Summary of Thesis. Elastic Moduli and the Bending Properties of Textile Materials.

Values for the tensile, bending, and compressive moduli of nylon 6, nylon 66, polyethylene, polypropylene, Saran and Terylene fibres have been obtained on an Instron Tensile Testing Instrument, Model TM. It has been shown that the moduli are similar in value for a specific materia The effect of variation in a number of experimental conditi has been investigated and found to be similar for each modulus of a material. In particular the effects of temperature and humidity on the bending modulus have been checked by experiment using a Cambridge Extensometer mounte over a Gallenkemp Conditioning Oven. The order of change of value even within the limits of general atmospheric fluctuations has been shown to be considerable, and the modulus may decrease until at high temperatures and humidit the value may be less than 25 per cent of the value at low temperatures and humidities. The relative decrease depend on whether the material is thermoplastic and hydrophilic or hydrophobic, and the pattern of change was closely akin to the results expected in tensile values under similar condit

The effects of time, history, type of fibre, and test method, have been considered in relation to the present

experiments and the work of other authors. The use of strain moduli to forecast the resistance of a fibre to bending where strains are outwith the immediate elastic region has been suggested. It has been shown that reason agreement existed between tensile and bending strain moduli up to a 5% level of strain, and the use of such strain mod to indicate stiffness has been discussed with additional reference to final, or breaking strain, stiffness.

Experience of bending test methods has shown the nee for an instrument capable of measuring accurately loads of the order of 1×10^{-4} grammes, and deflections of 1×10^{-4} centimetres, so that fine fibres may be studied.

If tensile tests were used then the sensitivity required would be 1×10^{-3} grammes, and 1×10^{-3} centimetre with reasonable scale deflection. The latter is just with the capability of the present instrument but 5 grammes load cell is required, compared with the present limit of 50 grammes, retaining the present scale magnification.

The problems of measuring the resistance of a yarn t bending have been discussed and it was found that the use o tensile measurements was justified in a number of cases. Results have been given for nylon, Terylene, and viscose ya chosen to reflect the effects of yarn and fibre tex, and number of fibres, on the tensile and bending properties.

At low levels of strain it has been shown that a yarn may behave as a number of individual components or fibres with the result that the bending modulus and flexural rigidity was the sum of the values of the components. On other occasions and at higher strains the flexural rigidity of the yarn was higher than the theoretical value because the fibres were no longer acting independantly, but the tensile strain moduli still gave a useful indication of bending performance even at break.

A number of fabrics have been analysed, their resista to bending forecast, and compared with the practical values found by experiment. The woven fabrics were selected so th monofilament, multifilament, and fibre constructions were represented and the materials were nylon, polyethylene, polypropylene, Saran, Terylene, and viscose rayon.

General agreement has been found between the values of flexural rigidity obtained by a standard cantilever test, and results obtained by beam and loop experiments, similar to those used for fibre and yarn measurement. Some problem relating to the estimation of the bending modulus of a fabri have been discussed and results compared between fabrics and with tensile moduli. Tensile strain moduli gave a useful indication of performance including the evaluation of the effect of physical and chemical finishing on a fabric.

Finally a collection of fabric data has been inspecte and information relating to tensile and bending measurements has been discussed.

It has been concluded that the use of tensile measurements to indicate the stiffness of a material is justified in many cases but that care is required in interpretation. The measurement of the thickness of yarns and fabrics, the changes of effective thickness under test, and comparison of these results with theoretical values are subjects requiring further consideration.

T H E S I S

on

"ELASTIC MODULI AND THE BENDING PROPERTIES OF TEXTILE MATERIALS"

Presented to

THE UNIVERSITY OF GLASGOW

In Accordance With
The Regulations Governing
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DEGREE of DOCTOR OF PHILOSOPHY

by

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A C K N O W L E D G E M E N T S

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TERMS AND DEFINITIONS

Stress = $\frac{\text{load}}{\text{area of cross-section}}$,dyn/cm^2,kgf/cm^2

Specific Stress = $\frac{\text{load}}{\text{mass per unit length}}$,gf/tex

Tensile Strain = $\frac{\text{Stretched length - original length}}{\text{original length}}$

Young's modulus = The slope of the tensile stress-strain curve at the origin, stress/strain, kgf/cm^2, gf/tex. Also called elastic modulus, initial modulus, or tensile modulus.

Yield point = The point at which the tangent to the stress-strain curve is parallel to a line joining the origin to the breaking point. The point is characterised by giving appropriate values of stress and strain.

or, Yield point = The point occurring at the stress given by the intersection of the tangent at the origin with the tangent having least slope to the stress-strain curve.

Compressive modulus, E_c	=	The ratio of compressive stress to compressive strain, expressed in same units as tensile modulus.
Shear modulus (n)	=	The ratio of shear stress to shear strain, the shear strain being measured in radians, kgf/cm^2, gf/tex.
Bending modulus, E_b	=	The slope of the bending stress-strain curve at the origin, kgf/cm^2, gf/tex.
Moment of Inertia I.		The moment of inertia of a cross-sectional area with respect to the neutral axis of that section is defined as the limit of the sum of the product of the elementary areas into which the area may be conceived to be divided, and the square of their distances from the given axis. The dimension of I is, therefore, the fourth power of a linear unit, as, for example cm^4.
Strain modulus	=	The ratio of stress to strain at a particular strain value. The term should be prefaced to indicate the form of strain e.g. tensile, bending, etc. kgf/cm^2, gf/tex.

Stress modulus = The ratio of stress to strain at a particular stress value. The term should be prefaced to indicate the type of stress involved e.g. compressive, bending, etc.

Secant modulus = The ratio of the change in stress to change in strain between two points on a stress-strain diagram, particularly the points of zero stress and breaking stress, the average stiffness.

Flexural rigidity = A measure of the forces involved in bending a material, the couple required to produce unit curvature, gf cm^2.

Torsional rigidity = The couple required to put in unit twist, that is unit angular deflection between the ends of a specimen of unit length, gf cm^2.

Stiffness (tensile) = The slope of the stress-strain curve between the origin and the breaking point. Sometimes used to denote the slope up to certain stress or strain value, kgf/cm^2 or gf/tex.

Stiffness (bending)	=	A term used to indicate the resistance to bending in conjunction with bending length, flexural rigidity, or bending modulus, the units being those of the appropriate term.
Work of rupture	=	The energy needed to break the material, the area under the load-extension curve, dyn. cm, gf cm. Also called toughness.
Toughness	=	$\frac{\text{Breaking strength x extension}}{2}$
Resilience	=	The ratio of the energy of retraction to the energy of deformation, other term, work recovery.
Elastic recovery	=	The amount of deformation recovered after the release of tensile or compressive strain, usually expressed as a percentage of the original unstrained dimension of the sample.
Cloth Assistance ratio.	=	The ratio of the strength of a strip of fabric of known width, divided by the number of threads to that width, to the mean single thread strength, both values being taken in the same direction of test.

Yarn assistance ratio. = The ratio of the strength of a yarn divided by the number of filaments in the yarn to the mean filament strength.

Bending length c. = The ratio of the resistance to bending and the weight of a fabric. The cube root of this ratio is termed the bending length meaning the length of fabric that will bend under its own weight to a definite extent.

$$c = \sqrt[3]{\frac{G}{w}}$$

Flexural rigidity G (of a fabric) = The couple on either end of a strip of unit width bent into unit curvature and given by $G = wc^3$ where w is the mass per unit area of the fabric in grammes per square centimetre, gf cm.

Bending modulus q = The specific resistance of a material to bending, or intrinsic stiffness, and given by $q = \frac{12G}{d^3}$ where d is the thickness of the fabric in centimetres, kgf/cm^2.

Symbols and Abbreviations. (B.S.1991: Part 1: 1954 and subsequent amendments)

Units of Mass	Abbreviation
Kilogramme	kg
gramme	g
pound	lb
ounce	oz
Units of force	
kilogramme-force (i.e. 980,665 dynes)	kgf
gramme-force	gf
pound-force	lbf
Mechanics	**Symbol**
mass	m
density	ρ
force	F
weight	W
moment	M
Units	**Abbreviation**
metre	m
micron	μ
centimetre	cm
minute	min

Units	Abbreviations
degree Celsius (centigrade)	^oC

Prefixes to abbreviations for the names of metric units.

$\times 10^3$: Kilo	k

Indicating sub-multiples.

$\times 10^{-3}$: milli	m
$\times 10^{-6}$: micro	μ

Common British Units.

inch	in
feet	ft
yard	yd

Terms	Symbol
work, energy	W
moment of inertia	I
radius of gyration	k
Young's modulus	E
shear modulus : rigidity	G
bulk modulus	K
bending moment	M
torque	T
coefficient of friction	μ
standard deviation	σ

CHAPTER 1. **INTRODUCTION**

This thesis is the result of work on the bending of textile materials undertaken to obtain answers to the following questions.

1. Are the values of the tensile, bending, and compressional moduli of a fibre the same?

2. Can the value of a tensile modulus be used to forecast the resistance to bending of a fibre, yarn, or fabric?

3. Does the ranking of fibres by such moduli agree with the ranking of resistance to bending obtained by other means such as stiffness and rigidity measurements?

The bending properties of a material include recovery from deformation as well as resistance to deformation, but this work has been confined mainly to aspects of resistance to bending, as otherwise the terms of reference would be too large for one investigation. It seemed logical to start with the properties of a fibre and to attempt to show that, within experimental limits, the values of the respective moduli were similar. If this were the case then the value of the tensile modulus could be used to forecast the bending behaviour being the value which is the easiest to measure as well as being the most widely known. Attention could then be turned to yarn and fabric and attempts made to forecast their bending behaviour from tensile measurements.

Because of their frequent use, and because it would be hoped that such knowledge might prove helpful in subsequent evaluation of results, where appropriate certain other parameters such as stiffness and flexural rigidity would also be measured.

A survey of literature has been made and matter considered relevant to the subject of bending has been classified under suitable headings. References relevant to these headings have been given. Any reference may also contain information suitable for inclusion under another heading, and therefore some references have been given on more than one occasion. Alternatively to avoid undue repetition sufficient information may have been given about a reference to enable it to be used out of context where necessary.

In Part I, the experimental work on fibres has been described. Results are given for all materials tested where those results are indicative of a property of a material, or are otherwise considered significant. When results are given to illustrate the effect of a variable, and all the materials would behave in a similar manner, one material has been selected.

Ideally the same material(s) should be used throughout in fibre, yarn and fabric form. This was not possible but an attempt has been made to ensure that any material which was used occurred in a number of experiments, the consequent overlapping leading to some degree of continuity. Monofilament materials were selected as being most suited to compressive testing and have been used in the section dealing with the tensile and compressive modulus. They were included in the next section and the value of the bending modulus of each filament was determined.

In Part II the range of the work was broadened to include multifilament and fibre yarns and finally the scheme of work was extended still further so that the bending properties of some fabrics could be considered in relation to their tensile properties. Certain other parameters of the materials were also measured and comments on the results have been made at the end of each section.

The results of the practical work have been discussed with reference to published work and the appropriate conclusions drawn.

It was decided to place all tables and figures within the text as near as possible to their reference note and to avoid undue duplication, with the result that some cross-checking will be necessary. It is hoped that the presentation will allow this to be done with a minimum of inconvenience.

CHAPTER 2. SURVEY OF LITERATURE.

1. The Bending, Tensile, Compressive and Shear Moduli of Fibres.

2. Factors which Affect the Value of a Modulus.

3. Other Properties of Fibres which May be Influenced By, or Be a Measure of, the Bending Property of a Fibre.

4. Consideration of the Bending Properties of Yarns and Fabrics.

CHAPTER 2. SURVEY OF LITERATURE

1. The Bending, Tensile, Compressive and Shear Moduli of Fibres.

Most standard works on the properties of matter contain a section dealing with the elastic properties of materials, in which the elastic moduli are defined as tensile, compressive, and torsional or shear, and a relationship between stress and strain is developed leading to the equations shown under the appropriate definition. The strain resulting from applied stress is generally considered only in the plane and direction implied in the appropriate definition and method of test. In the case of a fibre this is usually the major axis of the fibre except where shear is concerned.

The section dealing with the bending of a beam however will usually state that when the beam is bent, either as a cantilever, or beam supported at both ends, there is a neutral axis the material above this axis being extended while the material below the axis is compressed. According to Abbot et al[1] the fact that the neutral axis occurs at the geometrical centre of a symetrical cross-section has never been proved experimentally, but many workers have developed methods based on the assumption that provided the amount of strain is low the equations of classical physics apply even for anistropic materials such as textile fibres. However Carlene[2] and Guthrie et al[3] considered that in bending, the term bending modulus rather than Young's modulus should be used for the elastic modulus within the Hookean region because for the two terms to be synonomous the material would require to be homogeneous and isotropic. Meredith[4] stated that when a fibre is bent the elastic modulus called into play is the same Young's modulus that is involved in stretching provided that the fibre is uniform in property across the diameter of the fibre. Similarly Khayatt and Chamberlain[5], and Sen[6], considered that the value of the rigidity of a fibre was connected with the value for the Young's modulus of the material, again with the reservation that the relationship would only hold for homogeneous isotropic materials.

Thus it would appear that in any study of the resistance to bending of a textile material consideration has to be given to the extension and compression properties of that material but the bending tests will be described first.

<u>Bending Modulus and Flexural Rigidity</u>

References to static methods of testing the resistance to bending of a fibre are numerous. Khayatt and Chamberlain[5], Sen[6], and Guthrie et al[3] used a cantilever principle where the flexural rigidity of the fibre is given by:-

$$G = \frac{FL^3}{3d}$$

where G = flexural rigidity L = loaded length of fibre

F = deflecting force d = depression

If the quantities are expressed in c.g.s. units, then G is in units of dyne cm^2 and, for homogeneous isotropic materials, is connected with the Young's modulus by the relation, $G = E\,I$, where E is the Young's modulus, and I is the geometrical moment of inertia of the fibre cross-section.

Carlene [2] described a method using a fibre as a beam supported at each end and loaded by a weight at its centre such that the modulus of the fibre is given by:-

$$E = \frac{WL^3}{48\,yI}$$

where E = Young's modulus of elasticity

W = load on the centre of the beam

L = length of the beam between the supports

y = deflection of the beam at its centre

I = moment of inertia of the cross-section of the beam.

All quantities again in c.g.s. units.

This equation follows from the equation above and the method in fact allows the measurement of the flexural rigidity of the fibre if the dimensions of the fibre are excluded.

Carlene[7] also suggested a ring loop method, originally described by Peirce[8], where the flexural rigidity of the fibre is given by the relation:-

$$G = k\, w\, L^2 \quad \cos\theta/\tan\theta$$

where G = flexural rigidity

k = constant = 0.0047

w = applied load

L = circumferential length of undistorted ring

θ = $493d/L$

d = deflection of lower end of ring under action of applied load.

When W is given in grammes, and L and d are in centimetres, the flexural rigidity is derived in units of gf cm^2 and has the dimensions $M\ L^3\ T^{-2}$ as required by the definitions of this property.

The value of the elastic modulus may be obtained from the equation, $G = EI$ where I is again the moment of inertia.

Another method of measuring the resistance to bending has been given by Sakurada and Tusiwa[9,231] based on the stability of a loaded pillar. The value of the flexural rigidity is the quantity obtained, the value being calculated from the length and diameter of the pillar, and the deflection under a known load.

All of these methods relate to the bending of single fibres but there may be practical limitations in their application. Sen [6] used a number of fibres in parallel arrangement to magnify the load deflection effect, while Carlene [7] showed that a number of loops in parallel could be used so that magnification is also possible by this means.

These methods can also be applied to yarns with the measurement of flexural rigidity being fairly easy to accomplish. The difficulty in calculating the value of the bending modulus of a yarn lies in the estimation of the value of the moment of inertia but the advantages and disadvantages of yarn testing will be considered in the appropriate section. Extension of the principles to the testing of fabrics has also been deferred at this stage.

References to dynamic methods of measurement of the resistance of a fibre to bending are also numerous and, although it was not proposed that this work would include dynamic measurement, they are considered briefly because of possible consideration of their results in a later section.

Lochner [10] was primarily concerned with the measurement of the damping capacity of wool and other textile fibres, but he has described a method of obtaining Young's modulus of bending by exciting a fibre to resonate at its fundamental frequency. The value of the modulus can be obtained from the equation

$$E_b = \frac{51.1 \quad \rho \quad \nu^2 \; L^4}{D^2}$$

where E_b = Young's modulus of bending, dynes/cm^2

ρ = density of fibre, g/cm^3

ν = fundamental frequency, cycles/sec.

L = length of fibre, cm.

D = diameter of fibre, cm.

Lincoln[11] continued work on the method described above and also developed a method based on a rocking-beam oscillator, but was primarily concerned with the use of measurements of damping capacity and elastic modulus in the evaluation of flexural fatigue.

Guthrie et al[3], using further modifications of the resonance frequency method, measured the bending rigidity of fibres and compared the dynamic bending modulus with values which had been obtained for the static bending modulus. Values for the stretching modulus using a Cliff tester at a rate of loading of 2.5 gf/denier/minute were also given.

Kärrholm and Schroder[12] also used the resonance frequency method and measured the bending modulus of nylon, hair, viscose rayon and wool, while values for the dynamic modulus of wool [13] and many other fibres [14] are also available.

Tensile Modulus

This property of a fibre is so well known and widely used that it is somewhat surprising that at this time there is no standard method of measurement. The nearest is the method[15] advised for determining the (breaking) strength, but Meredith [16], Dillon [17], Morton and Hearle [18], and Hamburger [19] have also given details of particular methods. The modulus has been defined as the ratio of stress to strain, and the results expressed as stress per unit area of cross-section or stress divided by the mass of a standard length, and values for this property of different fibres are readily available.[20,21,22,23]

A number of authors have recorded values for the tensile modulus and bending modulus of a fibre but there does not seem to be any general agreement on the exact relationship between the two values.

Meredith [24] considered that the value of the bending modulus should be greater than the tensile modulus due to the anisotropic nature of the fibre and Guthrie [3] agreed with this provided that the value of the bending modulus was obtained by static methods.

Finlayson [25] suggested that the two values should be similar and Carlene [2], in turn, supported this point of view but recorded an instance where the value for the tensile modulus was lower, and suggested that this might be due to a difference in the size of the filament.

An instance where the tensile modulus value is the higher is to be found in the work reported by Khayatt and Chamberlain [5] while Beste and Hoffman [26] quoted the ratio of bending to tensile modulus of a polyamide to be 0.86 ± 0.14, and for polyethylene terephthalate to be 1.13 ± 0.12. Other opinions have been quoted by various authors [12,19,27,28,29,30] and it would appear that the order of result obtained, depends very largely on the method of test adopted, a not unexpected conclusion in the light of later comments on the factors affecting these properties of a fibre.

Compressive Modulus

By comparison this property of a fibre has been neglected and as a result there are few references to test method. Some details have been given by Backer [31] and Miles [32] and the units for the modulus are the same as those used for the tensile modulus.

Both Backer and Miles suggested that the value for compressive modulus was below that of the tensile modulus. They considered that the height diameter ratio might effect the result and stated that there were a number of experimental difficulties such as end effects, buckling, and the satisfactory mounting of the test specimen. The only other reference found was to work by Denby[33] who recorded the Young's modulus of keratin in compression to be approximately twice that of the tensile modulus.

It would appear therefore that before the relationship between the bending modulus, and the compressive modulus of a fibre can be considered the experimental difficulties in the measurement of the compressive modulus have to be investigated.

General sources on compression testing include Nadai[34] and Frisch-Fay[35], while Cook and Larke[36] considered end effects, cones, and height diameter ratio in an investigation into the compression properties of metals.

Shear Modulus, and Torsional Rigidity

Early records of testing the modulus of a fibre under torsion belong to Peirce[37] and Speakman[38] while more recently attention has been renewed by work by Meredith[39,40] Ray[41] and Guthrie et al[3]. The term implies shear strain and it is not expected that there will be any direct correlation with the bending properties of materials unless the conditions of bending contain a shear component. Meredith [4], and Ray [41], suggested that the ratio of tensional to torsional modulus might indicate the degree of anisotrophy or crystallinity present in a fibre.

There has been greater attention paid to the measurement of the torsional rigidity of a fibre. Descriptions of the methods of measurement of this property of a fibre may be found in the work of Peirce [37], Speakman [38] and Meredith [39], while Lochner [10], Meredith [24, 40], and Guthrie [3] have quoted values for some of the fibres with, in some cases, comparative values for stretching and bending modulus. Mention may also be made of the work by Cassie [42], and McLeary and Royer [44]. Factors which have affected the torsional properties of a fibre have been considered by Jencke, reported by Meredith [4] as having measured the torsional rigidity of dry viscose rayon at various temperatures, and by Speakman, reported by Carlene [45] to have found little change in wool fibre rigidity with initial regain of water. Meredith [4, 46], has also considered the relationship between the modulus of rigidity and the moisture regain of cotton fibres. The tensile properties of twisted single fibres has been investigated by Dent and Hearle [47] while some consideration has been given by Ray [41] to the theoretical aspects of tensile and torsional properties of textile fibres, values of the respective properties being quoted. It should be recorded that Platt [48] in a paper on some aspects of stress analysis of textile structures stated that shear, bending, and torsional stresses were relatively minor factors when compared with tensional stresses.

Maclay and Downes [49, 50] have written two papers also concerned with torsional rigidity. Other papers which have considered stress, relaxation, creep, or entropy stress include those by Dent [51], Platt, Chen et al [52], Coleman and Knox [53], and Price et al [54] whose paper also contained details of the effect of temperature and humidity. The mechanical behaviour of nylon filaments in torsion was studied by Hammerle and Montgomery [55] who concluded that the course of extensional relaxation fails to predict the course of torsional relaxation under the assumption that the nylon filament was mechanically isotropic. The torsional properties of single wool fibres with respect to torque twist relationships, and torsional relaxation in wet and dry fibres have been discussed by Mitchell and Feughelman [56].

When a fibre is bent some form of traverse shear stress might be expected and hence, depending on the conditions of test some correlation between such shear and bending properties might be present. Again however there would appear to be a paucity of experimental results available for inspection.

