanation about the reason (in addition to the increase in friction) of the two-end fabrics having lower elastic recovery than the one-end fabrics. A sudden yarn displacement befor the fabric rupture may also provide an explanation about the sharp departure from linear part of the load-extension curves (walewise) of the two-end fabrics shown in Fig.51 and 52.

There were difficulties involved in obtaining satisfactory pictures of the fabrics extended coursewise, but it is felt that similar effect is expected.

a. Fabric in normal state

b. Fabric extended walewise up to 50%

c. Fabric after removing the force

Fig.86: Fabric with loop length 10.2 mm, befor applying the force (a), extended up to 50% (b) and after removing the force (c).

CHAPTER 9

CONCLUSION

Although some points of conclusion have been drawn in some sections throughout the present work the most important conclusions which may cover the whole work are as follows:

1. The results of the dimensional and geometrical properties obtained by using the H.A.T.R.A. method show that most aspects of the dimensional and geometrical properties of one-end weft-knitted fabrics are in general agreement with the results of other workers in this field. However the results also show that the dimensional and geometrical properties are not only dependent on loop length (L) but they may be critically affected by the yarn diameter (d) and more precisely by the number of ends. The numerical value of K_c and K_w parameters and their relationship with the loop length for one-end fabrics are different from those for two-end fabrics in both states of relaxation. This was clearly described by the regression equations, where K_c value of two-ends fabrics is greater than those of one-end while K_w-values are lower for dry-relaxed and almost the same for fully-relaxed.

2. Fabric thickness which has been the subject of the most conflicting points of views, suggesting an inadequate experimental work, appeared to be affected mainly by two factors, the loop length and the type or

gauge of the machine used. The parameter $t/_L$ as fabric thickness indicator increases linearly with an increase in cover factor K for all fabrics. The absolute value of fabric thickness t for each fabric group knitted in a machine of different type or gauge when related to the loop length L behaved differently according to machine type or gauge and to the treatment.

3. Although the fabric air permeability may be correlated with either the cover factor K or the fabric thickness t, the fabric volume factor $V_F = 4 \dfrac{Ws \times Cs \times t}{\pi \times d^2 \times L}$ is obviously the major structural parameter for the air permeability of the knitted fabrics to correlate with. The results show that fabric air permeability correlated with V_F better when the fabrics are fully-relaxed than when they are dry-relaxed for both one- and two-end fabrics.

4. Abrasion resistance of the fabrics made from one end correlated differently from abrasion resistance of the fabrics made from two ends. In the case of one-end fabrics the relationship between the % weight loss and loop length is fairly linear, the % weight loss increases as the loop length increases. In the case of two-end fabrics this relationship is non-linear, the % weight loss first increases then decreases and starts to increase with an increase of loop length in the manner corresponding to yarn arrangement within the structural unit cell. Thus

the two-end fabrics with the medium range of K(10.2-11.3) have better resistance than the fabrics with low range of K.

A pronounced increase in % weight loss with an increase of loop length as the treatment progresses is observed. Also, for both dry- and fully-relaxed fabrics made from one and two ends, the % weight loss increases linearly with an increase in cycles of abrasion.

Correlation of % weight loss with other parameters e.g. with inverse cover $C^* = \frac{1}{S \times d \times L}$ is generally poor and does not contribute to understanding the abrasion properties of the knitted fabrics particularly those made from two ends.

5. Plots of fabric breaking load against strain % give a good indication about the importance of the intra-fabric friction and jamming effect in both principal directions. They also confirm a statement that the strong yarn does not necessarily produce strong fabrics since the fully-relaxed yarn is much weaker than the dry-relaxed one, but the fabric made from fully-relaxed yarn is stronger than the fabric made from dry-relaxed yarn.

6. Although factors such as friction, flexural rigidity and fabric binding were not introduced into the theoretical calculations, the theoretical breaking load and extension were in fair agreement with the observed breaking load and extension. The degree of agreement between the theoretical and observed values walewise

and coursewise of each fabric set depends on the factors above.

7. Plots of load against strain % in fourth cycle for selected one-end fabrics show that for each fabric the load increases rapidly as the strain % increases, but the amount of increase walewise is much higher than coursewise. They also show that at high strain level the load increases more rapidly as the fabric becomes tighter i.e. as the loop length of the fabric becomes shorter.

8. The total elastic recovery T.E.R. for the fourth cycle decreases as the strain level increases indicating that the permanent deformation resulting from energy loss in the fabric increases not only as the strain is repeated but also as the strain becomes higher.