Finlayson [57] is one of the few references found so far and the values of tensile strength and shear strength reported show little correlation. It is thought that shear conditions will only be set up at high bending conditions with the test length, fibre grips, and manner of loading playing a contributory part so that correlation may be difficult to obtain.

Meredith [4] commented that the more highly orientated cellulosic fibres had a higher shear strength and that from the ratio of tensile to shear strength it was possible to separate the well orientated cellulosic fibres (high ratio) from the less well orientated fibres. Values of breaking twist angle were also given. Some attention to the shear properties of fabrics in relation to fabric hand has been given by Kilby [58] who used a method described by Morner and Eeg-Olofeson.[59]

Lateral compression of a fibre should ultimately lead to shear, the method used by Finlayson[57] being in fact a form of high speed lateral compression of one section of a fibre relative to another. No reference to lateral compression as such has been found and it is felt that, as part of this work involves the measurement of the elastic properties of a fibre, an attempt might be made to measure this property of a fibre.

There are a number of references to the elastic performance of a fibre under torque, and the term rigidity has frequently been used so that care is required to avoid confusion with (flexural) rigidity, similarly between torsional shear and lateral shear.

2. Factors which Affect the Value of a Modulus

The value obtained in the measurement of any physical property of a fibre is known to be dependant on the experimental conditions used. Hence the need for standardisation of testing methods where such factors as speed of test, atmospheric conditions, and the dimensions of the test sample are closely controlled. The effect of such variable factors on the values of elastic moduli are now considered.

Effect of time, stress, and strain

However the value of bending resistance is expressed, being a stress-strain property of the fibre it will be affected by any variation in the conditions of test.

In all of the experimental methods previously mentioned where static measurements have been made, the results were quoted following one single bending operation but with each method a different time interval has been used. Carlene [7] used a 30 second interval before recording deflection, Khayatt and Chamberlain [5] 120 seconds, Sen [6] gave no time interval, while Guthrie [3] took 20 seconds, but did make some corrections for time effect when comparing bending modulus with rigidity and stretching modulus. Carlene [2], using another method, took 60 seconds as the time of test and also gave values for different rates of loading and for a second bending operation. The effect of time on the bending values of a fibre should be considered for single and cyclic bending leading up to dynamic methods.

Comment on the effect of time on tensile results has been made by Meredith[60, 61], and Sikorski and Woods [62], Hammerle and Montgomery [55] have considered time effects in relation to torsion, and Susich [64] has dealt with time effects in the sense of the mechanical conditioning of textile fibres and the effect on strength, extensibility, energy, and elastic recovery.

Beste and Hoffman[26,27] commented on the importance of time measurement in the assessment of stiffness, while Guthrie and Norman[65] in a paper with a more indirect bearing on the subject have given data on the time factor and the degree of elastic recovery from extension. Taking times of 0-5 minutes for both time under extension, and time of recovery, they showed that within the quoted time limits values ranging from 22% to 80% could be recorded as the elastic recovery of viscose rayon from 5% extension.

It is also probable that the time effect will be linked with the magnitude of stress and strain involved. Carlene[7] reported that the effect of the magnitude of applied load on the value of flexural rigidity obtained was negligible over the range of deflection used, but the loading effect, while also linked with time, must affect the degree of strain imposed, with, in a free system, the eventual possibility of going outwith the true elastic limit. Clark and Preston[66] considered relations between length of fibre, load imposed and the temperature, that may have some bearing on this point. Holdaway and Raws[67] have quoted values of 3 - 50% strain of fibre in a pleat, strain being estimated as the ratio of fibre radius to radius of curvature of the fibre centre line, while Hamburger et al [68], discussed some aspects of elastic behaviour at low strains.

Effect of temperature and humidity

The effect of temperature and humidity on the physical properties of textile fibres has been well reported, but mostly in connection with tensile measurements. For temperature Meredith [4], Warburton [13], Clark and Preston [66], Coplan [69], Forward and Palmer [70], Kaswell [71], Farrow [72] Guthrie [74], and Cheetham and Edwards [75], come under this category. Brown [76], and Bryant and Walter [77] reported work on the stiffness temperature behaviour of materials, but stiffness in these cases was comparable with the strength modulus of the materials.

Investigations have been made on the effect of temperature on the values of the initial modulus of polyethylene [78], wet nylon , Terylene and Orlon [74], and the effect of temperature on the rate of creep failure of 66 nylon has been investigated by Coleman et al [79].

Among the few papers dealing with bending property, Clayton and Peirce [80] measured the effect of temperature on the bending property of cotton over a temperature range of 0°C - 60°C but in fact they were chiefly concerned with the effect of changes in humidity on the modulus of rigidity, and flexural rigidity.

The effect of humidity and consequent regain on the rigidity of viscose rayon [49] and wool [38, 50] has been discussed, and there has been further discussion on the physical properties of wool fibres at various regain [81], with reference to stresses developed at constant strains, and the recovery from extension.

Considerations of the effect of humidity on the general elastic properties of fibres have been given by Hearle and Peters [82], Meredith [4, 24], Smith [83], Maginnis [84], and Hindman and Fox [85], while a summary of literature on the moisture relations of textiles was given by Carlene [45].

Effect of material, shape, and size

Consideration of other factors which might be expected to influence the bending property of a fibre would suggest the nature, shape and size of the fibre itself. There are numerous articles comparing the tensile properties of the various textile fibres [4, 24, 39, 46, 86, 87, 88, 89].
Comparisons of the rigidity of fibres have been made by Carlene [7] (viscose rayon) Guthrie [3] and Smith [83] (general). Values for the bending modulus have been given by Carlene for viscose rayon [7] and nylon [2]; by Khayatt and Chamberlain, and Sen, for wool [5] and jute [6] respectively, while dynamic bending modulus results have been quoted by Lochner [10], Guthrie [3], and Körrholm and Schroder [46] (general).

In considering a material the effect of molecular orientation [28], crystallinity [78], homogeneous state [56], and anisotropic property [91] have to be dealt with, as changes in these characteristics in fibres of a similar chemical classification result in changes in fibre performance. Meredith [90] discussed the effect of molecular orientation on the tensile properties of cotton while Tipton [91] mentioned a technique for measuring the change in birefringence of a fibre subjected to increasing strain.

There are a number of papers which refer to molecular structure [46, 92] in general behaviour and to theories of mechanical behaviour [93, 94, 95, 96, 97].

The shape of the fibre is important both in the practical effect on bending and in the theoretical calculation. Assumptions of a circular, elliptical, or other geometric shape have to be made in the consideration of the cross-sectional area of the fibre, while moments of inertia are required in the calculation of bending modulus.

Cooper [29] stated that fibre stiffness depended on the fibre material, the shape of the cross-section of the fibre and the denier, with the suggestion that variations over the cross-section might be one reason for a difference in the measured value of the tensile and bending modulus.

Carlene [2] used a relationship for an isotropic material, and, working with nylon monofil, assumed a circular cross-section. Khayatt and Chamberlain [5] have also discussed these factors fully and defined their experimental limits treating the problem as one concerning elliptical fibres (wool) while Sen [6], using a different experimental technique, also considered the problem as one concerned with the bending of fibres with an elliptical cross-section (jute). Sen quoted Smith [83] as saying that the effect of the shape of cross-section on stiffness is very small compared with the effect of the size of the cross-section, the material, and the structure.

Guthrie [3], working principally on synthetic fibres, gave reasons for adopting the same method as that used by Khayatt and Chamberlain.

In a general context some shape factors for various cross-sections have been given by Meredith [39, 40].

The effect of the size of the fibre has been discussed by Finlayson [25] in a survey of the effect of filament denier and diameter on the properties of textiles, and by Meredith [98] who illustrates the effect of diameter on the case of stretching and bending a fibre. Smith [83] and Cooper [29] have also made some general comment. More specifically

Carlene [2] mentioned that the value of the bending modulus of nylon monofil increased with decreasing fibre diameter and in some later work on continuous filament viscose yarns [7] concluded that the relationship between filament flexural rigidity and filament denier could be expressed by the equation:-

$$G = k D^n$$

where G was the flexural rigidity, k a constant, D the filament denier and n an integer less than 2, the value expected from theoretical considerations of the bending of a beam of an isotropic material. Departure from the theoretical value tended to be greater for highly serrated filaments having greater orientation in the skin than in the core.

Guthrie [3], on the other hand, apparently has quoted the same value of bending modulus for nylon filaments of different diameter.

Anderson [99] was concerned with the relationship between the strength and diameter of wool fibres, and Hertel [161] considered the strength of a cotton fibre as a function of fibre length and gauge length.

It is possible that the length of the test specimen and the diameter of the fibre have to be considered together and that in bending different radii of curvature and effective percentage strain are involved. The problem may be connected with the effect of the height: diameter ratio to be considered in tensile and compressional measurements [31, 32].

3. **Other Properties of Fibres Which May Be Influenced By, Or Be a Measure of, the Bending Properties of a Fibre.**

As bending a fibre involved stretching at least part of the fibre, it might be expected that other tensile properties besides the initial modulus would give an indication of the probable bending behaviour of a fibre.

Stiffness

This term seems to have been frequently used to denote the degree of resistance to bending but there appears to be a possibility of some confusion over its actual definition.

Stiffness has been used as a descriptive term by a number of workers [2, 5, 6, 7, 8, 24, 25] to signify an increase in resistance to bending, flexural rigidity, or bending modulus.

As used by Brown [76], and Bryant and Walter [77], the term is comparable with initial modulus being defined as stress per unit strain whereas Finlayson [25], Ray [41]

Smith [83], and Harris [89], refer to stiffness as stress per breaking strain.

Baste and Hoffman [27] supply a possible link between these definitions by suggesting that consideration might be given to the stress-strain relationship through the range of strain, and suggest the use of such terms as diminishing modulus and compliance ratio.

Inspection of one set of results [25] would suggest that the fibres are ranked in the same order by tensile modulus and stiffness but further interpretation would seem to be necessary as there was not a similar correlation when inspection was made of the values of the modulus of elasticity and stiffness given by Harris [89]. Among other experimental variables may be the question of comparing unlike units.

Finally the term would appear to have been used in yet another sense by Bostwick et al [101] when they discussed the influence of bending and shearing stiffness on bending deformation.

Toughness

Values for the toughness of various fibres have been recorded by Meredith [24] along with the values for the Young's modulus and torsional modulus for the same fibres.

Toughness was defined as the energy per unit mass to rupture the fibre, equivalent to the area under the stress-strain curve. Smith [83] has listed the toughness index and average stiffness of a wide range of fibres while Coplan [69] in a report on the effect of temperature on textile materials gave a comparison of the energy of rupture at a particular rupture tenacity again for a range of textile fibres. Further values of toughness have been quoted by Meredith [16] and Kaswell [71].

Resilience

Considering the compressional properties of a fibre there are many references to the subject of the resilience, but it is necessary to separate those that have been considering resilience as resistance offered to bending, from other work where recovery from bending has been taken as resilience. Beste and Hoffman [26, 27], and Hoffman [102] have made a study of this property from both points of view. They considered that the resistance to bending involved a knowledge of the stiffness of the fibre, and of the change in stiffness with elongation and time, reference being made to a "diminishing modulus" since apparently the change was usually, but not always, towards lower stiffness. Compliance of fibres was taken as strain over stress, equivalent to the reciprocal of stiffness, and a term Compliance Ratio evolved which was then compared with the tensile properties of a number of different fibres. Dillon[103] has given a number of useful references to literature definitions of resilience and came to the conclusion that the majority of workers had used the ratio of energy of retraction to energy of deformation as indicative of the property. In a paper on the overall specific volume, compressibility, and resilience of cotton, wool, nylon, viscose, and acetate fibres, Rees[104] defined specific volume as the ratio of all over volume to the weight of fibre, compressibility as the percentage reduction in volume as the pressure exerted was increased from 0.001 to 1.0 lb/sq.in., and resilience as defined above. Kaswell[20] has a chapter on compressional resilience in which reference is made to work by Cassie[42, 88] on the coiling and uncoiling of a spring and values are quoted for different fibres, while a general discussion on the compressional behaviour of textile materials has been given by Finch[105], and reference to the compressibility of wool has been made by Van Wyck[106]

Mark[107] dealt with the resilience of a textile fibre from the point of view of the molecular structure, Hamburger[108] introduced the concept of the relationship of resilience with the elastic properties of a fibre dealing more specifically with compression in a later article, while Mutschler[109] has given details of the changes in bulk elasticity of fibres during processing.

The term bulk compression may be used as by Fok and Finzel[110], who quoted results of compression and work loss for nylon, Dacron and Orlon, and by de McCarty and Dusenbury[111] who were concerned with the bulk compressional characteristic of wool fibres. They found that the resistance to bending was more in keeping with the impression of handle or harshness than the measurement of resilience and also recorded an inverse relationship between the load applied and the mean fibre diameter.

The compressibility of acrylic staple fibre under hot, wet conditions has been considered by Meldrum and Ward[112] while Finch[105] considered the measurement of the compressional behaviour of textile materials at a constant rate of deformation and the measurement of compression stress relaxation at constant deformation. Inspection showed that this work related almost entirely to materials in fabric form.

That there is need to rationalise definitions is shown by reference to a paper by Bryant and Walter[77] who gave values for the resiliency of wet and dry fibres as a function of temperature. Inspection showed that the property referred to was tensile elastic recovery.

Elastic Recovery

The elastic recovery of a fibre is a property which might be more appropriately considered if the recovery of a fibre from bending was being dealt with, but as there is the connection with bending it is included briefly at this stage. There are a number of general references[26,86,87,113,114,115], but there does not seem to have been any attempt to consider any relationship between tensile and bending recovery. Hoffman and Beste[26] stated that the recovery factor contributed to the hand of a fabric and certainly it might be expected that a fibre with a high tensional elastic recovery would also have a high bending elastic recovery possibly leading to an impression of stiffness due to the resistance offered to bending.

Following from the definition of resilience, if any great degree of correlation were to be established between tensile and bending properties then it would be interesting to compare the tensile resilience measured from a stress-strain load and recovery curve with the bending resilience at similar strain.

Knot Strength and Loop Strength

Other fibre properties that depend on the visco-elastic behaviour of the fibre include knot and loop strength, but little evidence of published work on either has been found. Platt [116] and Harrison [117] have investigated knot strength but without issuing a public report, while values of loop strength and efficiency have been quoted by Coplan [69] and some values of knot strength have been given by Kaswell [20]. As both of these properties must be affected by the ultimate bending properties of the fibre, it was considered worth while recording such properties wherever possible.

Fatique

Similarly some connection might be expected between the bending behaviour of a fibre and the response of a fibre to repeated flexing. Lincoln[11] considered the flexural fatique and visco-elastic properties of wool while Lefferdink and Briar [153] commented on the effect of fibre fatique under wear conditions, but in neither case was very much made of the effect of fibre diameter, radius of curvature, and effective strain. It would appear that further study of this aspect of bending behaviour is necessary.

4. Consideration of the Bending Properties of Yarns and Fabrics.

Flexural rigidity is the most usual term used to characterise the bending property of a yarn, and a method of measurement has been described by Peirce [8], and Carlene [7] using a ring loop. Cooper [29], using loop tests, expressed his results as equivalent bending lengths as defined by Peirce [8], taking account of the increase in denier of the continuous filament yarns due to yarn retraction.

There did not appear to be any great use of the term bending modulus as applied to a yarn, this being perhaps not surprising as there was equally no records of the value of the tensile modulus as such, all values being equated to fibre terms. The reasons for this will be discussed in a later section. Stiffness has been used to describe both a bending [7,29] and a tensile [76,100] characteristic as was the case with the fibre.

The effect of fibre stiffness on yarn stiffness has been discussed by Carlene [7], who concluded that, for continuous filament singles yarn of very low twist (less than 4 t.p.i.) and for the range of yarns studied, the flexural rigidity of the yarn was the sum of the rigidities of the component filaments. This was supported by Cooper [29,118] who stated that inhibition of filament movement should increase yarn rigidity up to a theoretical limit of the order of Nf/p times that for complete freedom, where Nf. is the number of filaments in the cross-section and p the packing factor [119]. Provided that ease of filament movement remains unaffected yarn twist should cause a slight descrease in yarn rigidity. The treatment of bending a model yarn was also given. Platt et al [119], and Backer [120,121,122] have carried out an exhaustive theoretical study on the effects on yarn rigidity of fibre dimensions, stiffness, torsional to bending rigidity ratio, yarn density, size, twist, fibre clustering, and prior relaxation treatments. This follows some earlier work by Platt [114] on the influence of fibre properties with respect to yarn strength, while Virgin and Wakeham [123] considered the relation between single fibre properties and the behaviour of bundles, slivers, and yarns. Fiori et al [124] who reported on the effect of cotton fibre bundle break elongation, and other fibre properties, on the properties of a coarse and a medium singles yarn, showed a relationship between fibre and yarn stiffness, cottons with low stiffness tending to give yarns with low stiffness.

As with fibres, articles dealing with the effects of temperature and humidity tend to be concerned with tensile properties, those by Dillon and Prettyman [119], Eckstein et al [125] Illingworth and Kilby [126], and Busse et al [127] coming into this category.

Properties of Fabrics

It is to be expected that the bending properties of a fibre will influence the behaviour, character, and handle of a fabric. It has proved to be difficult to separate papers in which specific mention is made to resistance to bending from those referring to recovery from bending due, partly to the nomenclature used e.g. crease resistance where in fact crease recovery is meant, and also to the probable interplay of the two aspects of bending on the crease properties of the fabric.

Similarly before the effect of fibre property on the handle of the fabric can be considered some agreement is required on the definition of handle, a subject over which there would also appear to be some confusion.

Some early work by Peirce [8] on the handle of cloth as a measureable quantity would appear to have been the starting point, but while many of the methods of measuring the stiffness of fibre, yarn, and fabric stem from this work, Peirce himself was mainly concerned with the fabric property and did not attempt to relate fibre behaviour with fabric behaviour although later papers [128,129] by the same author may have something to add on this point, while Abbott [130] made specific mention of the Peirce test when evaluating methods of measuring the stiffness of fabrics. The bending length, flexural rigidity, and bending modulus were among the terms used by Peirce, definitions of which have been given in an earlier section, and they enable consideration to be given to the effect of test length, fabric weight and thickness on the value of resistance to bending.

Methods of testing the stiffness, handle, and crease resistance properties of a fabric have also been given by Chu et al [131], Saxl [132], Schiefer [133, 134, 135, 136, 137], Steele [138] and Eeg-Olofsson [139]. Standard methods of analysis have been published [140,141], while reference to the A.S.T.M. Standards on Plastics showed that there were a number of test methods relating to flexural properties. In general they related to materials of a more rigid structure than most textile materials but they might be referred to if any point on instrumentation was involved. It was interesting to note that in one test for stiffness in flexure the American method was, in affect, to hold the sample in a horizontal plane and move the clamp. As with the British cantilever method this test did not distinguish between elastic and plastic deformation.

Hamburger[142,143] has given a general survey of the effect of fibre properties on fabric drape and hand, as has Smith[83], while Pollitt,[144] also considered certain fibre properties in his paper on the geometry of cloth structure. According to Hoffman and Beste[26], the handle of a fabric, and the liveliness and shape retention are controlled to a great extent by three properties of a fibre. These are the initial stiffness, used in the sense of a strength modulus, the change in stiffness as the deformation is increased, and the power of recovery when the load, or pressure, is released.

Steele[138] used an Instron tester to deform fabrics as in creasing. The resultant load deformation curves were found to be related to the stiffness, resilience, draping, and handling properties of the fabric.

Further aspects of fabric creasing have been discussed by Bostwick et al[101], including the influence of stiffness, elasticity, crease recovery and humidity.

Buck and McCord[145], while discussing the effect of cloth construction on the crease resistance of cotton, referred to the interpretation of stress strain diagrams and suggested that the ratio of elastic work to total work might be used as a measure of creaseability or resistance to creasing. Gagliardi and Gruntfest [146] considered the creasing and crease proofing of textiles and gave data on the stress strain properties of fibre and fabric with, and without, resin treatment.

Cooper [29] in a useful paper considered the factors affecting the bending of fibres, yarns, and fabrics. Comment was made on the effect of change of fibre denier on fabric stiffness, the effect decreasing as the fabric was made tighter (cover factor). Fabric stiffness was almost unaffected by denier at a level far below that expected for monofilament action in the yarns. The effect of crease-resist treatment was also discussed.

In a paper on judging the harshness of fabrics Bogaty et al [147] also commented on the effect of fibre diameter and stated that increasing the diameter tended to increase harshness of handle.

Chu et al [148] who considered the factors affecting the drapeability of fabrics were of the opinion that Young's modulus, moments of inertia, and weight factor were especially important.

Cooke et al [149] studied the mechanism of imparting wrinkle recovery to cellulosic fabrics and recorded some stress-strain properties of fibre, yarn and fabric. They considered that the elastic recovery property of the material was of prime importance but they gave examples of stress-strain curves of fibre, yarn, and fabric which could prove of interest.

The relationship between fibre property and fabric wrinkle recovery has also been illustrated by Daniels [150].

Conrad [151] has given details of fibre, yarn, and fabric properties in a detailed investigation of the mechanical behaviour of cyanoethylated cotton, while Gintis and Mead [152] stated that the bending stiffness of a fibre was an important factor in determining the pilling propensity of a fabric and showed that heat setting increased fibre bending stiffness which reduced pilling by lowering the fuzzing tendency of the fabric.

A paper with no apparent direct bearing other than geberal interest was that of Kilby [58] in which he dealt with shear properties in relation to fabric hand and also gave some examples of the effect of heat setting on nylon monofil fabrics.

Another paper concerned with stiffness was that of Lefferdink and Briar [153] who sought to interpret fibre properties in a study of the effect of single fibre flex fatique in the resistance of fabrics to abrasion.

Cook and Grosberg [154] who considered the load-extension properties of warp knitted fabrics gave a possible equation for the bending modulus of a yarn from consideration of a loop as an elastica, while a paper by Adams et al [155] dealt with the relationship between the structural geometry and the physical properties of a fabric.

Similarly Platt [48], Backer [156], and Platt and Hamburger [157] have considered the problems of the translation of inherent physical properties of fibres into textile structures.

As would be expected there were a number of papers dealing with the effect of a chemical finish on the handle, bending properties, or crease recovery properties of a fabric. Some, such as those by Cooper [29], Gagliardi and Gruntfest [146], and Conrad [151], have already been mentioned, but others include Woo et al [158], who compared the mechanical properties of fibre, yarn, and fabric in an untreated, and resin treated, state.

The effect of temperature and humidity on fabric property is probably covered by comments already made in the fibre section and few additional references were available. Coplan [159] discussed the effect of high relative humidity on the wrinkle resistance of a fabric and Eccleston and Hillier[160] while measuring the effect of temperature on the crease recovery of fabrics made from synthetic fibres gave some information on the dynamic tensile properties of the fibres as well as their second order transition temperatures.

PART I. TENSILE, COMPRESSIVE, AND BENDING MODULI OF FIBRES.

From the preceeding survey it appeared that experimental work was required on the measurement of the tensile, compressive, and bending modulus of a fibre. It was obvious that the greatest care would be required to ensure accuracy and reproducibility of result and this involved both sample and experimental conditions.

As bending was considered to involve both stretching and compressing a fibre it seemed logical to start by considering the tensile and compressive modulus, and then to proceed to compare the values of the tensile and bending modulus.

Such is the work of the next two chapters except that the work on the tensile and bending properties was extended beyond that of the consideration of the immediate elastic regions. Monofilament fibres of a fairly heavy count were adopted as being easy to handle, permitting greater accuracy in the measurement of stress and strain, and yet being representative of fibres in general.

CHAPTER 3. TENSILE AND COMPRESSIVE MODULI OF FIBRES

1. Tensile Modulus: Test Methods Using an Instron.

2. Factors Affecting the Value of a Tensile Modulus.

3. Compressive Modulus: Test Methods Using an Instron.

4. Factors Affecting the Value of a Compressive Modulus.

5. Details of Fibres.

6. Results of Tensile and Compression Experiments.

7. Discussion of Results.

CHAPTER 3. TENSILE AND COMPRESSIVE MODULI OF FIBRES.

1. Tensile Modulus: Test Method Using an Instron

It was noted that there was no standard method available and the test method adopted owed something to such information as had been published, to the appropriate standard methods for fibre testing [140, 141, 170] and to the needs of dimension, time, and accuracy peculiar to these experiments.

The general use of the Instron has been described by Hindman and Burr [162] and the only modifications, either in instrument or procedure, were the use of a gear train to reduce the rate of traverse of the cross-head, the use of a rigid jaw assembly in place of the normal linked assembly, and the use of a cathetometer to measure the extension of a fibre.

The modulus has been defined as the tangent to the stress-strain curve at zero stress, but as it was hoped to use other parameters the stress-strain curve for a fibre was allowed to proceed past the particular strain value in question and thus the initial modulus can be regarded as the modulus within the limits of elastic strain, while the other parameters have been referred to as (specific) strain moduli.

It was considered that, as long as the test length of the sample was equal to, or greater than, one inch, the amount or degree of extension could be set, or recorded, satisfactorily by reference to the Gauge Length and Return Dial controls and the chart. Thus in order to obtain one per cent extension on a sample the Gauge Length would be set to zero after the crosshead had been positioned to give the correct test length. The Return Dial would be set to read one per cent of the test length, the amount of extension required. The unit of length extension was generally the inch, this being the basis for the Instron controls.

For test lengths below one inch it was found that there was an increasing risk of error as the test length became smaller, so that some alternative method of measuring test length and extension was required. The method chosen in this case was the use of a cathetometer. The units here were generally expressed as centimetres this being the basis of the cathetometer scale, and the eyepiece and objective lens were selected to give a magnification of fifty times where a cross-wire was being used, or the calibration of the eyepiece scale was such that one division was equivalent to 1.2×10^{-3} cm. when the extension was being followed entirely by reference to this scale.

The cathetometer was therefore used in two ways. For those cases where the test conditions permitted, the instrument was used in a conventional manner, the length of the specimen being measured using a cross wire in the eyepiece as the reference mark, and reading the cathetometer scale when focussed at the top and bottom of the specimen. The appropriate extension was set on the Instron controls, and checked by noting the change in the reading of the cathetometer when re-focussed on the bottom jaw. A further check was provided by reference to the chart and noting the displacement along the ordinate. When the dimension was particularly small, as in the case of one per cent extension of, say, an 0.1 inch specimen, it was found preferable to use a graduated scale in the eyepiece, this scale being calibrated in terms of decimals of an inch, or centimetre. Thus the length of the sample, the initial position of the crosshead, and the amount of movement of the crosshead, could be controlled by reference to position, or movement, against this scale. The cathetometer was mounted on a Dexion stand which was made to fit over the control panel of the crosshead unit. The platform of the stand was adjustable to allow the instrument to be set at approximately the height of the crosshead bar, the eyepiece unit of the cathetometer being then finally adjusted on its own stand to the desired position. In view of the magnitude of the deflections being measured, care was required in the use of the cathetometer to ensure that the level of the magnifying unit was not altered by pressure or movement during a test. Such displacement during a test could lead to an error in strain stress measurement.

For those tests where fine vice grips were being used, the sample was mounted in the grips such that the test length was within the range chosen. Care was taken in the tightening of the grips that the sample was not subjected to undue stress, and the grips themselves were mounted in the normal jaws of the Instron. The appropriate load cell calibration, crosshead and chart speed, were chosen being dependent on the material and the test length involved. It was considered that the use of half scale calibration for load and a magnification of one hundred times the extension permitted reasonable accuracy in the recording of the results, the necessary crosshead speed where short lengths were concerned involved the use of an accessory reduction gearing which allowed the constant speed to be reduced to a minimum value of 0.02 inches per minute.

In order that the modulus at, say, one per cent strain could be obtained, the test length of the sample, under a stress of less than one per cent of the expected final load, was accurately measured by means of the cathetometer. For samples above one inch in length the appropriate extension was set in the controls and the test completed, the extension being checked by the methods already discussed. For short samples the sample was strained by one per cent, equivalent to a deflection corresponding to a given number of eyepiece divisions of the cathetometer. A reference mark of the cathetometer being focussed on the bottom jaw and the jaw depressed until it came into line with the second reference mark, the value of the load imposed at this strain being obtained from the chart. The displacement of the load cell assembly under increments of load had been measured, (Fig.1.) so that the apparent extension could be corrected for the movement of the assembly. This correction is considered vitally important when the test length of the sample is small.

For those tests where the ends of the sample were embedded in a fixative, the general test procedure was the same except that glass formers were inserted in the Instron jaws and the cathetometer reference grid was focussed on the edges of the formers instead of the edges of the vice grips.

The Instron fitments were standard except that on occasion the linked assembly between the load cell and the top jaw was replaced by a rigid assembly to prevent lateral displacement of the top jaw during a test.

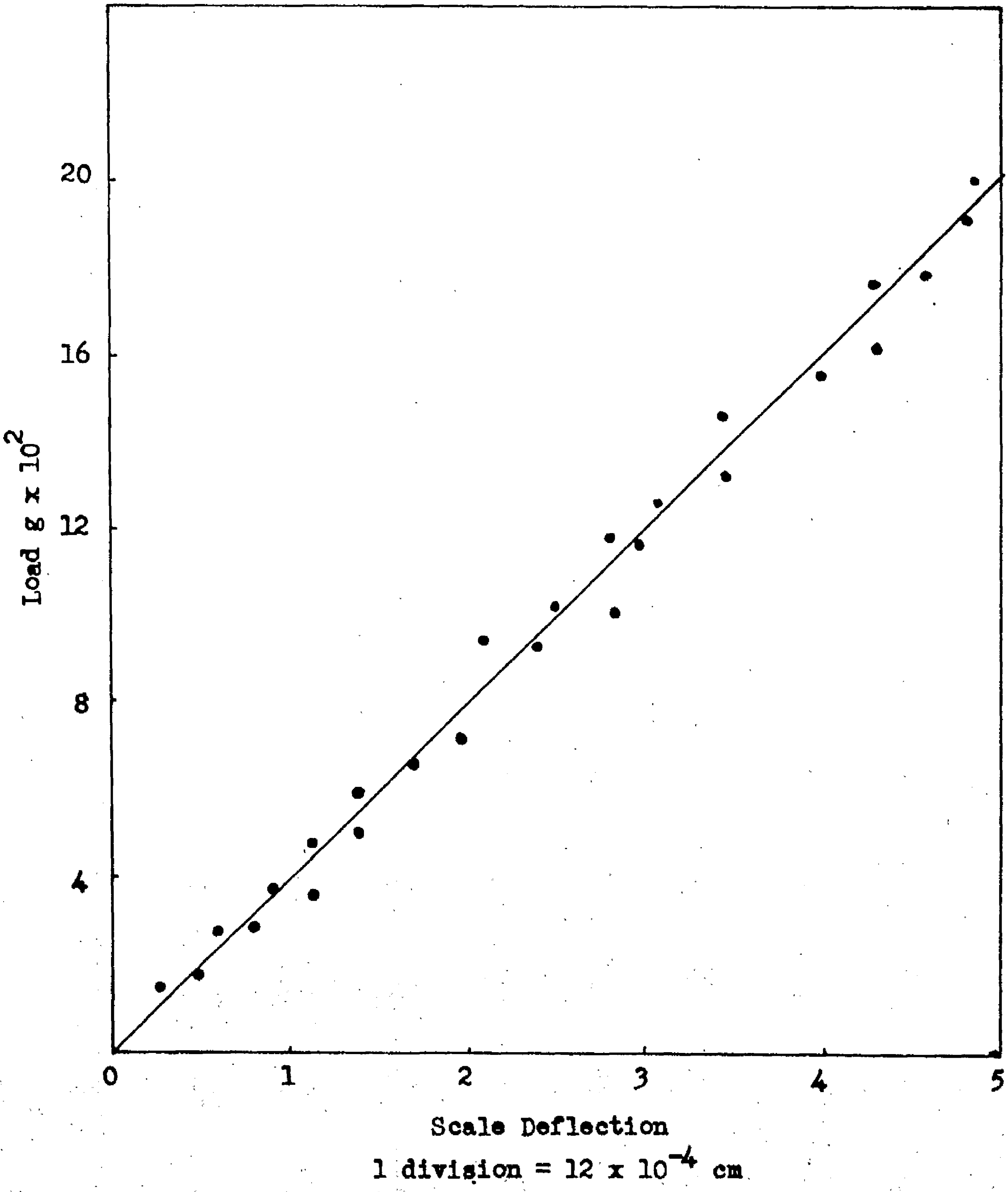


Figure 1 **Displacement of Instron Load-Cell Assembly with Load**

The general setting of the Instron may be summarised as shown below, while the foregoing text may be modified appropriate to the strain involved.

General setting

Load Cell B	2 kg Capacity
Cross-head Speed	10 per cent extension per minute
Chart Speed	100 times cross-head speed
Calibration	Half Scale
Test length	As required

2. Factors Affecting Value of a Tensile modulus.

The factors which may affect the accuracy of a result include the condition of the sample, variation in the diameter of the fibre, the effect of the test length of the sample, the amount of the extension, the effect of the type of jaw used to secure the specimen, and sundry instrument errors.

The condition of the sample

The value of the tensile modulus has been found to be extremely sensitive to any change, or error, in the method of preparing the sample for test, and in particular to the temperature at which the sample was straightened (to remove package curl), the tensions imposed during heating, and the time allowed for reconditioning.

This has been illustrated by Table 1 where the magnitude of the change has been shown.

Values for compression and bending modulus have also been given and further reference will be made in the appropriate sections.

Pre-treat* ment. Temperature °C	Time Reconditioning at Standard Conditions. Hr.	1% Strain Modulus $kgf/cm^2 \times 10^2$ Tension nylon 66.	Tension Saran	Compression nylon 66.	Compression Saran	Bending nylon 66.	Bending Saran
None	24	276	101	-	-	-	-
60	48	271	101	273	-	273	98
100	1	439	-	-	-	435	-
100	3	439	50	-	-	432	52
100	24	371	-	-	-	373	-
100	48	274	49	-	51	276	51

* 2 minutes, tension 0.1 gf/tex in each case.

Table 1. Effect of Pretreatment of Fibre on Moduli.

Nylon and Terylene samples were considered to be affected in the sense that heating involved a drying of the sample with a rise in modulus value. The change was reversible, or recoverable and as would be expected the effect was most noticeable for the nylons and only slight for Terylene. The effect also provided an interesting illustration in rates of diffusion and conditioning under different temperatures. In sixty seconds at 100°C. 0% r.h. the modulus value of the nylon 66 sample was altered from 27,000 kgf/cm^2 to 44,000 kgf/cm^2 and it took more than a day at 20°C. 65% r.h. for the sample to regain its original value. The olefine and vinyl samples suffered an irreversible change in modulus directly related to the temperature of treatment, and presumably due to heat allowing molecular realignment to take place with consequent longitudinal shrinkage and lateral swelling.

Inspection of the stress-strain charts for each material showed that no measurable strain was likely to ensue with the use of a tensioning load of 0.1 gf/tex. which was sufficient to assist in the unbending of the samples.

The conditions finally chosen were those which allowed the straightening of the sample with the minimum of change of fibre property, but whatever the purpose of the specific experiment, unless samples have been given identical treatment then there could be a risk of attributing a false significance to any difference in modulus obtained. It also follows that comparative tests could be made provided the control value of the modulus was known.

It was considered that errors likely to arise through local fluctuations in the values of temperature and humidity during test would be small. A careful check was maintained on these values by reference to the appropriate control chart to ensure that they had remained within the stated limits. Further discussion on the effect of temperature and humidity on modulus values will be found in a later section.

Fibre Dimension and Weight

Variation in measurements of these properties of a fibre could occur in two ways, either as a real difference between sample and sample, length to length, or as a result of an error in measurement.

Diameter

Tests showed that the diameter of these monofilaments could vary as much as $\pm$ 4%, while it was considered unlikely that the measurement of the diameter of a sample would be in error by an amount exceeding $\pm$ 1.0%. It has also to be remembered that in calculating the modulus the value of the diameter is squared. The effect that an error might have has been shown by the modulus values in Table 2 where the values for the load were kept constant for the purposes of the illustration. These results have been given in detail for ease of reference in discussion. Values for a real difference in practice would be compensated by the difference in the load required for extension but it was still extremely important that the diameter of each sample was accurately checked. It is generally agreed that the diameter of a fibre is most accurately obtained by measuring a cross-section of the specimen, because with a longitudinal specimen it is often difficult to bring both edges of the fibre into focus at the same time although this difficulty can be partly overcome by the use of polarised light and by appropriate focussing of the Becke line. Another advantage of sectional measurement lies in the opportunity afforded for examination of, and detection of, non-circular shapes.

Fibre Diameter cm x 10^{-3}	Modulus $kgf/cm^2 \times 10^2$	
	Tensile Compressive	Bending
47	304	336
48	292	312
49	282	292
50	270	270
51	258	250
52	250	232
53	242	218

Table 2. Values of the Tensile, Compressive, and Bending Modulus over a range of $\pm$ 6% Mean Diameter, (assuming a constant load value).

It was noticed that the monofilaments were easily compressed either while clamping in the section cutter or during the cutting operation, so that care was required to avoid permanent deformation of the sample with consequent change in diameter. This observation proved of value when bending tests were undertaken, but at this stage it was felt that the risk of compression change outweighed any errors in focussing so that in the event the diameter of each specimen was checked on a projection microscope using a longitudinal mount. All fibres were considered to be circular in section unless otherwise stated.

<u>Weight per unit length</u>

Tests showed that the variation in the weight of a monofilament material was of the order of ± 2%, while it was considered unlikely that the error in measurement exceeded 1%.

For general descriptive purpose the tex count of each material was determined based on the mean weight of ten lengths of one metre under standard conditions. An Oertling precision torsion balance was used reading to 1 mg. or 10 mg. the choice depending on the sample. On any occasion where it was desired to check the weight of a short length of fibre a Shirley cantilever micro-balance was used.

Again there were two instruments and the choice depended on the test sample involved. The sensitivities of the balances were in milligrams and micrograms respectively. The use of such a balance has been described by Lord [163].

Effect of test length

Other workers have commented on the effect of the length of the test specimen on the stress-strain [4, 161] characteristics. It was also known that short lengths would be required for compression comparison, and longer lengths for bending comparison. Values for the tensile modulus of each material were obtained over a range of test lengths from 0.25 cm. to 25.40 cm. Mention has already been made of the importance of measuring the actual extension of the specimen as opposed to the apparent extension. This has been illustrated in Table 3 where the tensile modulus for Terylene is given calculated from the actual and the apparent extension. A similar change in the order of the modulus was obtained with all the monofilament materials unless corrected.

The accuracy was found to be partly dependent on the measurement of the original test length. The reference grid of the cathetometer has to be focussed on a reference point of the top and bottom jaw and it was found that considerable

Fibre	Test Length cm	Length: Diameter Ratio	Modulus Tensile (a)	Modulus kgf/cm² x 10³ (b)	Modulus Compressive
Terylene	0.26	5:1	102	59	101
	0.53	10:1	103	85	104
	1.72	34:1	100	95	-
	3.03	60:1	103	102	-
	10.04	-	104	-	-
	25.38	-	101	-	-
nylon 66	0.90	8:1	27.0	-	26.1
	"	10:1	26.5	-	26.8
	"	12:1	26.0	-	-
	"	17:1	26.8	-	27.1
	"	40:1	26.4	-	-

(a) Based on actual extension

(b) Based on apparent extension

Table 3. The Effect of Test Length and Length: Diameter Ratio on the Tensile and Compressive Modulus.

practice was required before a reasonably consistent result was obtained. It was essential that the cathetometer be sited on a stable base and, because of the magnification, the focal length was small with the risk of the specimen going out of focus during a test. In the case of samples mounted in Araldite it was necessary to discard any samples where the specimen/Araldite/former edge was not clear and level, otherwise there was a risk of the actual test length being longer than registered because the Araldite edge was sunk within the bore of the former. Conversely a short test length could result from the Araldite fixative overrunning the test length.

The Amount of Extension

The tensile modulus is a parameter obtained as an indication of the stress strain characteristics of a material within the elastic region where stress is primarily proportional to strain. An attempt will be made later to show that the value of a tensile modulus outwith this region has some significance. However it follows that the value of any result unknowingly obtained outwith this region will be in error, and hence it was considered important that the limits of extension for each material be known.

One experimental factor here is that when a stress-strain curve is obtained for a long test specimen it is not usually necessary to magnify the extension. There is thus the possibility that a section of the curve is considered linear whereas there is a very slight curvature, which will become evident when the scale is magnified. The risk that such curvature could be caused by an instrument error has been considered in another part of this section.

Figure 2(a) shows the complete stress-strain curves for all the monofilament materials without magnification; Figure 2(b) shows the same materials with the extension magnified ten times, the extension being limited to five per cent.