The amount of the decrease in T.E.R. for both one-end and two-end fabrics walewise is marginally higher than coursewise and this indicates that jamming effect is more pronounced walewise.

In both sets, one- and two-end fabrics the effect of crimp rigidity resulting from the treatment is not particularly significant.

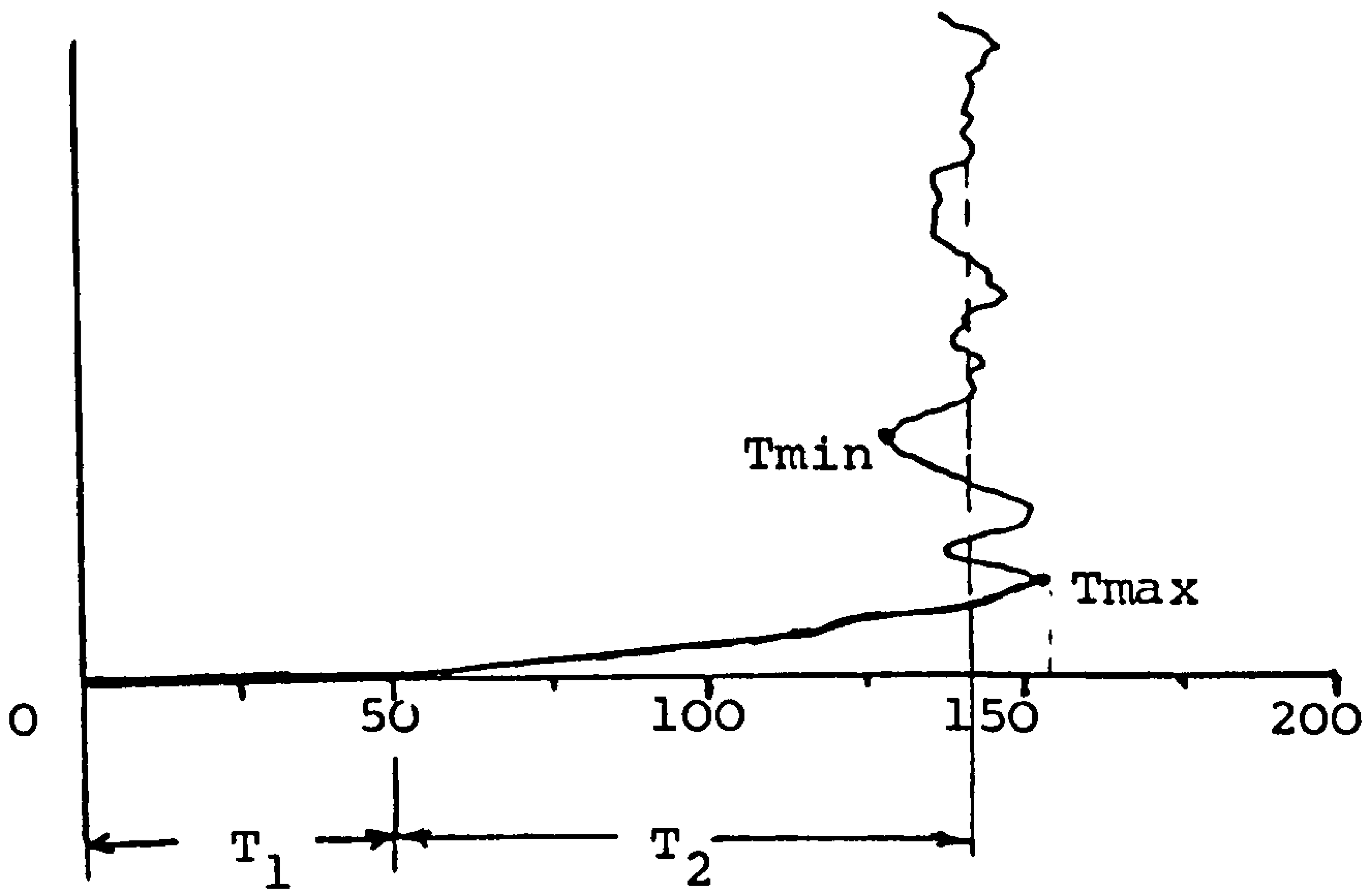
9. The fabric total elastic recovery does not always relate to the loop length linearly. It appears that the linearity of this relationship depends on the strain level, the treatment, the direction of recovery and the

number of ends used in the fabrics. The departure from linearity for example is greater walewise than coursewise and the linear relationship holds better for dry-relaxed fabric than for fully-relaxed fabrics. For the fully-relaxed fabrics, the linear relationship is better in one-end fabrics than in two-end ones. The linear relationship at low level (10%) for one-end and two-end fabrics shows an increase in T.E.R. with an increase in loop length while at higher strain levels (30% and 50%) it shows a decrease with an increase of loop length.