Figure 2(a) is typical of the normal presentation and shows the all-over pattern of stress-strain behaviour allowing general comparison of the various fibres. Scrutiny of Figure 2(b) will show that there are some grounds for believing that there is a tendency to curvature much earlier than would be suspected. It follows that judicious magnification of any part of the graph is advisable either by increasing the load scale, extension scale, or both. For this reason it was the practice in these experiments to measure the strain modulus at 0.5% strain as well as the

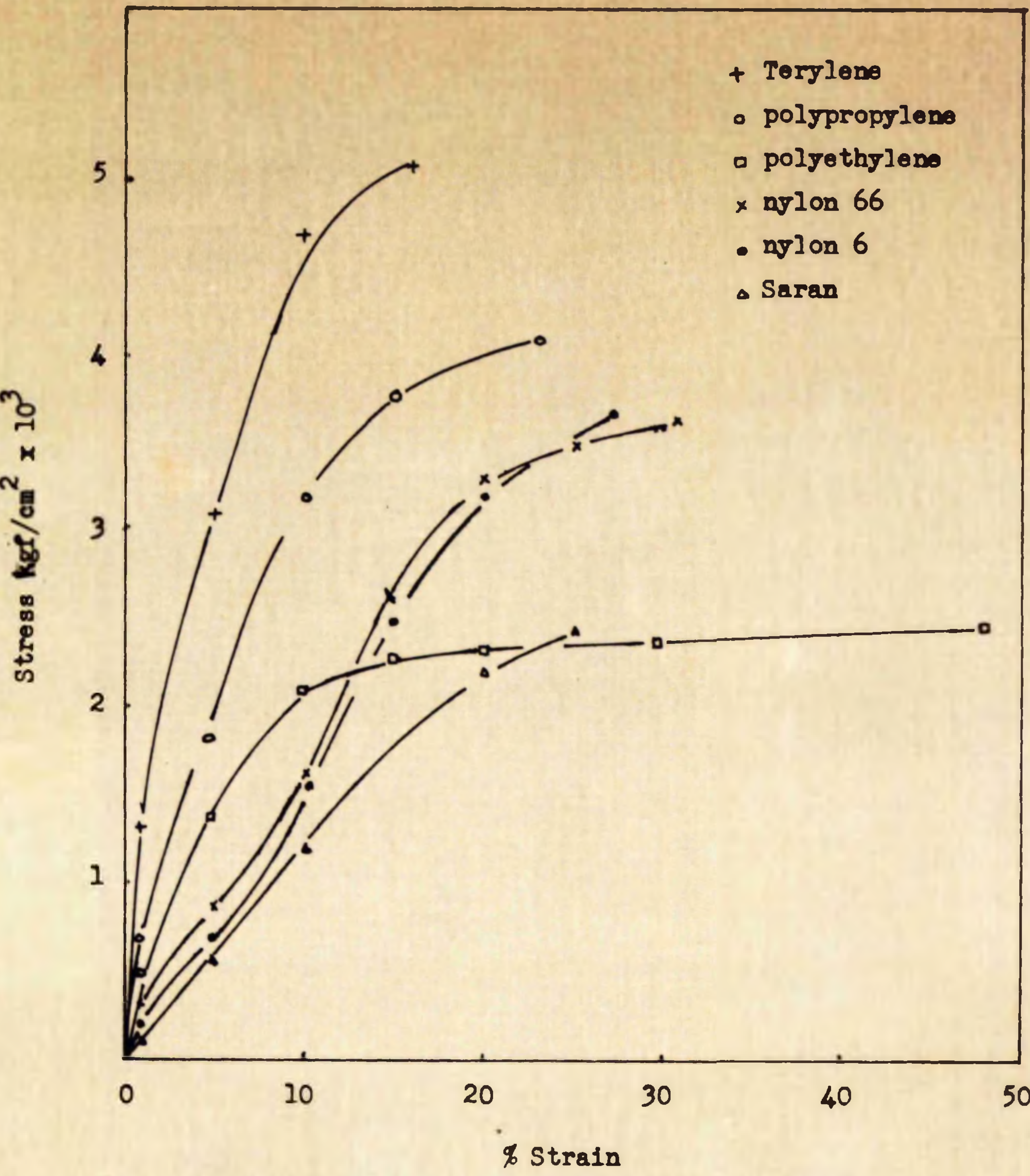


Figure 2(a) Stress-strain Curves for Monofilaments

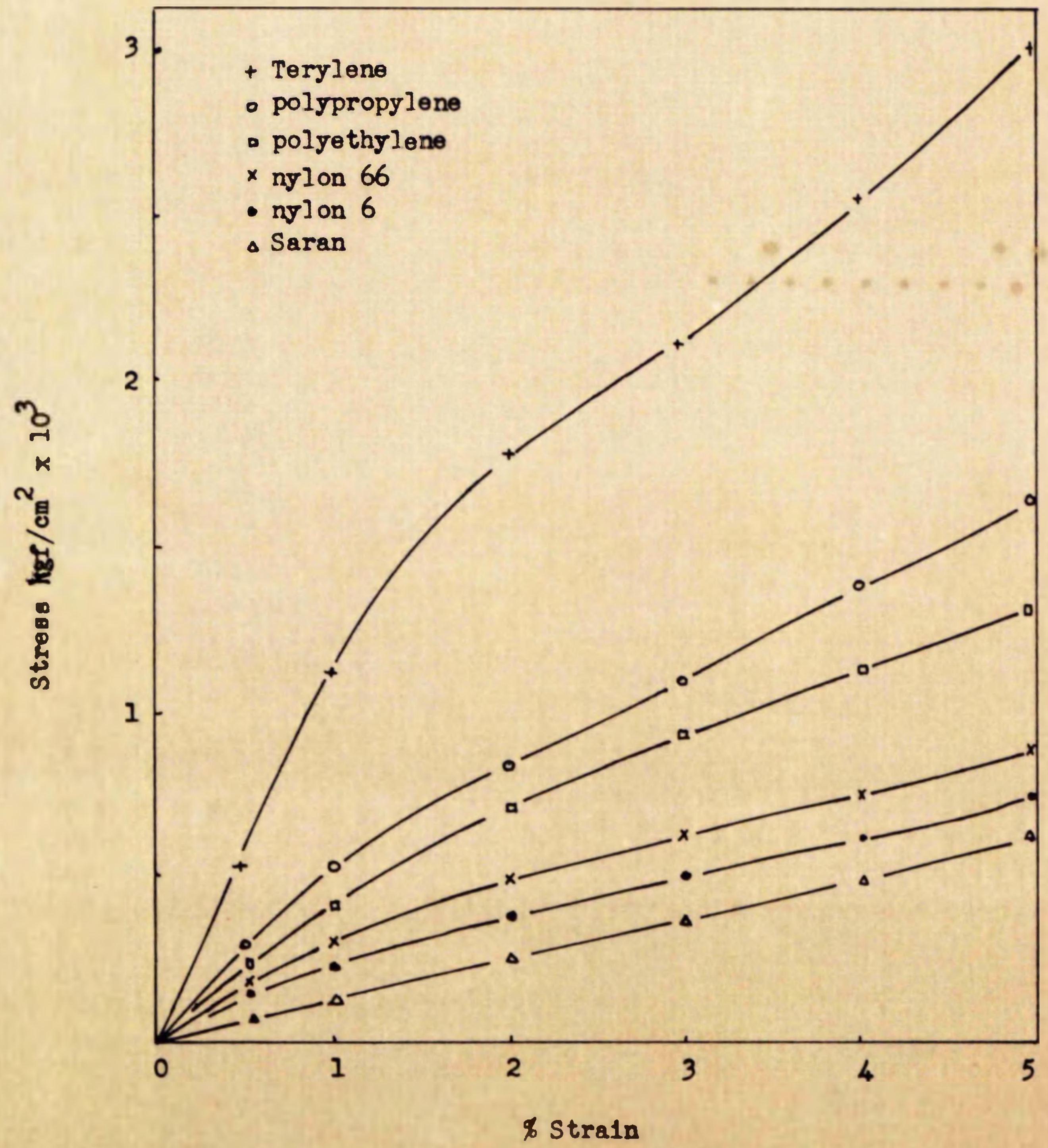


Figure 2(b) Stress-strain Relationship up to 5% Strain

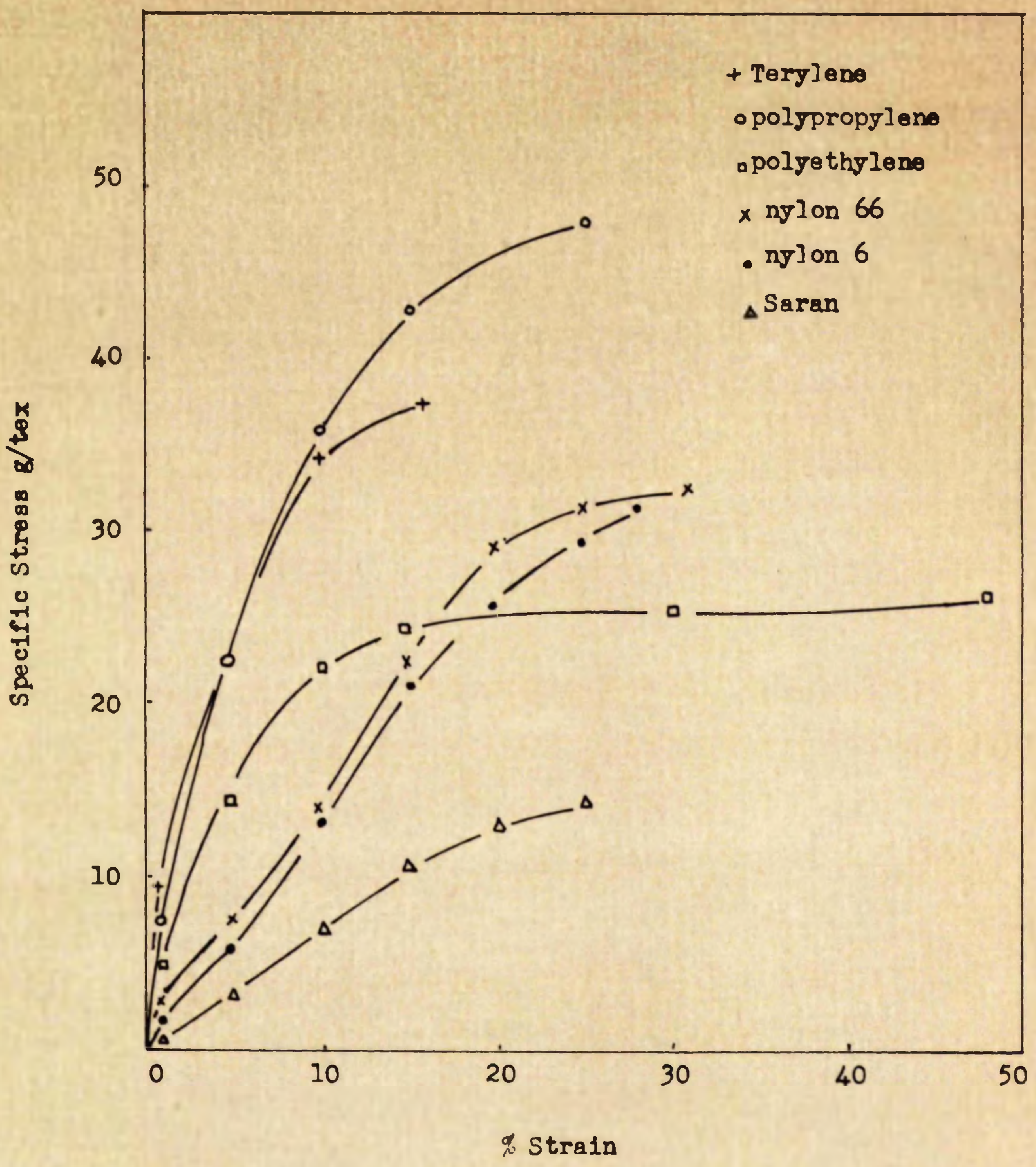


Figure 2(c) Specific Stress-strain Curves for Monofilaments initial modulus. Reference has been made to the drop in value of the strain modulus about the 1% strain load, and further consideration of strain moduli will be found in a later section.

A check was also made that the extension was common to the whole specimen test length. This was done by marking the specimen at points near the top jaw, centre, and bottom jaw. Then using the cathetometer the relative distances between jaws and marks before, and after, extension could be measured.

These measurements confirmed that any part of the fibre was extended in proportion to any other part, or to top and bottom jaw.

The amount of extension is governed by the movement of the cross-head, including the bottom jaw, relative to the top jaw and load cell. It was found that there was some displacement of the top jaw assembly under load, and a calibration curve has been shown in Figure 1, and the magnitude of the possible error in Table 3. It will be seen that unless this displacement is allowed for there is a danger of attributing a decrease in modulus value as the test length of the sample is decreased.

Finally it follows that whether the value of the modulus be calculated from the straight line portion of the stress-strain curve, or from the stress at a stated strain, the strain and stress must be correctly recorded.

Jaw Effect

In order to check whether the type of grip used to hold the sample affected the result tensile (and compression) tests were carried out using:-

(a) the normal flat clamp grips supplied for use with Load Cell B.

(b) Pin vice grips, chosen because they gripped the sample on four sides compared with the two of the normal Instron grip. These were further improved by using a vice with four circular edged jaws.

(c) Araldite grips. Samples were embedded in Araldite using either glass tubing, or nylon tubing, with an internal bore just larger than the diameter of the specimen. The Araldite could be hardened in 30 minutes at 100°C. or in 24 hours at room temperature. The high temperature method is very quick and effective but the sample must be capable of withstanding such treatment. Comment has already been made on the need to ensure careful setting and resultant test length measurement.

In the event it was found that similar results were obtained using the pin vice and the Araldite mountings, provided that care was taken that no undue jaw pressure was exerted by the vice grips as this could cause lateral compression of the material and alter its behaviour. Similar results were also obtained with the Instron type grips except that the risk of slippage was increased. Marked slippage would result in a flattened portion of the stress-strain curve but even slight slippage could be detected by inspection through the cathetometer eyepiece during the test.

There was no evidence of fibre necking under the present test conditions.

The use of a rigid top jaw assembly

Values for the tensile modulus of nylon 66, and Terylene were obtained keeping all experimental conditions constant, except that in one case the normal linked assembly was used, while in the other case the rigid assembly was used. Similar results were obtained which suggested that any error due to the use of a rigid assembly was negligible. The reasons for the use of such an assembly are discussed in the section dealing with compressive testing.

The speed of pen response

Load. It was stated that the load scale was usually restricted so that the load required for any extension fell within half scale deflection. Within this limit, and in view of the fact that the time of test usually exceeded six seconds, it was considered that any error due to pen response could be neglected as it was found that the pen would follow, within an error of less than 1% of full scale, any straight line load function which would require at least 3 seconds to travel full scale.

Chart speed. It was not thought that any error could be attributed to the chart speed used. The value of the load recorded was checked, and found to be the same whether the extension magnification was 1:1, 10:1, or 100:1. There was no occasion to use a higher chart speed than ten inches per minute, but it was considered likely that there might be some over-run of the chart from the time of the control signal at extremely high speeds.

Switch response. There could be two sources of error each dependent on the time lag between signal and response. In the case of long specimens the desired extension was set on the Return Control Dial, the Gauge Length Dial being set at zero. It was not considered that any significant error was caused by the pen continuing to respond in the fractional interval between the return signal and pen response with the crosshead stopped, close agreement being obtained between the value of load observed for, say, 1% extension when the instrument was allowed to continue past this point, and the value when the instrument was stopped at this point. The question of pen response would be critical with high speed testing there being the likelihood of a considerable overshoot under these conditions.

The second source of error was likely with short specimens where the degree of extension had to be judged by means of the cathetometer. The value of the load recorded on the chart was that corresponding to the normal signal stopping the crosshead. It was considered however that the degree of over estimation, and under estimation, would tend to cancel each other when the mean value of a number of observations had been taken.

3. <u>Compressive modulus: Test methods using an Instron</u>

No standard method was available for the determination of this property of a fibre. It was known that the problem of buckling would be encountered and that in consequence the length of the test specimen would have to be kept as short as possible.

The compressive modulus was determined as the tangent to the compressive stress-strain curve at the point of zero stress and strain. Compressive strain moduli were determined within the limits of strain imposed by buckling of the sample.

The general procedure adopted was similar to that already described for stretching tests except that the crosshead of the Instron was raised instead of lowered. The test length of the sample having been determined, the reference mark of the cathetometer was focussed on the bottom jaw and the jaw raised by an amount equivalent to one per cent (or other) compression, the appropriate value of the load being obtained from the chart. The value of the compressive modulus, or strain modulus was then calculated, the necessary correction being made to convert the value of apparent compression to the actual percentage compression.

The use of a tensile load cell for compression testing has been considered but a point of experimental interest was that by this method the same specimen could be stretched and compressed, or compressed and stretched. Thus as long as the strain applied was within the elastic limit of the fibre, a direct comparison of the respective moduli was possible, the position of zero stress being adjusted on the chart so that the chart recorded positive, or stretch, stress and negative, or compressive, stress, along the same abscissa.

The general settings of the instrument were the same as those listed previously (Page 49).

4. <u>Factors affecting the Value of the Compressive Modulus</u>

The factors which may affect the accuracy of a result include the condition of the sample, variation in the diameter of the fibre, the effect of the length diameter ratio, the amount of compression, the type of grip or jaw used, the behaviour of the sample under load, and the possibility of instrument errors.

<u>The condition of the sample</u>

It was found that the effects of the condition of the sample on the value of the modulus were similar to those on the value of the tensile modulus. The magnitude of the possible change in value has been shown in Table 1.

<u>Variation in fibre dimension</u>

The comments made in the tensile section were found to be equally applicable to compressive testing. The change in value of the modulus assuming an error was made in measuring the diameter of a fibre has been shown in Table 2.

The length : diameter ratio

It has been stated that if the length of a sample under compression is greater than ten times the diameter of the sample then the sample will buckle rather than undergo uniform compression. Thus there is a limiting factor in compression testing, that does not find a parallel in tensile testing, and the test length of the sample that can be used is therefore initially dependant on the diameter of that sample.

In the case of the monofilaments, whose diameters were of the order of 0.5 mm. this meant that the limiting length that should be tested was 0.5 cm. Reference to Table 3 will show that the effect of varying the test length within this limit on the compressive modulus was slight, it being remembered that as with the tensile modulus the value is dependant on accurate measurement of the actual strain. This meant that the value of the modulus did not change appreciably when the length diameter ratio was altered. In this case the diameter was kept constant and the test length varied but tests were also carried out on samples where the test length was constant and the diameter varied.

It will be appreciated that this was technically more difficult to achieve being dependent for success, practically and theoretically, on a number of conditions being satisfied. With a constant diameter and variable test length, samples from the same source could be used for each test and therefore a constant modulus could be assumed. With a constant test length and variable diameter samples from different sources had to be used so that a similar modulus could not be assumed until checked. The test length had to be chosen so as to be within the limit for the smallest diameter, so that it had to be assumed that there was no effect of test length on the other samples.

Tests were carried out on nylon 66 and the results are shown in Table 3. Comments on the method and accuracy of test length measurement also apply.

It will be seen that the value of the compressive modulus remained virtually unaffected by changes in the length diameter ratio provided the necessary corrections were made, and provided no buckling occurred.

The amount of compression

In a comparable section it was suggested that the value of the tensile modulus depended on the amount of extension. A similar relationship might be expected for the values of the compressive modulus. It has proved difficult in these experiments to compress a sample beyond 2%

without that sample buckling. Within this limit the behaviour under compression seems to agree with that under extension. Fig. 3 shows the tensile stress-strain graphs and the compression stress-strain graphs superimposed on the same scale and because they are in such close agreement it is felt that this offers strong evidence that the initial deflection in compression and the initial deflection in tension are similar. The sudden change in the compression curve denotes the onset of buckling.

Jaw effect

As in the case of the tensile modulus no measurable effect on the compression modulus was noted when different type grips were used. It was essential that the test specimen be vertical and for this reason it was possibly easier to line up the samples mounted in Araldite where the bore of the tubing, or former, acted as a guide. It was found however that, with experience the vice grip could be lined up accurately. Any low results, or unduly variable results would suggest that the samples were not vertical and straight when mounted, the curve breaking away at an early point in compression.

Instrument error

It has already been mentioned that the tensile modulus

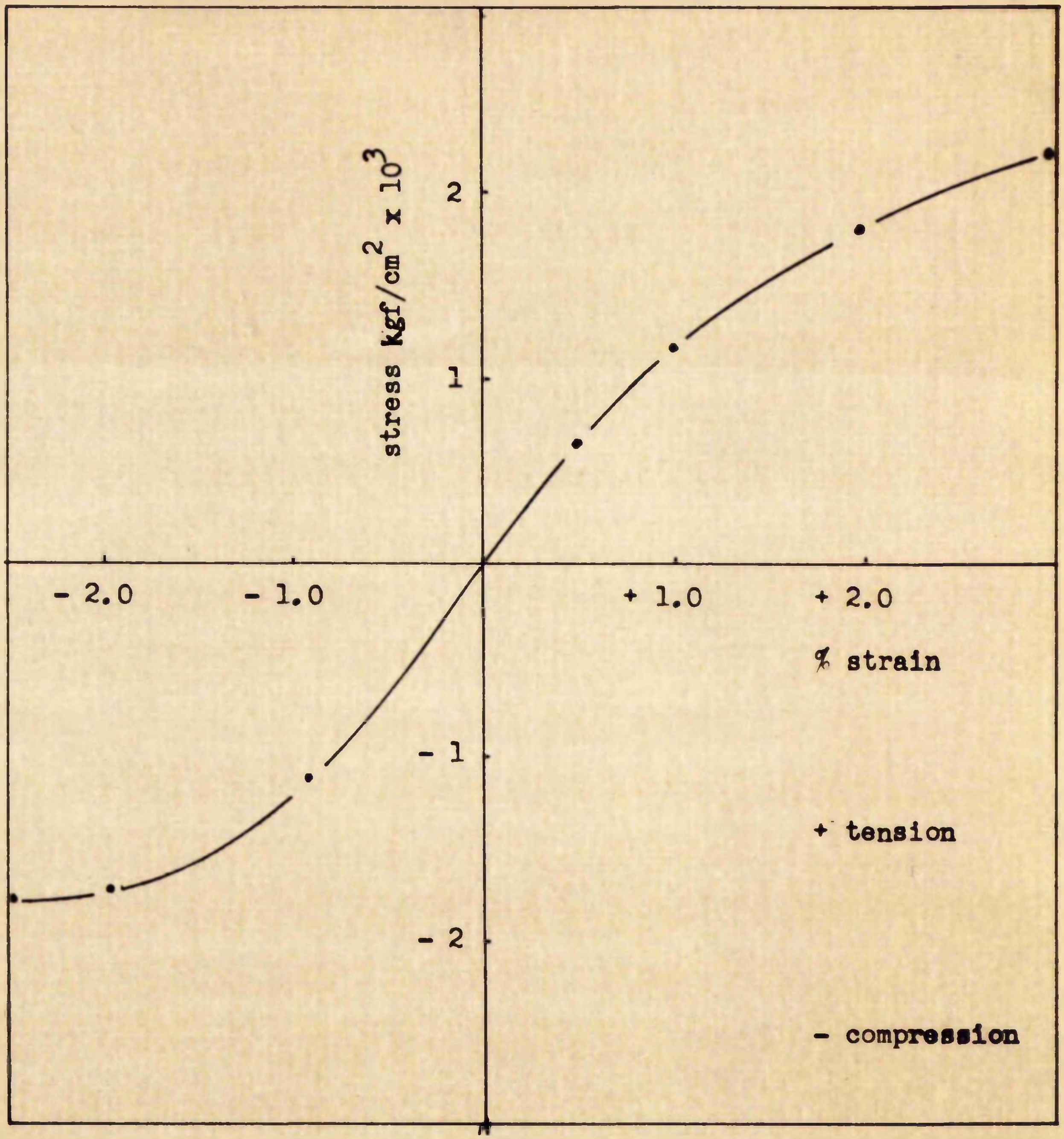


Figure 3 Tensile and Compressive Strain of Terylene Fibre

results obtained by use of the rigid assembly and the linked assembly were similar. The reason for using the rigid assembly was that it had proved extremely difficult to compress a sample with the linked assembly because the system usually bent at a link thus rendering the test useless.

Another modification was to secure the load cell unit to the frame of the instrument so that there was no displacement of the unit under the upward thrust of the crosshead during compression. It has been assumed that the compression behaviour with the rigid assembly is accurate and that a fair value of the compression modulus can be obtained and it is felt that this assumption is justified.

It was also considered that comments already made on pen response, switch, calibration, and speed should also apply in the case of compression testing, as, apart from the direction of crosshead traverse, all conditions of test were similar.

One outstanding point required to be checked, namely that the load cell would record what might be called negative loads.

In normal use the Instron is adjusted with zero load corresponding to zero pen response, at the zero ordinate of the chart. Pen response is then calibrated over the required load range such that the abscissa scale of the chart now corresponds to a particular load scale. Thus, provided the calibration switch is not altered, the displacement of the pen about any abscissa (axis) remains constant, but the actual position of the pen can be altered by the balance control to any desired zero ordinate. The pen response of course records measurements of decreasing load as well as measurements of increasing load, an example of this being found in stress relaxation experiments. Thus it can be arranged that the pen zero is set at the mid point of the abscissa scale with the displacement of, say, 100 gf. arranged to coincide with a unit scale division. If 200 g. are added then the pen response will be indicated by the pen moving two divisions to the right. If 100 g. are removed then the pen will move one division to the left. The calibration of the Instron with the normal load cell and rigid assembly for the addition and removal of 100 g. load is now known.

It would seem reasonable to assume that if the pen response is one division to the left when an upward load of 100 g. is applied to the load cell, then the load cell is capable of measuring the load characteristics with upwards deflection.

This was checked by placing 100 g. on the jaw assembly so that the pen recorded one division to the right, and then placing 100 g. on an end of a simple beam pivoted about its mid point and arranged so that the downward thrust of the weight was balanced by the equal and upward thrust on the jaw assembly. The pen response was one division to the left. In other words the effect was equivalent to the removal and addition of 100 g. load. There are limitations to the use of a tensile load cell in this way. The cell is calibrated to a capacity of 2 kgf. and there is a safety margin above that limit of a further 2 kgf. There will not be the same capacity in the reverse direction, but the cell has been used successfully up to a capacity of -0.8 kg.

5. <u>Details of Fibres.</u>

Details of the fibres used in this section have been given in Table 4. All test samples were straightened at 60°C. and 10% r.h. under a tension of 0.1 gf/tex for 2 minutes. They were then conditioned at 20 ± 2°C. and 65 ± 2% r.h. for 48 hours and tested under these conditions. Particular care was taken that samples for comparison of tensile and compressive moduli were prepared at the same time so that there was a minimum risk of local error.

Material	Tex		Diameter cm x 10^{-3}	
	mean	σ	mean	σ
nylon 6	255	2.4	52	1.3
nylon 66	252	1.9	52	1.4
polyethylene	205	5.3	53	2.4
polypropylene	160	1.8	48	1.3
Saran	355	3.9	52	2.0
Terylene	272	3.1	50	2.0

Table 4. Fibres Used in Tensile, Compression, and Bending Experiments.

The diameter of each test sample was measured to an accuracy of one per cent, the mean of three readings being taken, and when necessary the weight per unit length of the sample was also determined.

Ten results per sample per test were taken.

6. Results of Tensile and Compression Experiments

The value of the tensile modulus and the compressive modulus were calculated as the tangent to the stress-strain curve at the point of zero load and extension. In practice this was often equivalent to the strain modulus at 0.5 per cent strain but was usually higher than the modulus at 1.0 per cent strain. The modulus was expressed as stress or specific stress, the cross-sectional area being calculated from a knowledge of the diameter of the fibre, and the count of the fibre being known.

The mean values of the initial tensile and compressive moduli and respective strain moduli for certain monofilament materials have been shown in Table 5.

7. Discussion of Results

Taking the foregoing factors and variables into account it is felt that the values obtained for the tensile and compressive moduli of each monofilament material show a remarkable similarity to each other and that within the present

Fibre	Tensile Modulus kgf/cm^2 x 10^2 Initial	Tensile Modulus kgf/cm^2 x 10^2 1% Strain	Compressive Modulus kgf/cm^2 x 10^2 Initial	Compressive Modulus kgf/cm^2 x 10^2 1% Strain
nylon 6	215	195	218	197
σ	6	5	6	6
nylon 66	300	273	305	271
σ	10	8	8	9
polyethylene	300	264	296	270
σ	15	11	16	14
polypropylene	440	370	436	375
σ	13	9	14	9
Saran	110	100	107	100
σ	5	5	5	5
Terylene	1330	1220	1290	1210
σ	56	44	53	44

Table 5. The Tensile and Compressive Moduli of Certain Fibres.

limits of experimental accuracy they can be regarded as equal. A comment on statistical significance has been made later.

In the survey mention was made that values for the initial modulus of many materials were available for comparison and Table 6 shows some of these results together with their source. Allowing for variations due to molecular orientation and method of test it will be seen that the values obtained in the present experiments compare favourably with those other results and this has been taken as verification of the experimental procedure.

It follows that if the tensile results were correct then the compression results should also be correct as the procedure was so similar to that used for stretching the material and was checked stage by stage. Before considering the compression results however further comment can be made regarding the value of the initial modulus and the tensile strain modulus. It has been shown that considerable changes in the value of the Young's modulus are possible. The reasons for these have been adequately described but the extent of such changes may be summarized. The difference between the value of the modulus at zero stress and strain, and stress at one per cent strain has been found to be a drop in value of the order of 10%. The value of the modulus

F I B R E

Property		nylon 66	polyethylene	polypropylene	Orlon	Terylene	Viscose rayon
Initial Modulus	(1) g/tex	200/747	18/180	810	18/99	774/1090	800
	(2) kgf/cm^2 x 10^3	27/85	2/20	74	3/27	100/145	220
Stiffness	(1) g/tex	126/410	18/108	135/290	90/180	120/207	99/630
	(2) kgf/cm^2 x 10^3	14/46	2/10	12/25	35/27	17/28	-
Elastic Recovery %							
from 1% strain		90/100	65/100	40/98	70/100	98/100	67/100
2% strain		95	-	-	100	95	-
5% strain		90/100	60/98	-	60/100	65	32/90

References. 20, 21, 22, 23, 27, 37, 212, 210.

Table 6. Reference Values for Initial Modulus, Stiffness, and Elastic Recovery of Fibres.

could change by 50% due to preparation, while inspection of other results suggested that the possible range of modulus of fibres of the same type was also 50%. Fluctuation in value due to changes in atmospheric conditions have not been considered at this stage.

It is felt that there is a strong case for defining the preparation of test samples as well as conditions of test. The initial modulus value is rather an unrealistic value subject to error in actual measurement and it is thought that the strain modulus is at once a more realistic term, is more definitive, and may possibly be extended to cover any particular strain which is expected to be representative of the end use of the fibre. It was noted that the value of the modulus has been expressed in various units in the literature references but beyond commenting that this renders immediate comparison difficult, discussion on units will be kept to a later point in this thesis. Similarly the question of strain moduli will not be developed further at this stage because of the restrictive nature of compressive strain leading to buckling.

Some idea of the possible change in value of the tensile modulus has been given and will be considered more fully in comparing tensile and bending properties, where the order of strain will be shown to be high under certain circumstances.

Several writers[31,32,161] have commented on the decrease in modulus value with decreasing test length. It has been shown that decreasing values will be obtained unless the actual strain of the sample is accurately measured and the author is satisfied that failure to do this is a major cause of error. Against this there is the theory of weak links propounded by Peirce[164] and others[18, 165]. This relates to breaking stress and strain but if there had been some correlation with initial yield the modulus values should have increased with decreasing test length. This was equally not the case.

Thus it is felt that the value of the modulus is unaffected by the test length provided the gradient of stress relevant to strain has been accurately obtained and that the values of stress and strain are such that necking, lateral compression and similar effects do not occur.

Backer[31] measured the initial modulus of compression of a nylon monofilament and a polyethylene monofilament by means of a single lever chainomatic loading device, the compressive deformations being measured by means of a travelling microscope. He concluded that the value of the initial modulus was strongly influenced by the height;

diameter ratios of the specimen, being generally below that of the tensile modulus but approaching that value as the height; diameter ratio was increased.

Extrapolation of the initial compressive modulus to the case of the infinitely long specimen provided moduli of comparative value. Exact experimental details were not given and are not readily available being apparently contained in unpublished work[166,167]. The range of height: diameter ratios were from 0.4 to 2.0 and, as far as can be gathered, the sample was unrestrained although not lubricated. The range of percentage strain imposed was of the order of 10 to 15 per cent but, from inspection, there was a difference in behaviour with changing height: diameter ratio from at least 1% strain. The method used for the determination of the tensile modulus was not given. From what information is available the following items are of interest. The value of the initial modulus was shown to be approaching that of the tensile modulus as the height diameter ratio increased but the highest value quoted was 2.0 whereas in this work the range of ratios were from 4.0 to 10.0. The value of 1% strain showed a minimum difference between moduli and it is at these low extensions that the need for accuracy has to be greatest. The effect of decreasing modulus with decreasing height: diameter ratio is similar to that noted for the tensile behaviour earlier in this thesis. The reason then was found to be due to an experimental error in the measurement of the actual extension of the specimen due to failure to allow for the movement of the top jaw assembly, and when this was corrected the value of the modulus remained unchanged. The extrapolated values of the compressive modulus and the values given for the tensile modulus are low compared with those quoted from other sources but it has to be assumed that this was due to the type of nylon and polyethylene that was used in these experiments.

Miles[32] also measured the compressional behaviour of nylon and recorded a difference in behaviour between the tensile and compressional properties. The method used for measuring the tensile properties was not stated, but the compression values were obtained on an Instron by means of a compression load cell. The bearing surfaces were lubricated in order to obtain as nearly as possible unaxial compressive stress. No evidence of buckling was recorded and the deflection of the load-measuring cell was allowed for by measuring the separations of the bearing surfaces. The height: diameter ratio was slightly less than 2 and no values for different ratios were quoted. Miles recorded the stress-strain curve of nylon and stated that above about

1% strain the curve for the compression strain differed from that of the tensile strain but that the accuracy of measurement was not sufficient to determine whether the curves below 1% strain were, in fact, identical. At 2% strain the stress in compression was about 15% less than that in tension. Mention was also made that the elastic recovery of the compressed sample was somewhat lower than that of the tensional sample up to about 10% strain after which the two were equivalent.

There is agreement between the results of Miles and those above in that both suggest that the value for the tensile and compressive modulus is similar up to 1% strain. Thereafter the shape of the stress-strain curves suggests that buckling occurs so that agreement need no longer be expected. It is considered that the agreement also suggests that the comments made in a previous section concerning the mounting of a sample are correct. Then it was shown that the manner of mounting the specimen had not had the effect expected from consideration of other writers and that no difference had been found between samples clamped and hence under pressure, and those that might be considered as subject to shear only.

The agreement in results now suggests that there is no difference between clamp, friction, and free mounting, at least at low values of stress or strain. The specimen in the work carried out by Backer was also unrestrained but was not lubricated and Backer commented that there was no evidence of the specimen barrelling despite the difference in initial modulus obtained. It would appear that there were no hard or conical zones in these axial tests of fibre compression because if such zones existed the shorter specimens should have offered greater resistance to compression.

Very short samples of wool were used by Denby[33] in measuring the modulus of keratin in compression. It had been shown by Edelman[168] that, for a block whose length and diameter are equal, the error introduced by neglecting friction forces between the end blocks and the specimen was less than 5%. All compression samples were cut such that the sections had approximately equal length and diameter. Small increments of load were applied to the sample and the strain measured by an optical method involving the change of the interference pattern. It was stated that there was linear stress strain from 0.2% to 1.2% strain in the dry state and from 0.6% to 1.3% for wet fibre from which a dry compressional modulus of 9.5×10^7 gf/cm^2 and a wet modulus of 2.8×10^7 gf/cm^2 were obtained. The latter value was reduced to 1.5 when the time of test was increased to

2 minutes. The comparable stretching values were 4.4 x 10^7 gf/cm^2 dry, and 1.2 x 10^7 gf/cm^2 wet based on a 5 centimetre test length.

Unfortunately Denby gave no details of dry conditions and it was not possible to compare the times of the two tests exactly. Some idea of the time dependance of the property was given by the 50% reduction in modulus value when the time of test was increased one hundred fold. A high value might be obtained from a very short test length because of the lack of weak links but a value of 8 x 10^7 gf/cm^2 for the tensile modulus of wool has been given by Feughelman[169] and in fact this order of result seems to find general support. The low value of tensile modulus obtained by Denby would therefore appear in doubt but for reasons unknown.

It was stated that the amount of compressive strain that could be applied had been limited by the tendency to buckle. According to the linear theory of buckling[34, 35] and provided the sample has been correctly mounted in a vertical position relative to the compressing surfaces, the sample should remain straight as long as the load remains below Euler's critical value F_{cr} where the value is given by:-

$$F_{cr} = \frac{4\pi^2 EI}{L^2}$$

for a sample with both ends free, or

$$F_{cr} = \frac{4\pi^2 EI}{L^2}$$

for a sample with both ends clamped where E is the compressive modulus, I the moment of inertia, and L is the length of the column under compression.

Application of the latter formula was attempted with the present results for nylon 66 (0.16 inch test length) and Terylene (0.12 inch test length) but it was found that buckling occurred before the (calculated) values of load were reached.

$$F_{cr} \text{ nylon 66} = \frac{4 \times 9.87 \times (27 \times 10^{6}) \times (358 \times 10^{-9})}{(165 \times 10^{-3})}$$

$$\doteqdot 2.4 \text{ kg}$$

$$F_{cr} \text{ Terylene} = \frac{4 \times 9.87 \times (10 \times 10^{7}) \times (310 \times 10^{-9})}{(92 \times 10^{-3})}$$

$$\doteqdot 12.0 \text{ kg}$$

Inspection of the load compression curves suggested that the critical loads were nearer to the values that would have been expected for the compression of a sample having both ends free.

One reason for this might lie in the difficulty in ensuring that the sample remains absolutely vertical during loading or it may be that the sample was bending in such a manner that the effective bending length in practice was greater than that presumed in theory. It is considered that this aspect of the work requires further study.

Above the critical load buckling occurred and thereafter the stress-strain curves were not directly comparable. Up to this point however it has been found that the tensile and compressive stress-strain curves are identical.

Values of critical load were calculated for the data given by Backer[31], agreement was reached with the apparent yield value of about 0.08 p.s.i. for the polyethylene sample where the height diameter ratio was given as 0.706.
According to Backer however as this ratio increased the yield stress increased slightly. As the same sample was used each time so that the diameter was constant, an increase in ratio implies an increase in test length which should result in a decrease in the value of critical load. If it is argued that the height diameter ratio is so low that buckling of the sample cannot be recorded, then the change in gradient could be due to failure to record the actual strain imposed

but the yield point is still too low. A possible explanation might be that it reflects a compromise between the yield point which should be higher and the buckling point which should be lower.

Applying the theory of buckling to the results shown by Miles also gives some interesting results. The fibre was nylon, 1.5 mm diameter, with a test length between 2.2 - 2.7 mm. The modulus was not quoted but would appear to be about 0.16 g/den by inspection. By calculation the value of the critical load is 0.3 g/den., which again by inspection appears a reasonable value coinciding with a marked yield point on the compressive stress-strain curve.

Miles also measured the elastic recovery of a sample after tensile, and compressive, strain. Elastic recovery has been considered briefly in a later Chapter but comment can be made that the author has found high, and equal, recovery from low strains, whereas Miles reported a low recovery from compressive strain.

Finally reverting to the present results, the mean values of tensile and compressive moduli were checked to see whether the difference between the respective means was statistically significant. It was found that for a probability level of 0.05 the difference between the means did not exceed twice the standard error of difference, and it was concluded that at the present level of experimental accuracy the differences between the values of the two moduli were not significant.

For the tensile and compressive moduli to be the same the stress-strain relations in tension and compression must be the same. A practical illustration that this is so has been given, but from a theoretical aspect this would mean that the properties of strain, creep and recovery, and stress, transmission and decay, must show similar tendencies whether stress is positive or negative. It is known that the history of a sample influences the value of either modulus, and the sample can be regarded as being stable at an instant of time only when its structure is at equilibrium with conditions of test. Given a small increment of stretching strain and held in its new position, decay will occur such that the path of a subsequent small increment of strain, recorded as a stress-strain curve, will repeat the path of the previous change in state. Alternatively, if after the first increment the sample is not held then recovery occurs and again the pattern can be repeated with a subsequent increment. It is argued that if the sample in the stretched state were subjected to compressive stress then recovery might be accelerated but the pattern of behaviour would be the same at least in semi-static tests and provided the increments of strain were low. The behaviour would be the same if the sample was given one increment of compressive strain in the first instance. It is agreed that this could only be expected to be true for materials whose degree of orientation and crystalline/amorphous content was such that the molecular chains were not in a fully extended rigid parallel state. The effect in fact being likened to a trellis network where the force required to stretch or close the lattices a small amount from an intermediate position could be the same. It is appreciated that this is perhaps an over-simplification of facts because of the complex theories relating to elastic behaviour but some support has been noted in the comments by Meredith[4] on the relation between creep and recovery. The possibility of a mirror image between the two properties was deduced and the statement made that according to Boltzmann's Superposition Principle, removal of load can be regarded as equivalent to the application of a negative load. It is known that the initial stress-strain relation varies as a function of time and the relaxation of stress for small strains is also approximately linear with time on a logarithmic basis. No reference to the relationship between comparative rates of additional and subtractive stress has been found and it would be expected that consideration of various rheological models would be required but during experimental work cyclic tensile compressive stress-strain curves were obtained which were similar to force-length curves discussed by Stein et al[230]. In this paper, which was part of a series on stress-strain relations, it was stated that the force-length working curve described the hysteresis behaviour of a Maxwell element at constant elongation rate. It was further stated that operations were usually only shown for positive forces because of the impossibility of compressing a fibre. The present experiments have shown that heavy tex monofilament materials could be used for further study on this point.

CHAPTER 4. TENSILE AND BENDING MODULI OF FIBRES.

1. Tensile Modulus: Test Methods for Measuring.

2. Bending Modulus: Test Methods for Measuring.

3. Factors Affecting the Value of the Bending Modulus.

4. Test Methods for Measuring Friction and Birefringence.

5. Details of Fibres.

6. Results of Tensile and Bending Experiments.

7. Discussion of Results.

CHAPTER 4. TENSILE AND BENDING MODULUS OF FIBRES.

One interest lay in the measurement of the initial tensile modulus to allow direct comparison with the bending value and this involved the accurate recording of the stress-strain relationship at low strain.

A survey of literature had shown that there was no specific statement that the tensile and bending modulus of a fibre were one and the same thing. In fact there were a number of conflicting statements and it was hoped that the reasons for these might be found by a critical examination of test methods.

However the strain was also continued up to breaking point to allow inspection of strain modulus values and comparison of tensile and bending moduli at any particular strain. It was hoped that such results would be used in later work concerned with the stiffness of a material.

1. Tensile Moduli: Test Methods for Measuring.

Instron

The general principles of testing were kept the same as previously described except for some minor modifications. A ten inch test length was adopted as this proved a convenient length for measurement, calculation, and accuracy, but tests were also made on lengths over the range of one to ten inches as a further check on the work of the previous section. When a longer length was used and small strains were involved, the chart speed was restricted to ten times that of the crosshead speed because of the reduced need for magnification of extension. For stress-strain relationships up to breaking strain little or no magnification was required. Load Cell C, 100 kg capacity, was used in place of Load Cell B where required, the normal linked assembly also being used. The crosshead speed remained at 10 per cent extension per minute for all work involving small strains, but was increased to 20 per cent extension per minute for strains above 5 per cent.

Cambridge Extensometer

This instrument[171] was used for some work where it was desired to measure the tensile and bending property of a fibre under identical conditions. For the tensile part this involved choosing gears that would give a comparable rate of strain to the bending test. The selection was not as large as that with the Instron and it is possible that some divergence in results could be attributed to a time difference.

The extension was magnified 20 times giving an ordinate of 1 inch for 1% extension.(5 inch test length.) The abscissa was usually chosen so that the load scale was of the order of 2 inches for 1% extension.

Comments on experimental accuracy and errors are largely similar to those already made and need not be repeated.

2. Bending Modulus : Test Methods.

The bending modulus of the materials has been obtained using the beam method and the loop method, both of which have already been mentioned.

Beam Method. Cambridge Extensometer

The method used initially was similar to that used by Carlene [2]. Reference will show that measurements of the deflection of a beam under increments of load are required, the test length and the diameter of the sample being experimental variables.

When the Cambridge Extensometer was used to provide the necessary increments of load, the speed of the spring motor was set at two inches per minute and that of the fibre motor at six inches per minute. By use of a suitable spring the load scale was of the order of two inches, and the deflection of the specimen completed within thirty seconds. The deflection of the beam was magnified twenty times by use of a special gear assembly fitted to the Cambridge, the normal limit being five times.

It would have been preferable to use a constant rate of depression but this was not possible with the Cambridge unit because the extremely small deflections and the limited speed range involved (0.2 inches per minute was the smallest possible) would have meant the deflection being completed in a fraction of a second, an interval of time well outwith the sensitivity of the Cambridge. By using a suitable spring, constant spring motor and gear ratio it was possible to produce a smooth load-deflection curve with both the load and deflection on a suitable scale.

The instrument was mounted over an oven so that bending tests could be carried out under different conditions of temperature and humidity. An outline of the assembly is shown in Figure 4. The main changes from the usual assembly were to lengthen the fibre support rod, provide a spring support rod, mount the make and break contact and top fibre support in the oven, and provide a long lead to the control panel so that some mobility was possible. It was essential that the extensometer be mounted centrally over the oven with a minimum of friction between the moving rods and the wall of the oven, that the fibre could be easily observed in situ, and the deflection measured. The mobility of the control panel ensured that a test could be carried out while observing the specimen, or the chart, whichever was desirable.