10. Most properties of the fabrics knitted from two ends are clearly affected by the yarn arrangement within the structural unit cell. While the frequency of courses is moderately greater than the frequency of wales for one-end fabrics, it is comparatively much greater for two-end fabrics. A clear effect of yarn arrangement pattern within the structural unit cell on the abrasion properties of the two-end fabrics is evident, the % weight loss follows the pattern of yarn arrangement. It is also clear, but to a lesser degree, that both the elastic and tensile properties of the two-end fabrics are affected by this arrangement.

APPENDIX I

The values of T_1 and T_2 were determined from the typical diagram below which was obtained from the Instron Tensile Machine as follow.



$T_2 > T_1$

$$T_2 = \frac{Tmax + Tmin}{2}$$

APPENDIX II

Nominal yarn diameter:

Yarn count $N = \frac{L}{m}$ (m/g)

where, L - length of the yarn in (m)

m - mass in (g)

$$m = \frac{v}{V}$$

where, v - volume of the cylinder

V - Nominal specific volume of the yarns

Then, $m = \frac{\pi d^2}{4V}$

$$N = \frac{4V}{\pi d^2}$$

a) $d = \frac{2\sqrt{V}}{\sqrt{N\ \pi}} = 1.130\ \frac{\sqrt{V}}{\sqrt{N}} = (\text{m m.})$

b) $d = \frac{2\sqrt{V\ \text{tex}}}{\sqrt{\pi\,1000}} = 0.0357\ \sqrt{V \times \text{tex}} = (\text{m m.})$