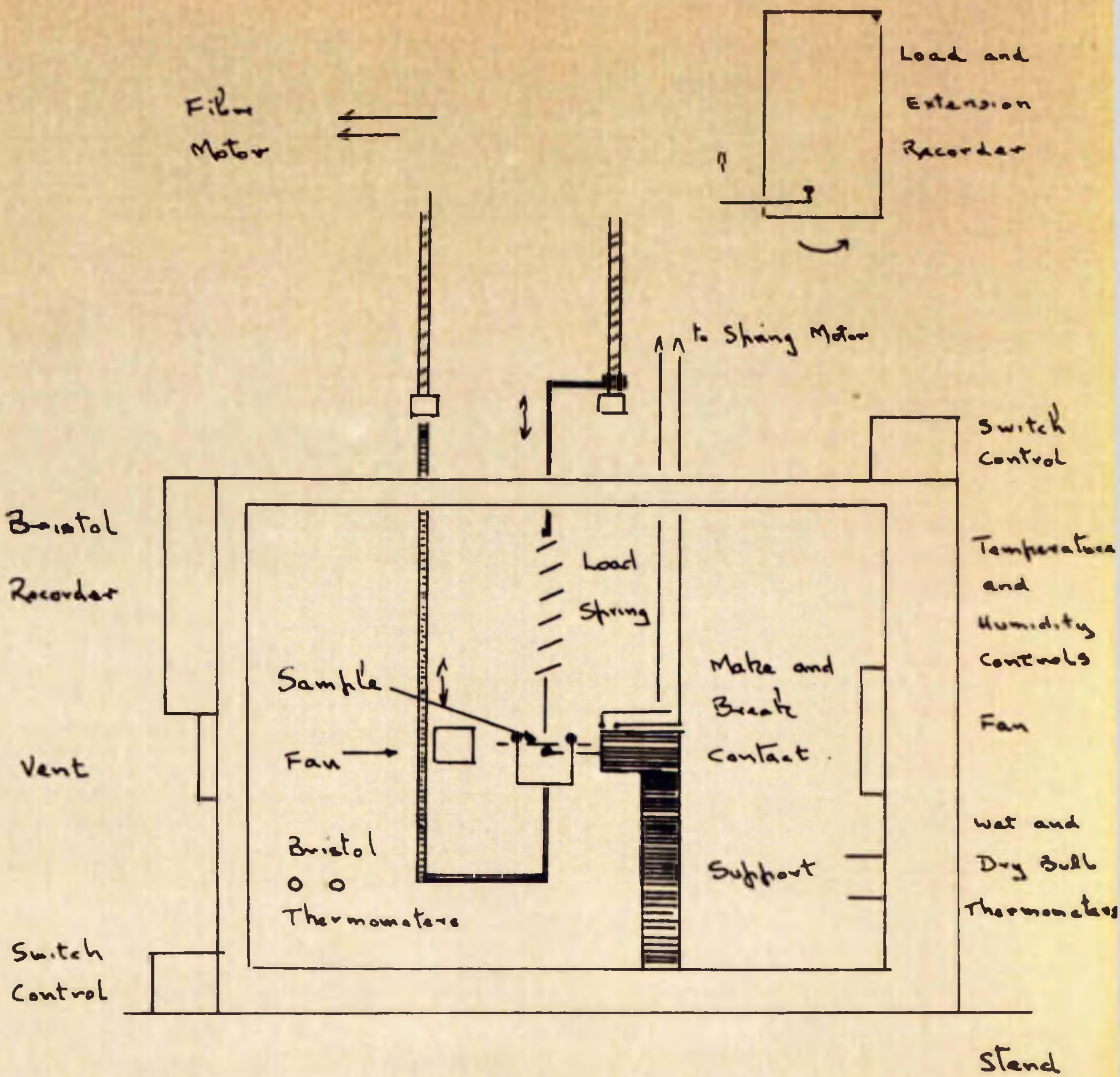


Figure 4 Gallenkamp Oven Assembly

All springs used were the standard Cambridge springs which require a specific load (ounces) to extend them by one inch. The designations were useful as a means of reference to the spring used and as a guide to the range of load to be expected, but in practice each spring was calibrated in grammes under the conditions of test, and this calibration was checked at the completion of each experiment, a suitable range of gramme weights being kept for this purpose. A check was also made periodically that the extension or deflection recorded on the chart was twenty times that of the movement of the fibre assembly, while the deflection itself was accurately measured by use of a cathetometer. A small knife edge was linked to the load assembly, and two blades, set to the correct distance apart, were linked to the extension assembly. The unit was mounted this way to keep the weight of the assembly as low as possible so that the low load, or more sensitive, springs could be used. The rigidity of the assembly had also to be watched so that there was no risk of the supports contributing to the apparent bending of the sample.

<u>Beam Method: Instron</u>

An Instron assembly was also used, partly as a check on instrument accuracy, and partly because it was desirable to be able to vary certain test conditions more easily than was feasible with the Cambridge assembly.

Either Load Cell A or B was chosen depending on the range of load required; the single pivot was suspended from the top jaw, and the instrument adjusted to compensate for the weight of the pivot. The Instron was then calibrated so that the maximum load likely to be recorded corresponded to half scale deflection.

A double blade assembly was mounted in the lower jaw, care being taken that the assembly was level and that the position of the single blade (pivot) lay parallel to and midway between the two blades.

The crosshead speed was chosen so that the time of the test corresponded as nearly as possible to that of the comparative Cambridge test, unless the effect of speed of test was being measured: in some experiments the speed was adjusted to give rates of strain comparable with tensile tests. A decade reduction gear was essential, permitting crosshead speed to be as low as 0.02 inches per minute. The chart speed was set to the appropriate speed, it being possible to magnify the deflection up to one thousand times compared with the limit of twenty times with the Cambridge test. For convenience a magnification of one hundred times deflection would normally be chosen.

With both instruments the beam length selected was dependent on the diameter of the fibre and the strain required but was usually 0.2, 0.4, or 0.6 inches. The inch unit was used because of ease of reference with instrument controls.

Loop method : Cambridge

Details of the method used to measure the flexural rigidity of a loop of yarn by means of the Cambridge Extensometer have been given by Carlene [7], while experimental details concerning the use of the Cambridge for beam experiments have been given above. The difference is that measurements of the amount of deflection of a loop under increments of load are required, the test length and the diameter of the sample still being experimental variables. Thus the beam supports had to be replaced, or modified, it being found easiest to use hooks although knife edge supports were also used. The load spring and gear ratio were chosen so that the sample could be extended in a time as near as possible to that of any comparable test. The depression of the loop was magnified twenty times.

Loop method. Instron

The test method used was similar to that already described except that the beam supports were replaced by hooks. Care was required that the top and bottom hooks were in the same vertical plane so that there was no lateral displacement of the test sample. The Instron was zeroed so that the weight of the top hook was allowed for, and the appropriate load sensitivity chosen. The chart speed setting was one hundred times that chosen for the crosshead setting.

Loops were normally either 1.7 , 4.2, or 8.7 centimetres. diameter being prepared on a Perspex former.

It was found that if the sample was held round a circular former of the required (loop) diameter, and a reef knot tied so that the fibre was not allowed to slacken, loops of the appropriate diameter could be made.

A plastic sheath in close contact with the former, and yet capable of sliding over the surface of the rod, enabled the specimen to be removed with the minimum of distortion. The effect of the size of the loop will be considered but the effect of the position of the knot in relation to the loop assembly has already been discussed by Carlene [7], who advocated that the knot be placed at the 2 o'clock position with the loop.

With the loop method it is the value of the flexural rigidity of the material that is obtained, the value of the bending modulus being obtained by substitution in the appropriate equation, having calculated the moment of inertia.

With both the beam and the loop method on the Instron the error caused by top jaw displacement is negligible because of the low load involved.

3. Factors Affecting the Value of the Bending Modulus.

The factors, and the variables, that were considered as likely to affect the value of the bending modulus were the method of test, the condition of the sample, the diameter of the sample, the test length, the percentage strain imposed, while instrument errors included the type of beam or loop support used, and time and scale effects.

Method of test

Method of test

Values for the bending modulus of all the monofilament materials were obtained by the beam and loop method on both the Cambridge Assembly and the Instron. The conditions of test were kept as similar as possible and it is considered that the two methods and two instruments gave identical results although the risk of error is decreased with the Inston because of the greater control sensitivity and increased scale magnification. The beam method has the advantage of giving a direct value of the bending modulus, allowing the amount of strain to be directly measured, while the sensitivity may be controlled by the selection of a suitable test length. It does require a reasonably straight specimen and the test is terminated by the slipping of the sample.

The loop method has been used successfully over a range of monofilament materials, was sensitive to the state of the material unless decay has occurred, and there was no problem of slippage. The immediate result however is flexural rigidity, a calculation involving angular displacement, and further calculation is required before the value of the modulus is obtained.

Condition of sample

This does not refer to the effect of temperature and humidity on the sample at the time of test, but to the general physical state of the sample due to the past history of the sample.

Reference has already been made to the fact that the value of the tensile modulus obtained was very much influenced by the state of the material when tested, and that this applies also to the value of the bending modulus is shown by the results in Table 1. It is considered significant that the changes in the values of the bending modulus echo so closely the changes in the values of the tensile modulus.

A second form of the effect of the condition of the sample was found when some samples of the same material, but of differing diameter, prepared in the same way were found to have a different value of bending modulus. The tensile modulus of these samples was then obtained and as shown in Table 15 (p.143) it was found that the difference in modulus was maintained. Thus the value for the modulus of a fibre may vary from sample to sample of the material where the samples considered are of different origin.

A third form of the effect of the condition of the sample was considered as likely to lie in the actual form of the material. This may be illustrated by reference to later work where the values of the bending modulus of multifilament nylon are given.

There are certain difficulties with regard to the form of the specimen, not so much in the actual experiment as in the calculation of diameter, shape factor and moment of inertia and the best method of expressing the results, and these will have to be considered more fully in their appropriate section.

<u>Diameter of sample</u>

Whether the value of the modulus is obtained from the value of the flexural rigidity, from the beam method or the loop method, the final calculation involves the raising of the value of the diameter of the specimen to the fourth power.

Mention has been made earlier of the possibilities of error in the actual measurement and also of the presence of some actual variability in diameter. Table 2 shows the magnitude of the difference in bending modulus assuming different initial diameters. With fibres of the same material but different diameter there should be a direct relationship between the load and the fourth power of the diameter if all other conditions are kept constant. This served as a means of checking that the correct deflection was being used, while in other cases the lack of correlation confirmed the fact that the materials had different modulus even though they were chemically similar fibres.

Effect of test length

Beam. In theory there should be no difference in the value of the modulus obtained when the test length is altered provided that the strain remains within the elastic limit, and in fact this should serve as a means of checking the accuracy of any specific result or method as the value of the load required for a specific test length should vary inversely as the cube of the test length. It is important that the test length be accurately measured as any error is magnified, and it was usual to check that the load length relationship held.

Apart from the question of errors and accuracy there is a practical point to be considered. If the beam is short then the deflection is small and a large load is required to cause deflection. If the beam is long, the deflection is factually greater and may be more accurately measured, but the load required may be small. Thus for fine filaments the former is the more likely while for coarse filaments the latter is preferable.

This of course is discounting the concept of bending in terms of percentage strain.

<u>Loop</u> In this case the concept of length is circumferential length, related to loop diameter and, as will be shown, also related to percentage strain, and we find the term raised to the second power. The accuracy depends on the accuracy of the measurement of the loop diameter and while this could be taken as equivalent to the diameter of the former used for the making of the loop where fine filaments were involved, the diameter of the loop was usually checked by means of cathetometer measurements.

In theory, again the value of the flexural rigidity, and hence bending modulus, should be independent of test length provided that the strain is within the elastic limit, and some further comment is made on this point in the next section.

It can be stated that similar values of bending modulus were obtained with different test lengths. This would support the contention made in the tensile section that the results so often attributed to a short test length are due to failure to record the actual change in dimension.

Percentage strain

It was shown in a previous section that the value obtained for the tensile modulus of a material was dependent on the strain imposed, the value of the modulus usually dropping outwith the truly elastic region, and this has been confirmed in the present section.

It might be expected that the value obtained for the bending modulus would also be affected by the amount of strain imposed during bending. This implies consideration of the methods by which such strain may be estimated, and of the extent of a true linear relationship between stress and strain.

Beam

Reference to Figure 5 will show the possible configuration of a beam under stress. The following example has been inserted to show the form of calculation. Let the test length of the sample between the beam supports be 0.6 inches and the diameter of the sample be 0.02 inches.

Then Strain $= \frac{a}{r}$ where a is the radius of the sample (in). and r is the radius of curvature.

curvature $= \frac{1}{r}$

$\sin\theta = \frac{\ell}{r}$ where ℓ is half the test length of the sample.

and, $\cos\theta = \frac{r - y}{r}$ where y is the deflection of the sample at the mid point.

Therefore for one per cent strain we require that

$$0.01 = \frac{0.01}{r}$$

so that $r = 1$

and hence $y = 1 - \cos\theta$

but $\sin\theta = 0.3000, = 17^\circ 28'$, and $\cos\theta = 0.9539$.

therefore $y = 0.046$ inches

$= 0.92$ inches on chart (magnification x 20)

Similarly the deflection required to producea given strain, or the strain for any deflection, c an be calculated for any fibre when the test length and diameter of the

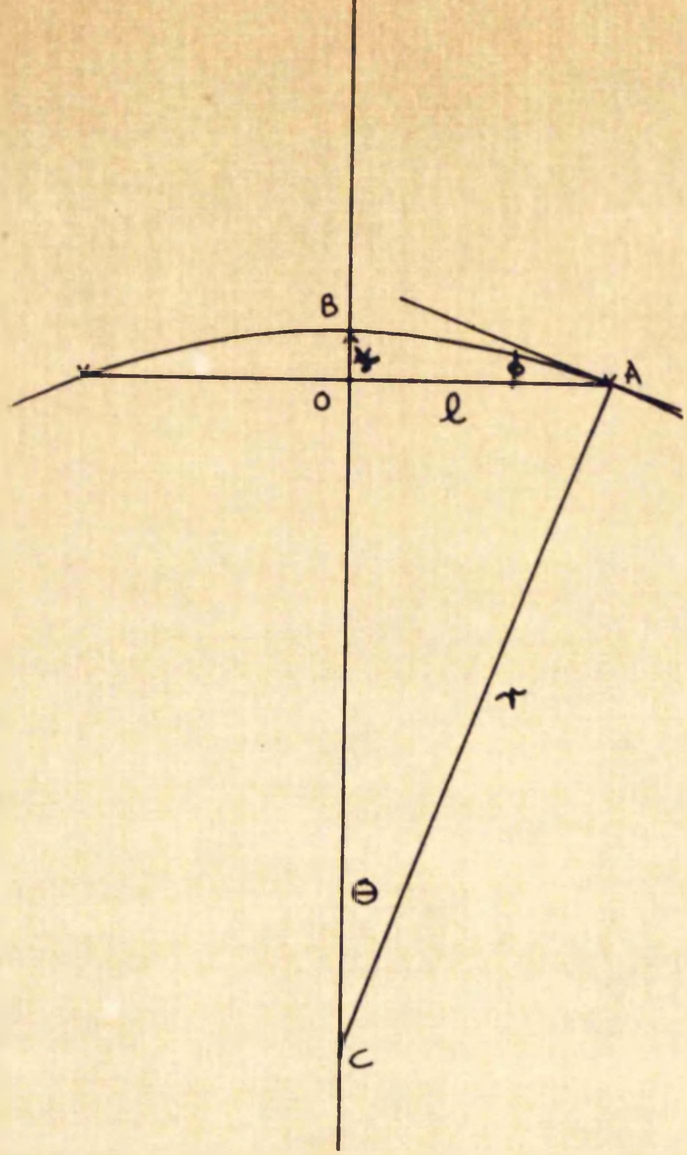


Figure 5. Simple Geometry of a Bent Beam

test sample are known.

The deflection strain values for different beam lengths for a fibre have been given in Table 7. Comment has been made that it proved impossible to deflect a fibre by the amount necessary to strain the mid-point, centre to wall, by 1% without slippage. It is considered significant that there was continued agreement with strain and modulus calculated on the present basis.

Loop

The amount of strain imposed in the formation of a loop of material is given by the ratio d/D where d is the diameter of the sample, and D the diameter of the loop. It would be expected from what has been said concerning the linearity of stress-strain relationship, modulus, and percentage strain imposed, that the modulus obtained by the loop method would be constant provided that the strain imposed was within the elastic limit, and generally decrease as the strain increased.

This latter point was confirmed by experiments whereby the flexural rigidity and hence the bending modulus of nylon 6 was obtained with samples of differing loop size tested immediately after loop formation. (Table 8)

Strain	Beam Length	in.	
	0.2	0.4	0.6
%	Deflection	in	
0.5	-	-	0.0230
1.0	0.0050	0.0202	0.0461
2.0	0.0101	0.0418	0.1003
3.0	-	0.0675	-
4.0	-	0.1000	-
5.0	0.0268	0.2000	-

Table 7. Deflection Strain Values for Different Lengths of Test Beam.

	Loop size D cm.			
	1.7	3.2	4.2	8.6
Bending modulus $kgf/cm^2 \times 10^2$	115	159	186	200
% strain before test.	3.1	1.6	1.2	0.6

Table 8. Effect of Loop Size on Bending Modulus of Nylon 6.

The question of linearity and elastic limit during the actual test itself can be confirmed by reference to the load deflection curve obtained during a test, while according to theory the ratio $W/(\tan\theta/\cos\theta)$ should be constant over the elastic region, as proved to be the case.

It was found that for some materials two, while for other materials three, values of flexural rigidity could be obtained and while the calculations may be questioned they do give information on the bending property of the material under low and high bending conditions.

There are two factors involved in loop deformation. The geometry is such that the effective test length is rapidly reduced while on the other hand the strain imposed may be past the immediate elastic region. It was found that correlation with tensile tests was not achieved unless the inherent strain was allowed to decay, or the diameter of the loop was sufficiently large in relation to the diameter of the material, and the deflection was kept as low as possible.

For both the beam and the loop method a knowledge of the amount of actual strain imposed is most important because of the effect on the order of the result. Equally the chance of successful correlation of either method with any other parameter such as a tensile modulus is dependant on comparative stress-strain behaviour. As long as there is a linear relationship then, provided the values of stress and strain are known, the same value of modulus would be obtained at any point,but once the relationship becomes non-linear then the value of the modulus obtained may be higher,if the deflection per unit stress has decreased,or lower if the deflection per unit stress has increased.

The bending load-deformation curves obtained for the 20 mil monofilament materials were often found to be non-linear after approximately 0.5% deformation.

This non-linearity either took the form of concavity to the deformation axis suggesting an increased rate of deformation with increments of load, or sigmoidal non-linearity represented by concavity followed by convexity. Both represent forms that can be found in the tensile stress-strain behaviour of textile fibres but other possible explanations for non-linearity include the following items:-

(a) During bending the fibre is stretched requiring a component force causing departure from the theory of simple bending.

(b) If the force at the point of contact exceeds the frictional force the sample will slip causing an increase in fibre length which will be registered as deformation due to bending.

(c) The possibility of an error in calculation due to the assumption that the test length being deformed does not change during bending. If the length does increase as the angle of bending increases, i.e. as a function of Θ, then increasing departure from linearity might be expected.

(d) The presence of a shear factor which probably becomes increasingly important with thicker filaments. The result would be to give a higher apparent value of W_b throughout the graph with the deflection of the beam being due to a bending component and a shear component.

(e) The presence of some experimental error.

(1) The assumption that 1% bending was equivalent to 1% extension of the outside of the fibre

rather than 1% extension of a point midway between the centre and the circumference of the fibre.

(2) Initially the experiments were carried out using knife edges as supports and these were changed to rod or cylinder mounting in case there was any friction or cutting effect due to the sharp edges.

(3) The effect was first noted on the Cambridge assembly where there was known to be some inertia in the contacts and drive. Some experimental work was therefore repeated on the Instron assembly.

(a) Considering these in turn Table 9 shows the values of load required to stretch the fibre by one per cent and the probable values of the friction force F to be overcome, the value being taken as $\frac{W\mu}{2}$ grammes where W is the load acting on the beam and μ the coefficient of friction.

From inspection it can be assumed that, even allowing for the approximation made when calculating the friction force the degree of tensile extension during bending must be regarded as so small that it can be neglected as a factor on this occasion.

(b) A practical check was made where a fibre beam was bent to give 1% strain and the angle of bending was measured and found to be 14°, the component angle

Fibre	Load at 1% Tensile Extension	μ	F.
	G.		G.
nylon 6	370	0.39	2.0
nylon 66	530	0.41	2.9
polyethylene	600	0.25	1.5
polypropylene	1200	0.25	2.0
Saran	180	0.46	0.7
Terylene	2000	0.30	7.7

Table 9. Comparison of Stretching Forces and Frictional Forces.

being 76°. If T is the force acting along the fibre, W the load normal to the fibre at point of support, and the coefficient of friction is known, then

$$T = \frac{W}{2} \cos 76^\circ = \frac{W}{2} \cdot 0.24 < F_r = \frac{W}{2}\ 0.30 \text{ Terylene}$$

$$< F_r = \frac{W}{2}\ 0.41 \text{ nylon,}$$

$$< F_r = \frac{W}{2}\ 0.46 \text{ Saran}$$

Again allowing for assumptions and approximations it would appear that the fibre will not slip until, or approaching, the 1% value. The values used for the coefficient of friction required to be checked and the method used has been given later in this chapter.

(c) Error in calculations.

In the formula for the bending of a beam the length of the beam is assumed to remain unchanged. This is sufficiently correct provided the degree of bending remains small but will be in error as the deflection of the beam increases. In order to check the amount of this error at the maximum conditions of test two corrections were made. In the first the length of the arc of the bent fibre was substituted for the original length, and referring to Figure 5 :-

Length of chord OA $= r \sin\Theta$

Length of arc BA $= r\Theta$

$$= \frac{\Theta}{\sin\Theta}\,\ell \qquad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Again $r - y = r \cos\Theta$

and $\ell = r \sin\Theta$

Thus $\cos\Theta = \dfrac{1 - y \sin\Theta}{\ell}$

or $\cos^2\Theta = 1 - \dfrac{2y}{\ell}\sin\Theta + \dfrac{y^2}{\ell^2}\sin^2\Theta$

or $1 - \sin^2\Theta = 1 - \dfrac{2y}{\ell}\sin\Theta + \dfrac{y^2}{\ell^2}\sin^2\Theta$

$- \sin\Theta = - \dfrac{2y}{\ell} + \dfrac{y^2}{\ell^2}\sin\Theta$

and $\dfrac{2y}{\ell} = \sin\Theta\left(\dfrac{y^2}{\ell^2} + 1\right)$

Thus $\sin\Theta = \dfrac{\frac{2y}{\ell}}{\left(\frac{y^2}{\ell^2} + 1\right)}$

and $\Theta = \sin^{-1} f\left(\dfrac{y}{\ell}\right)$

But $E_b = \frac{wL^3}{3yI}$

$$= \frac{wL^3}{3yI} \cdot \left(\frac{\Theta}{\sin\Theta}\right)^3$$

corrected for length from (1)

The value for $\frac{wL^3}{3yI}$ is constant for the present purpose, and

values of 0.3 inches and 0.023 inches as representative of experimental conditions of test length and deflection we get

$$Eb = k \frac{\sin^{-1}\left(\frac{0.1533}{1.0058}\right)^3}{\left(\frac{0.1533}{1.0058}\right)^3}$$

$$= k \cdot 1.03$$

The result may therefore be out by 3 per cent by omission of correction for length, a value within the present experimental accuracy. It was interesting to note as general confirmation that substitution of 14 degrees, a value for ϕ noted by observation, in equation (1) also gave an answer of 3 per cent.

For the second correction in the derivation of the original formula for deflection of a beam the angle that the tangent to the curved beam made with the horizontal axis was taken as

$$\frac{dy}{dx} = \tan \phi = \frac{WL^2}{2EAk^2} = K L^2 \qquad (1)$$

$$\text{instead of} \quad \sin \phi = \frac{WL^2}{2EAk^2} = K L^2$$

$$\text{Since} \quad \sin \phi = \sqrt{\frac{\tan^2 \phi}{1 + \tan^2 \phi}}$$

We should solve

$$\frac{dy}{dx} = \tan \phi = K L^2 (1 + \tan^2 \phi)^{\frac{1}{2}}$$
$$= K L^2 (1 + \tfrac{1}{2}\tan^2 \phi) > K L^2 \qquad (2)$$

The fractional error in using (1) instead of (2)

$$\simeq \tfrac{1}{2} \tan^2\phi$$

For $\phi = 14^\circ$, $\tan \phi = 0.25$

and $\tfrac{1}{2} \tan^2 \phi = \tfrac{1}{2} (0.063)$

$= 0.032$

Thus the percentage error

$= 3.2$

Both of these corrections suggest a reason why the value of the bending modulus calculated from the simple formula might be increasingly lower than the corrected value but this departure would still be linear in behaviour and would not account for non-linearity.

Further corroboration on the value of the modulus was obtained by using equations for the bending of a cantilever. Using the same symbols as before it may be shown[172] that for small bending of a cantilever,

$$E_b = \frac{WL^3}{3y\,Ak^2}$$

where A = area of cross section

k = radius of gyration

As this is virtually the same formula as that used for the bending of a beam, it is not surprising that substitution of the appropriate values produced a similar value of modulus. However for considerable bending of a cantilever,

$$E_b = \frac{W\,\frac{a^2}{2}}{Ak^2 \sin\phi}$$

where a = the projected length of the cantilever

ϕ = angle of bending

As a first approximation the error in assuming that the projected length of the bent cantilever is equal to the length of the cantilever is less than 0.3%. The angle of bending, when one end of a 0.3 inch cantilever was depressed by 0.046 inches, was measured and found to be of the order of 14 degrees. The angle was estimated by lining up an eyepiece cross-wire of a microscope on the end of the fibre, deflecting the fibre, realising the cross-wire and noting the angular movement on a protractor scale attached in close proximity to the eyepiece. Confirmation was obtained by fitting a protractor scale into the eyepiece in such a way that an image of the scale and the fibre could be inspected at the same time. In this way the fibre, and scale, could be zeroed at the start of the test and the change in angle of bending noted as displacement proceeded.

A typical result was that of a Terylene monofilament shown as follows:-

$$E_b = \frac{W \frac{a^2}{2}}{Ak^2 \sin\phi}$$

$$= \frac{32 \times 0.29}{3 \times 10^{-9} \times 0.25}$$

$$= 124,000 \text{ Kgf/cm}^2$$

Inspection of general results will show that this value is in close agreement with other values for Terylene.

(d) In the general equation for the bending of a beam the term for the shear component is generally omitted. In the following example shear has been included and the calculation shows the order of error that might have to be considered.

Let the deflection result from bending and shearing, then

$$y = \frac{wL^3}{48IE_b} + \frac{wL}{4An}$$

where n is the rigidity modulus and A the cross-sectional area of the fibre.

Thus
$$y = \frac{wL}{4}\left(\frac{L^2}{12EI} + \frac{1}{nA}\right)$$

$$= \frac{wL}{\pi d^2}\left(\frac{4L^2}{3Ed^2} + \frac{1}{n}\right)$$

and substituting values for say nylon 66 and taking a

constant
$$y = k\left(\frac{4 \times (0.6)^2}{3 \times 30 \times (0.02)^2} + \frac{1}{4}\right)$$

$$= k\ (400 + 2.5)$$

where $L = 0.6$ inches, $d = 20$ mils, $E_b = 30 \times 10^3$ Kgf/cm^2 and $n = 4 \times 10^3$ kgf/cm^2 (from Meredith[40]).

Thus the possible error in neglecting shear is < 1.0%, again within the limits of present experimental error.

According to Guthrie et al[3] the expression due to direct shear may be neglected provided the ratio of the loaded length of the fibre to the radius of the fibre is greater than 20 and the depression restricted to values less than a tenth of the test length. The ratio in these tests usually fell between 20 and 60 to 1, while the deflection for 1% strain was well below the limit imposed.

On a practical point, and dealing with nylon 66, the deflection for a shear force of 60 grammes was found to be 12×10^{-5} inches, while the beam depression was 46×10^{-3} inches. Thus the depression due to shear was approximately 0.2% of the total depression. Experimental accuracy does not permit such measurement, neither does correction in formula materially affect the result, so that it is considered that deformation due to shear may be neglected.

(c) <u>Experimental error</u>

(1) The calculation of the deflection of the beam required to give 1% strain comparable with tensile extension was based on the relationship

$$\text{Strain} = \frac{a}{r}$$

where a = radius of monofilament, cm.

r = radius of curvature.

It may be argued that in tensile strain the extension is not simply at the outer surface of the fibre but, in theory at least, involves the whole fibre including the core. In bending there is extension radially outwards and compression radially inwards from a neutral axis which is assumed to be unstrained. The significance of this may be shown by recalculating the bending modulus at a value of 1% extension based on stretching a section of the fibre at a point halfway between the centre and the surface of the fibre by 1%. It being argued that this represents a better approximation or average to the tensile strain condition.

For one per cent strain on a monofilament whose diameter was 20 mils the calculated deflection was 0.1 inch but it proved experimentally impossible to bend a 0.6 inch beam by this amount without slippage taking place. For 0.5% strain the required deflection was 0.046 inch and the value of the modulus at this strain was equivalent to that obtained for 1% strain where the strain was calculated on the complete radius.

The direct correlation that will be shown to exist between 1% stretching and 1% bending would suggest that the method adopted of calculating strain is preferable and further support has been found in the work and and comments of Hamburger [68] and Bostwick [173].

(2) The use of a knife edge mounting had been suspect in case of any cutting action or shear at the point of contact. It was found however when the fibre mounting assembly was altered so that 20 mil rods were used in place of the knife edges that the experimental results obtained remained unaltered. This may not signify that there is no error due to shear or friction, but it does suggest that the amount of such an error may be neglected in the present experiments.

(3) In case there was some unrecognised error inherent in the use of the Cambridge assembly, experiments were duplicated on a similar assembly but with the motivation supplied by an Instron. The results obtained were the same and this would suggest that the reasons for non-linearity and for any difference in modulus between tensile and bending were not due to a specific instrument error.

It is known that the tensile stress-strain behaviour of textile materials departs from a linear relationship in a manner dependant on the visco-elastic properties of the particular material being tested. Thus it is probable that the non-linearity observed during the bending experiments is a property of the material and not the symptom of any error in method. Ideally a linear relationship between tensile stress and strain is expected to be maintained until the yield point of the material is reached, and the material is stated to be obeying Hooke's Law in this region. Various authors [4, 18, 60] have shown that the position of the yield point is affected by the method and the conditions of test.

The stress-strain diagrams of the materials under discussion have been shown in Figure 2b. If there had been no sign of non-linearity within the region of 1% tensile strain then the behaviour in bending must be taken as a separate item but as there has been non-linearity then the problem is one concerning the general elastic properties of the respective materials. It was noted that departure from linearity occurred with the same material at the same strain in both tension and bending.

Further evidence in favour of similarity in bending and tensile behaviour was noted during bending tests under increasing temperature and humidity. The linearity of the bending curve decreased in a similar manner to the effect noted in subsequent tensile tests which in turn altered as mentioned by Meredith[46], Coplan[69], and Farrow[72,73].

Type of support

Tests were made with both the beam and loop method to check the effect of using knife edge supports or rod supports on the value of rigidity or modulus. No difference was noted up to the level of 1% strain and it was possible to superimpose the respective stress-strain curves on each other. It will be shown later that the type of support may influence performance at higher levels of strain where the effective compressive force may lead to cutting if a sharp edge is used.

Time effect

Reference to Table 10 shows the effect of the time of test on the results obtained for the bending strain modulus of nylon 6.

The order of results for the tensile modulus show a change of about 8% per tenfold change of time which is in general agreement with published data[18,61,62,232]. It will be noted that the values of the bending modulus display a similar change and this is taken as evidence of a similarity in elastic properties involved in stretching, compressing, and

	Units of Time.		min.	
	1	10	100	1000
Tensile Modulus (1% strain) $kgf/cm^2 \times 10^2$	193	178	166	149
Compressive Modulus (1% strain) $kgf/cm^2 \times 10^2$	202	185	171	-
Bending Modulus (1% strain) $kgf/cm^2 \times 10^2$	196	180	166	151

Table 10. Time Dependence of Moduli.

bending. The effect was repeated on the other monofilaments tested.

Scale effect

Cambridge A constant rate of deflection could not be adopted because of the small deflection involved and the restricted gear speeds available (o.12 inch/min.) The size of the load scale that can be obtained was governed partly by the property of the fibre being tested and partly by the capacity of the load spring used. It was not possible to simply select an (arbitary) scale size as the rate of bending of the sample was affected. The deflection (extension) scale can be magnified one, five, or twenty times. Thus the accuracy and magnification of the measurements that can be made are restricted, particularly in the case of the extension. A magnification of 20 means that an actual movement of 0.023 units is recorded as 0.46 units, the load at this deflection having virtually to be taken to the nearest degree of accuracy, namely 0.45 units, and the degree of approximation increases as the deflection decreases, so that with fine materials it is unlikely that an accurate reading can be obtained.

Instron These disadvantages do not occur with the Instron where it is possible to select and magnify the load scale without affecting the rate of loading of the sample. A minimum rate of deflection of 0.02 inch/min. was available which did permit the time of test to be within 10 seconds, although even another tenfold speed reduction would be preferable. The extension or deflection may be magnified at least 100 times. It is considered therefore that it should be possible to observe load and deflection to an accuracy of two per cent.

4. Test Methods for the Measurement of Friction and Birifringence.

Coefficient of Friction

During the course of investigating the possibility of error in the measurement of the bending modulus it was necessary to know the value of the coefficient of friction of the fibres. Values have been quoted by Harris[89] and Roff[174], while methods of measurement and results have been given by Howell et al[175].

As the present measurement of modulus was a static method involving the bending of a fibre about a point it was considered that the cylinder method described by Howell[176] came nearest to simulating test conditions and this method was adopted whereby

$$\mu = 0.736 \log \frac{W_1}{W_2}$$

where W_1 = total load in direction of motion

W_2 = total load opposing motion

μ = coefficient of static friction, fibre/steel.

A smooth steel cylinder of 4.6 inches diameter was chosen as the friction surface.

The results are shown in Table 11 and it will be seen that only one confirmatory reference could be found despite the large amount of published work on friction. Inspection showed that the bulk of this work was concerned with other fibres, with the measurement of kinetic friction, the friction of fibre on fibre, or the effect of tension, lubricant and such variables on the frictional value. It was felt that the one result at least offered some confirmation of experimental accuracy.

Coefficient of Friction

μ, fibre to steel

Fibre (Table 1)	Experiment	Reference
nylon 66	0.41	0.36/0.42[227]
nylon 6	0.39	-
polyethylene	0.25	-
polypropylene	0.25	-
Saran	0.46	(0.55)^x
Terylene	0.30	(0.58)^x

x Fibre to fibre friction[228]

Table 11. Values of the Coefficient of Friction of Certain Fibres.

Birefringence

Meredith[90] measured the double refraction of a fibre and related this to the molecular orientation. It will be found that there is a difference in the value of elastic modulus between some samples of nylon and polypropylene. In order to check that these differences were attributable to the specific fibre, measurements were made of the refractive indices of the fibre and the results are shown in Table 12, and experimental details have been included at this stage.

For nylon a range of liquids varying in refractive index from 1.515 to 1.525 was prepared from α- bromonaphthalene, n = 1.658, at 20°C, and liquid paraffin, n = 1.4824 at 20°C, the refractive index being measured on a Hilger refractometer. A Watson Service microscope was used for measuring the refractive index of the fibre, a x 10 eyepiece, 16 mm objective, polariser, and analyser being fitted.

A fibre was mounted in each liquid in the range, starting with the liquid of lowest refractivity until no visible change of the Becké line was noted. The Becké line moves to the medium of highest refractive index as the microscope is focussed down. The experiment was continued with at least the next liquid in the range to check the

Fibre	Diameter.	Refractive. Index.		Birefringence. Double Refraction.	Initial Modulus.
	cm x 10^{-3}	n_1	n_2	$n_1 - n_2$	kgf/cm^2 x 10^2
nylon 66	13	1.5810	1.5210	0.0600	306
"	30	1.5808	1.5197	0.0611	297
"	44	1.5803	1.5203	0.0600	297
"	51	1.5785	1.5193	0.0602	305
"	58	1.5808	1.5217	0.0591	303
polypropylene	19	1.5202	1.4937	0.0265	430
"	25	1.5280	1.4837	0.0443	1160
"	28	1.5220	1.4887	0.0333	550

n_1 = plane polarised light with electric vector vibrating parallel to fibre axis.

n_2 = plane polarised light with electric vector vibrating perpendicular to fibre axis.

Table 12. Refractive Indices and Birefringence of Nylon and Polypropylene Fibres.

reading, the Becké line should now move to the liquid as this has now a higher refractive index than the fibre.

The procedure was repeated for fibres in the perpendicular position using a series of liquids with a range of refractive index from 1.5780 to 1.5800.

For polypropylene the same liquids were used in proportions to give ranges of 1.5210 to 1.5290 and 1.4880 to 1.4940. According to Fox and Finch[177] a change of index reading of 0.0004 may be expected per degree Centigrade rise in temperature, so that care was taken that the temperature during all readings was maintained at 20 ± 0.2°C. A single reading on the refractometer can be read accurately to the third place of decimals and with fair estimation of the fourth figure, and five readings were taken for each fibre.

It was found that for polypropylene the values for the tensile modulus reflected the increase in molecular orientation shown by the rise in birefringence and further that the values of the bending modulus also rose by a comparable amount. It was also noticed that with nylon it was possible to get a considerable range of fibre count and diameter within which the modulus remained unchanged. Such fibres were found to have a similar value of double refraction.

Woods[178] quoted a value of 0.06 for the birefringence of nylon so that values obtained by experiment would appear to be of the correct order. No confirmatory values were found for the polypropylene fibres.

5. Fibres

Details of the fibres used in this section have been given in Tables 4 and 13. At least ten tests were made for any parameter being measured, and all tests were carried out at 20 $\pm$ 1° C, 65 $\pm$ 2% r.h. unless otherwise stated. In this section care was taken that any samples for comparative test were prepared in the same way. This usually implied that the samples were removed from the supply package, relaxed at 60° C. under a tension of 0.1 g/tex for five minutes, and conditioned for 48 hours before test. In any cases where a severer treatment was necessary to ensure that a sample was straight, treatment in water at 100°C. for 15 minutes was followed by drying at the same temperature for a further 30 minutes, the samples being under tension during both processes. A final conditioning period of 48 hours was again allowed.

6. Results of Tensile and Bending Tests.

The results of the experimental work on the bending modulus of fibres are shown in Tables 14 and 15. Those in Table 14 refer to fibres whose tensile and compressive values have been given in the previous section (Table 5).

Reference has also been made to Tables 1, 2, 6 and 10 in the preceding script.

Material	Tex mean	Tex σ	Diameter cm x 10^{-3} mean	Diameter cm x 10^{-3} σ
nylon 6	29	-	18	0.3
nylon 66	1.0	-	3.4	-
	1.3	-	4.0	-
	1.6	-	4.4	-
	2.2	-	5.0	-
	16	0.2	13	0.2
	86	0.9	30	0.3
	173	1.9	44	0.9
	326	2.4	58	1.7
nylon 610	65	-	28	-
polypropylene	25	0.3	19	0.3
	40	1.0	25	0.7
Saran	89	2.2	26	0.4
	708	28.1	76	1.1
	1308	52.0	100	2.1
	2090	98.0	130	2.7
Steel wire	256	-	20	-

Table 13. Details of Additional Fibres used in Tensile and Bending Experiments.

	Tensile Modulus		Bending Modulus	
	kgf/cm^2 x 10^2		kgf/cm^2 x 10^2	
	Initial	1% Strain	Initial	1% Strain
nylon 6	214	197	220	197
σ	6	6	6	6
nylon 66	305	269	303	274
σ	9	9	9	7
polyethylene	301	271	310	272
σ	12	9	13	10
polypropylene	450	377	442	379
σ	14	10	15	12
Saran	108	100	106	99
σ	5	3	5	4
Terylene	1300	1210	1270	1230
σ	42	42	47	36

Table 14. Tensile and Bending Moduli of Certain Fibres.

Fibre*	Tex	Tensile Modulus Kgf/cm^2 x 10^2		Bending Modulus Kgf/cm^2 x 10^2	
		Initial	1% Strain	Initial	1% Strain
nylon 6	29	219	194(4)	220	194(4)
nylon 66	1.0	478	436(16)	469	440(18)
	1.3	476	429(11)	450	428(16)
	1.6	481	457(14)	482	451(11)
	2.2	481	442(16)	472	437(15)
	16	306	262(5)	293	264(5)
	86	297	260(9)	303	268(7)
	173	297	273(9)	288	260(6)
	326	303	273(4)	302	270(6)
nylon 610	65	-	364(11)	-	371(13)
polypropylene	25	430	371	430	360
	40	1160	1000(37)	1100	970(41)
Saran	89	107	100(3)	108	102(5)
	708	113	100(5)	112	104(5)
	1380	111	104(4)	109	99(5)
	2090	111	103(5)	108	102(6)
Steel Wire (10^4)		207	-	210	-

* Details Table 13.

Standard Deviation Values in parenthesis.

Table 15. Tensile and Bending Moduli of Certain Fibres.

7. Discussion of Moduli Results.

Inspection of the results in Tables 14 and 15 will reveal that the values of the tensile and bending modulus of a fibre were in close agreement with each other. The values of the tensile modulus of the fibres in Table 14 have already been considered, (p.78) and it was shown that they depended on the conditions at time of test, but that general confirmation of their value could be found in literature. Similar comments regarding the effects of experimental variations can be advanced for the fibres in Table 15 and it is not considered that they need be repeated in this section. The difference in some of the values for the same material has been explained as being due to differences in the draw ratios of the materials, support for this being found in the irreversible effect of temperature noticed during the preparation of the olefine and Saran samples, and in the different optical properties of the nylon and polypropylene fibres.

It has been shown that the factors which affect the actual value of the bending modulus of a fibre are largely these which affect the value of the tensile modulus. It has also been shown that the numerical effect is closely similar in every case except where differences in test method or calculation introduce a new factor, and even then the factor may be such that proportionality is retained.

Reference to Table 6 will show that the results quoted in literature have also been given and it will be noted that there is general agreement as far as the order of result is concerned. It is felt that there was no difference between the values of the tensile and the bending modulus that could not be explained by reference to the test conditions and accuracy.

Experiment has shown this to be true provided that the measurements were restricted to the linear elastic strain region or to comparative strain values

Measurement outwith linearity was critical due to the magnification involved in calculation. A corollary of the method used was that any variable which caused a change in the stress-strain character of the material changed the numerical value of either modulus. One important variable was time, the effect of which has been shown separately, Table 10, but which must be constant, or corrected, in any comparison.

Mention was made in the survey however that there was some disagreement on the relationship between the tensile and bending moduli and the statements of the various authors are now examined.

Khayatt and Chamberlain [5], using a simple cantilever, reported that the value of the tensile modulus was higher than the value for the bending modulus. The materials in this case were animal fibres and they concluded that the value of the bending modulus was less than that of the modulus obtained by stretching, the results for human hair and Cotswold wool being only approximately half the stretching modulus. Some idea of the possible range of result may be gathered from the fact that the value of the stretching modulus of wool has been reported by another source [12] as half that of the value of the bending modulus.

Particular care was taken to avoid compression of the sample at the point of bending, the sample was wet out to remove temporary set andallowed to dry for 30 minutes under standard conditions and the time of loading was 2 minutes.

The tensile test was conducted on a Cambridge extensometer and the value of the modulus found from the initial straight line portion of the load-extension curve. It was stated that the time taken to stretch the fibre was approximately 2 minutes so that the rate of deformation was comparable in both cases.

It was not stated whether the fibres in the tensile test were also wet out to relax tension and it is felt that one possible explanation for the lower value of the bending modulus might be that the samples were not in fact at equilibrium with standard conditions but at a higher regain. A second point is that the authors show a load-deflection curve for wool the linear portion of which appears to go past the region of 20 per cent strain, if the strain values are calculated from the quoted values of fibre diameter and deflection.