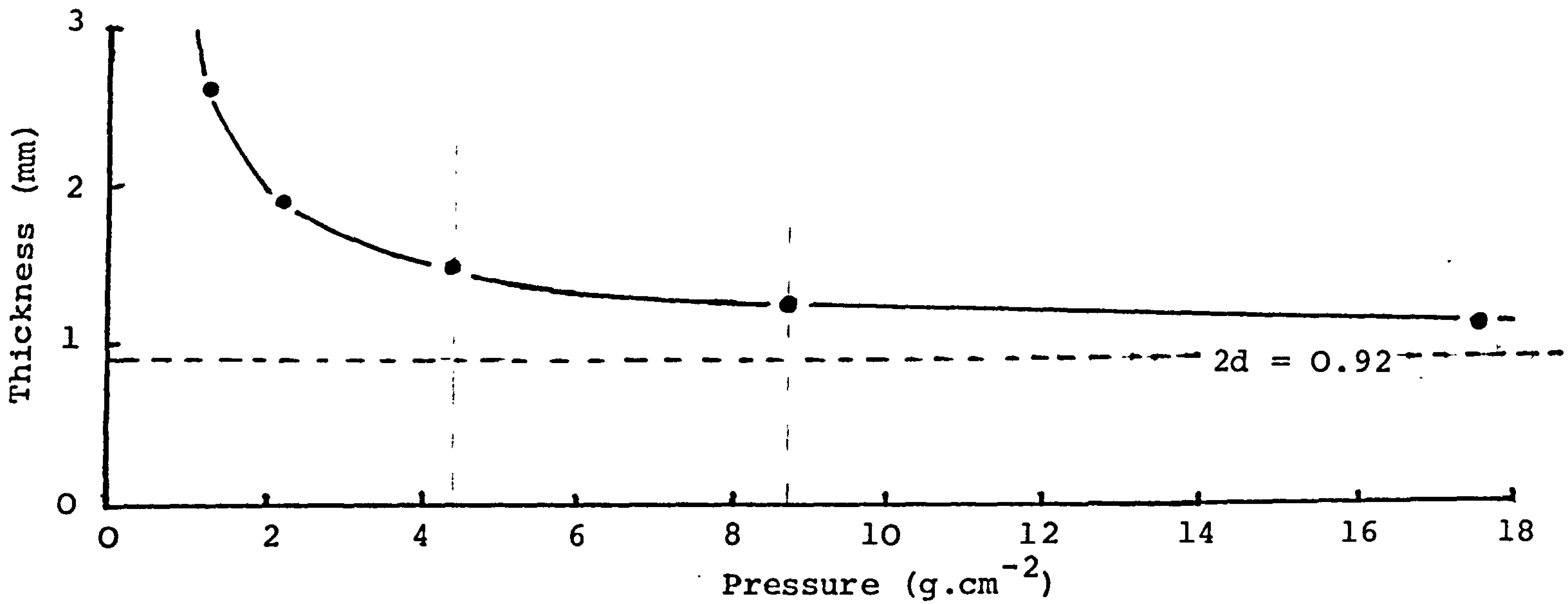
APPENDIX III

Statistical evaluation of ten readings of courses per 5cm length of each one-and two-end fabrics in both dry-and fully-relaxed states.

One-end fabrics									
Dry-relaxed					Fully-relaxed				
Fabric No.	No. of courses	S.D. σ	C.V. %	S.E. $\sigma/\sqrt{n}$	Fabric No.	No. of courses	S.D. σ	C.V. %	S.E. $\sigma/\sqrt{n}$
21	50.5	0.52	5.2	0.165	21	54.1	0.31	3.1	0.099
22	44.4	0.51	5.1	0.162	22	49.3	0.67	6.7	0.213
23	44.0	0.81	8.1	0.258	23	48.2	0.78	7.8	0.248
11	41.3	0.48	4.8	0.153	11	45.9	0.73	7.3	0.232
12	35.5	0.85	8.5	0.271	6	41.5	0.84	8.4	0.268
6	32.7	0.67	6.7	0.213	12	40.3	0.48	4.8	0.153
7	32.1	0.31	3.1	0.099	7	37.4	0.69	6.9	0.220
13	30.4	0.51	5.1	0.162	13	35.3	0.67	6.7	0.213
8	26.4	0.51	5.1	0.162	8	32.4	0.51	5.1	0.162
14	26.1	0.73	7.3	0.232	14	32.6	0.51	5.1	0.162
15	24.9	0.57	5.7	0.182	15	31.6	0.51	5.1	0.162
9	24.8	0.42	4.2	0.133	9	30.0	0.67	6.7	0.213
10	20.8	0.78	7.8	0.248	10	26.7	0.82	8.2	0.261
Two-end fabrics									
1	26.3	0.67	6.7	0.213	24	30.2	0.42	4.2	0.133
24	26.4	0.51	5.1	0.162	25	29.0	0.47	4.7	0.150
25	23.9	0.73	7.3	0.232	1	28.1	0.73	7.3	0.232
2	23.0	0.67	6.7	0.213	26	27.9	0.56	5.6	0.178
26	21.7	0.67	6.7	0.213	2	25.9	0.42	4.2	0.133
3	21.2	0.42	4.2	0.133	27	26.0	0.00	-	-
27	19.4	0.51	5.1	0.162	3	23.7	0.48	4.8	0.153
28	17.8	0.42	4.2	0.133	28	24.0	0.00	-	-
18	18.1	0.73	7.3	0.232	18	24.0	0.94	9.4	0.299
4	18.3	0.48	4.8	0.153	4	22.3	0.48	4.8	0.153
5	15.9	0.56	5.6	0.178	5	20.8	0.42	4.2	0.133
19	16.5	0.52	5.2	0.165	19	21.2	0.48	4.8	0.153
20	15.8	0.42	4.2	0.133	20	20.3	0.48	4.8	0.153

APPENDIX IV

Typical curve of the relationship between fabric thickness and pressure for fully-relaxed one-end fabric No.8 .



APPENDIX V

Fabric thickness measured by Shirley Thickness Tester and Instron Tensile Testing Machine under pressure 1.3 $g.cm^{-2}$

Fabric made from:	Fabric No.	Fabric thickness (mm) measured by:	
		Shirley Tester	Instron
Two-end*	17	3.7	3.3
One-end	8	2.6	2.8

* After completing all tests and measurements, specimens from all fabrics were not available for additional tests to determine fabric thickness by using the Instron Tensile Testing Machine. Thus a fabric specimen which was subjected to elastic tests was used to measure the thickness of two-end fabric 17. The result is not very close to that obtained by using Shirley Tester perhaps because the fabric specimen may be flatened after the elastic tests. By contrast, because such case did not exist, the results of one-end fabric 8 are very close.

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