Meredith[24] stated that higher values were found for Young's modulus in bending than in stretching, gave no figures to support this statement, but commented that this was probably due to the greater orientation of the molecules near the surface of the fibre. Guthrie et al[3] quoted this statement and gave experimental evidence that the bending modulus for the acylic, polyamide, and polyester fibres tested was greater than the stretching modulus. They measured the bending modulus by dynamic and static methods and the results obtained by the dynamic method were on average some 50 per cent above the static value. This order of difference has been noted from inspection of the results of other workers and has been ascribed to the difference in the time of loading and effective strain between the static and dynamic methods.

Guthrie et al found no evidence of a sharp skin-core division and suggested that a more likely situation was a gradation of Young's modulus from the surface to the axis of the fibre quoting results of the ratio of rigidity to the square of denier as support for the statement that the ratio of the radii of the skin and core remained constant, independant of denier.

Inspection of their experimental results showed that the values of the static bending modulus were originally below the results of the stretching modulus, but that they had applied a correction to the stretching modulus to allow for the rate of extension being some 100 times greater than that sused in the static bending method. This correction of some 20 per cent brought the values of the stretching modulus below those of the bending modulus. Sikorski and Woods [62] on the other hand quoted a 10 per cent correction for a hundredfold difference in rate of extension, albeit for wet wool.

These remarks illustrate very clearly the need for accurate and comparative testing of moduli.

The correction applied was attributed to Meredith [61], and a comment can be made that on checking the application of this correction, although it was found that the results were lowered below the mean value of the bending modulus quoted they were still well within the range of bending modulus shown. There was no corresponding range of tensile modulus results available for further comparison. It is felt that there is further support for suggesting that the results of Guthrie et al are not conclusive when it is realised that a constant rate of loading was used in both the static bending test and the stretching test and that any comparison of rates of extension must therefore contain a considerable variable.

Kärrholm and Schroder[12] quoted the (resonance) bending modulus of nylon as 4.04×10^{10} dynes/cm^2 with a range of 0.2×10^{10} dynes/cm^2, and 6.16×10^{10} dynes/cm^2, range 0.7×10^{10} dynes/cm^2 for Lincoln wool. They comment that the dynamic Young's modulus for fibres will be greater than the static value although for ideal elastic bodies the two values should be the same. They also support the argument that a difference between the bending property and tensile property may be due to a difference between the outer and inner parts of a fibre giving a value of 1.06×10^{10} dynes/cm^2 to the dynamic bending modulus of viscose rayon compared with a value of 0.68×10^{10} dynes/cm^2 for the dynamic tensile modulus. They stated that it was necessary to maintain larger stresses in the fibre for stretching measurements than for bending measurements, but that if a lower stress was used the effect would be to increase the ratio of bending modulus to tensile modulus, a lower value of tensile modulus being obtained as the stiffness decreased with decreasing tensile stress in the fibre. This appears to contradict the conception of change of stiffness with strain that will be developed in a later section, and even at this stage it would appear more likely that a higher modulus would be obtained if lower stress implies less strain. They showed that the dynamic bending modulus of a steel wire was only slightly greater than the static tensile modulus but it is a pity that they did not proceed to compare the dynamic bending modulus of the wire as well.

A value of 11.0×10^{10} dynes/cm^2 for the dynamic tensile modulus of viscose rayon was recorded by Tipton[30], so that there are some grounds for believing that the value quoted above was low: Tipton also showed that the value of the modulus decreases sharply with a reduction in static strain below 5 per cent.

A value of 5×10^{10} dynes/cm^2 was recorded for the dynamic modulus of nylon rising to about 20×10^{10} dynes/cm^2 depending on the degree of strain and the type of nylon. A considerable range of value was also shown for Terylene, the results being from 17 to 30 x 10^{10} dynes/cm^2 also depending on the strain and type of Terylene.

Lochner[10] quoted values of 3.5 x 10^{10}, and 7.5 x 10^{10}, dynes/cm^2 respectively for nylon and wool, although the conditions of temperature and humidity were uncertain, compared with the static values of 3.0 to 4.6 x 10^{10} dynes/cm^2 for nylon[2], and 1.6 to 2.6 x 10^{10} dynes/cm^2 for wool.[5]

Vibrascopic measurements of the elastic bending modulus of nylon 66 and Dacron filaments of various draw ratios were made by Wakelin et al[28]. They also made static measurements of Young's modulus of extension and found it was generally lower than the dynamic bending modulus at the same draw ratio. The difference was greater for nylon 66 than for Dacron, was more pronounced at low draw ratios, and indicated that the effects of creep and stress relaxation operate to decrease the modulus when measured under static conditions.

Scrutiny of these dynamic methods also suggests that care is required in ensuring that the units used to denote modulus are fully understood. Thus Tipton[30] is correct in stating that the value of the dynamic modulus decreases with decreasing static strain if reference is being made to the numerical value of stress. On the other hand the gradient of stress to strain increases with decreasing strain and the value of the modulus referring to strain will increase.

Carlene[2] in comparing the results of the bending modulus of nylon monofils quoted agreement with the results for Young's modulus of nylon yarn recorded by Meredith[16], but higher results than those shown by Finlayson[25]. In neither case were the experimental conditions the same and the author has shown that variation in the modulus can be expected from fibres of the same chemical type but differing in the degree of setting, orientation, etc. This could also account for the high value quoted by Carlene for a fine monofilament.

The present work has in fact shown results in agreement with all those quoted above and the reasons for the different values have been discussed in the text.

It is interesting to note that Finlayson placed on record the fact that, for textile filaments, the formula for bending held, with considerable accuracy, for degrees of bending extending far outwith the limits corresponding to the engineer's "small deflections" within which application of the formulae are supposed to be restricted.

Again reverting to the present results, statistical tests, for the standard error of difference between the respective mean values for tensile and bending moduli, showed that the differences were not significant at the probability level of 0.05. This comparison was extended to consider the three moduli, tensile, bending, and compression and it was concluded that at the present level of experimental accuracy the differences between the mean values for a specific fibre were not statistically significant.

CHAPTER 5. EFFECT OF TEMPERATURE AND HUMIDITY ON THE BENDING MODULUS OF FIBRES.

1. Gallenkamp Conditioning Oven.

2. Humidity at Constant Temperature.

3. Temperature at Constant Humidity.

4. Discussion of Results.

CHAPTER 5. EFFECT OF TEMPERATURE AND HUMIDITY ON THE BENDING MODULUS OF FIBRES.

Comment was made in the survey that there were not a great number of references to the effect of changes in temperature and humidity on the bending properties of textile fibres.

It was thought that comparison of the effects of changes in atmospheric conditions would offer further evidence whether the tensile and bending behaviour was similar.

The Cambridge Extensometer had been mounted over the conditioning oven with these points in mind, and it was thus possible to measure the tensile and bending modulus on the same apparatus, under the same conditions and on a similar time scale. An outline of the assembly has been shown in Figure 4.

It would have been preferable to mount the make and break contact outside the test atmosphere because of the risk of tracking at high humidities. However it was found that the sensitivity was affected because of the suspension of too great a weight on the contact arm, and the system was used as shown.

Although in practice textile materials reflect changes in both temperature and humidity due to atmospheric conditions it was convenient to separate the two effects.

The variable with the greatest everyday effect would be expected to be changes in humidity at a temperature corresponding to normal climatic conditions. e.g. 15°C/20°C. any change in the value of the bending modulus being possibly reflected in changes in the handle of the material. On the other hand, in processing, the behaviour of materials over a range of temperature may be of interest.

1. <u>Gallenkamp Conditioning Oven.</u>

The range of temperature used was from 10°C - 90°C., the limiting factor at the lower end of the scale being the ambient temperature of the laboratory while the oven was not designed to operate above 95°C. Theoretically the range of relative humidity should be 0% - 100%, but in practice it was found that a working range of 10% - 90% was comparatively easy to achieve and, perhaps more important, easy to maintain. In any experiments where the effect of temperature and humidity were being measured it was possible either to keep the temperature constant and vary the humidity, or to keep the humidity constant and vary the temperature. Both methods were used but it was found easier to vary the temperature at a constant humidity, there being a tendency to overheat when increasing the humidity at a constant temperature. In both cases it was usual to start at the lowest values and increase these values, the only exception to this being when low humidities were required after high humidities had been used. Here it was advantageous to use high temperatures to ensure thorough drying of the oven. It was found that the use of appropriate saturated salt solutions[179] increased the speed at which stable conditions were achieved, while of course being absolutely essential in those cases where the ambient humidity was above the value required by test condition. Measurement of the temperature and humidity in the oven was made from the following sources.

(a) The standard wet and dry bulb thermometers used to regulate the temperature and humidity of the oven.

(b) One pair of wet and dry thermometers linked to a Bristol chart recorder which allowed a continuous record of temperatures to be kept.

(c) One pair of wet and dry bulb thermometers mounted near to the position of the test sample.

Reference was made to Air Ministry tables from which the value of the humidity corresponding to the appropriate wet bulb depression could be obtained.

In practice it was found that the values of temperature and humidity measured by all three methods generally agreed to within test limits of ± 2°C. and ± 2% rh. A direct reading hygrometer was sometimes fitted close to the sample for ease of reference.

It was considered that there were three likely sources of error. The wet and dry bulb temperatures set on the regulating thermometer were reached before the overall conditions in the oven were stable. The time lag depended on the temperature gradient involved but at least sixty minutes should be allowed after setting temperatures have been recorded unless other thermometers sited in the oven indicate the correct temperatures.

The Bristol chart record also tended to give a delayed reaction taking at least thirty minutes to settle after changes had been made in conditions. It was most useful as a means of indicating long term changes once conditions were stabilized, but did not record the extent of any minor change of short duration although the interruption to the chart would signify that some change had taken place. Temperature readings on the regulating and Bristol thermometers were found to be in agreement at least to 1°C, after vents were adjusted and auxiliary fan fitted.

For short term observations and as a means of detecting local variations within the oven, it is considered that some method of measuring temperatures near the position of the test sample should be available. A normal wet and dry bulb thermometer was used in this instance having been shown to be in agreement with readings taken on a recording hygrometer of the Gregory type which could have been used if additional records were required of local changes. It was found that the regulating temperatures needed to be set a degree or so higher so that conditions were correct at the test point in the oven.

The existing door of the oven was replaced by another door in which two glove ports had been fitted together with an observation window. By this means it was possible to mount, test, and replace samples while maintaining any desired conditions.

While the presence of these ports would increase the rate of heat loss from the oven, control, and as the recording charts showed steady control, with a minimum of fluctuation, was still possible. There were two limitations which might prove troublesome in any prolonged testing procedure. At high temperatures, and particularly when coupled with high humidities, the hand required additional protection other than routine powdering. A combination of cotton mesh gloves and rubber gloves was found successful provided that access was only required for a minute or two at a time, and that the reduced dexterity did not impair the handling and positioning of samples.

Again with high humidities considerable condensation occurred at the glove ports. This also had the effect of impairing the handling of samples while tending to cause excessive overall humidity within the chamber.

It should be noted that tensile tests could be carried out by a simple modification of the jaw assembly unit. Such tests were carried out on nylon yarns with a 2 inch test length, magnifying the extension twenty times, and using the appropriate gear ratios to obtain comparable times of strain.

2. Effect of Humidity at Constant Temperature.

Tests were carried out at 20 ± 2°C. with the relative humidity varying by steps over the range of 20% r.h. to 90% r.h. This procedure was repeated at different temperatures up to 80°C. All samples had been kept in dessicators for at least six hours before test under conditions nearest to the desired humidity, and had previously been treated in the same way as the fibres in other tensile and bending tests. The samples were removed from the dessicator and inserted in the oven which was maintained at the desired conditions. No test was conducted until an hour after conditions had been allowed to stabilise. Difficulty was sometimes encountered if test conditions were at an extreme from ambient conditions, and thus it was usual to carry out low temperature and low humidity work when the outside conditions were most suitable. There was no refrigeration unit with this oven and hence temperatures could not readily be reduced below ambient, but humidity control was assisted by use of an appropriate salt solution.

The results have been given in Figures 6(a) and 6(b) where the decrease in the value of the bending modulus of nylon 6 and nylon 66, has been shown as the humidity was increased at a specific temperature. It will be noted that the results for the two forms of nylon are comparable on a basis of percentage change in modulus. It is also of interest to note the possible change in modulus over the range of expected atmospheric conditions. Thus considering 20°C. and 60% rh as an average condition, the modulus would be 33% higher on a dry day, (40% rh) and 33% lower on a wet day, (80% rh). If the value of the bending modulus has any connection at all with the handle of a material, then such a change goes some way to explain why opinions on the handle

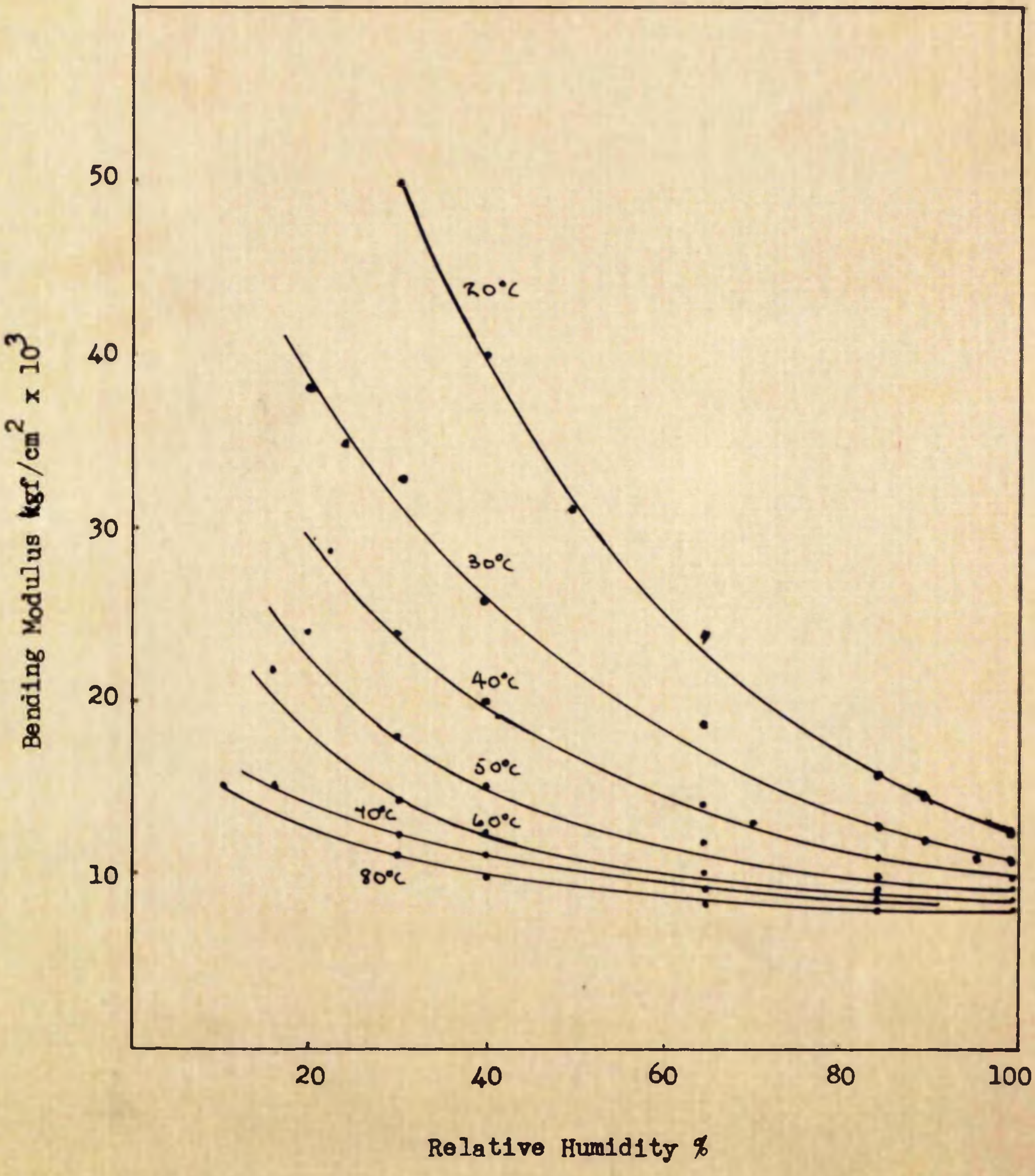


Figure 6(a) Effect of Relative Humidity on the Bending Modulus of Nylon 6 at Different Temperatures

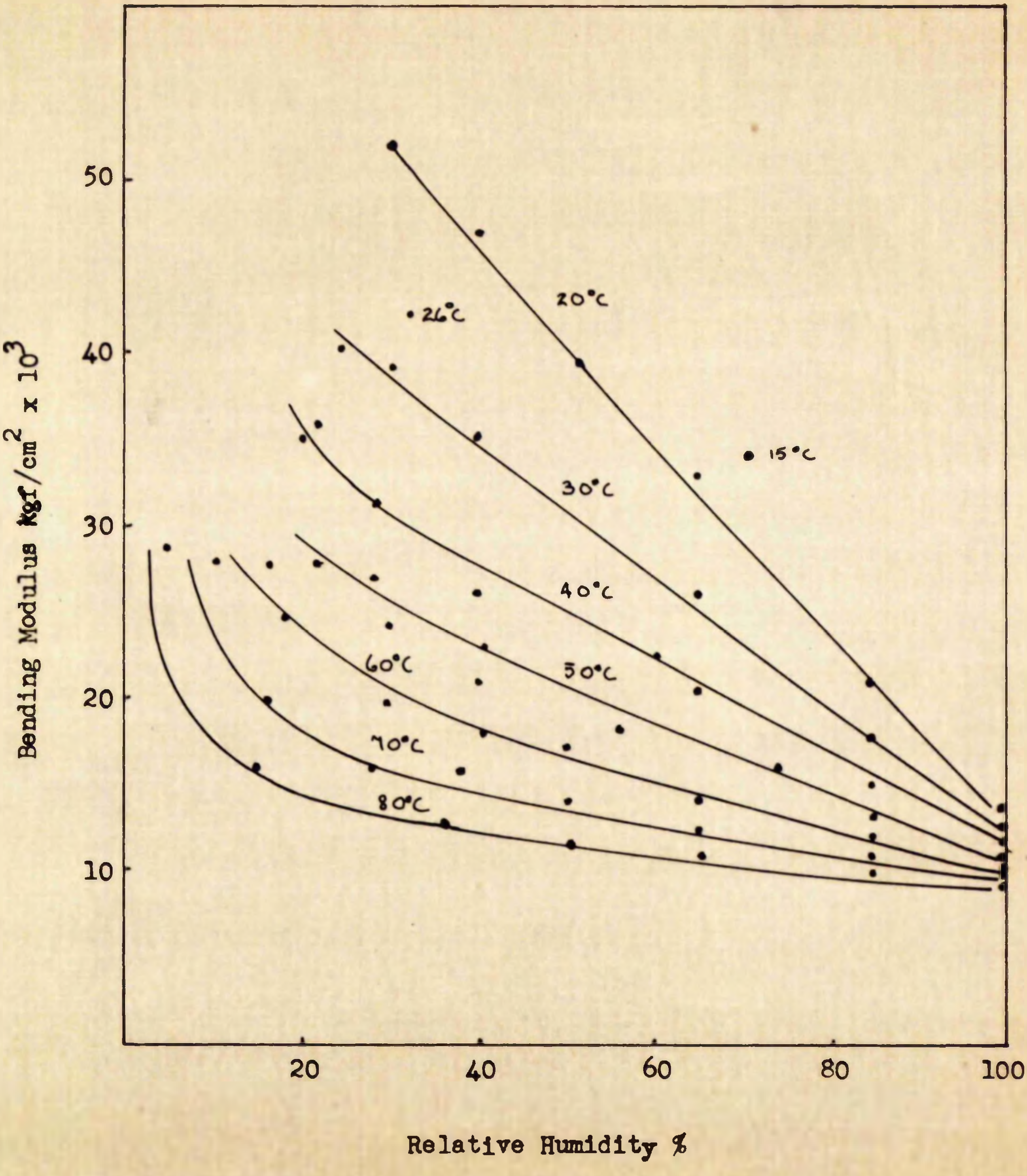


Figure 6(b) Effect of Relative Humidity on the Bending Modulus of Nylon 66 at Different Temperatures of the fabric can differ, unless examined under constant conditions.

The effect of humidity appears to decrease with temperature in both cases although this is the effect of a percentage change of a smaller number.

A tendency to an upward swing was noted at humidities below 20% rh., the change being most noticeable with the nylon 66 fibres.

There was no change in the values of the bending modulus with changes of humidity for the polyethylene, polypropylene, and Saran fibres. A slight change was noted for Terylene but a separate figure has not been given as the effect can be estimated from Figure 7(d). It will be seen that increasing humidity lowers the value of the modulus. There was virtually no change in modulus with humidity at 65% rh. under normal atmospheric temperatures, a change becoming apparent about 40°C. for the two higher humidities and not until about 60°C. with the lowest humidity.

3. <u>Effect of Temperature at Constant Humidity</u>.

Tests were carried out at 20% ± 2% r.h. with the temperature varying by steps over a range of 20°C. - 80°C. These tests were repeated at different values of humidity up to 80% r.h. The general procedure was as described in the previous section and of course the effect of temperature at constant humidity could also have been obtained by inspection of these results previously obtained. It was felt however that the use of the two methods provided additional results and at the same time served as a check on test methods.

The results have been given in Figures 7(a) and 7(b) for nylon 6 and nylon 66, Figure 7(c) for polyethylene, polypopylene and Saran, and Figure 7(d) for Terylene. The results for the two forms of nylon are again comparable, and a change in handle with temperature variation is a possibility, the change in bending modulus being of the order of 20% or more, per 10°C. change in temperature. It will be noted that values showing the change in tensile behaviour of nylon 66 have been included in Figure 7(b) and that they coincide with the comparable bending curve.

These tests carried out on the same material in the same atmosphere and on basically the same apparatus are taken as offering further evidence that the tensile and bending modulus within the elastic region are one and the same thing.

It was found that at 65% r.h. there was about a 5% decrease in modulus of Terylene per 10°C. rise in temperature but that this effect was not noticeable until about 40°C. Thus changes in atmospheric temperature will not affect the modulus of the material but changes may be caused as a result of processing temperatures.

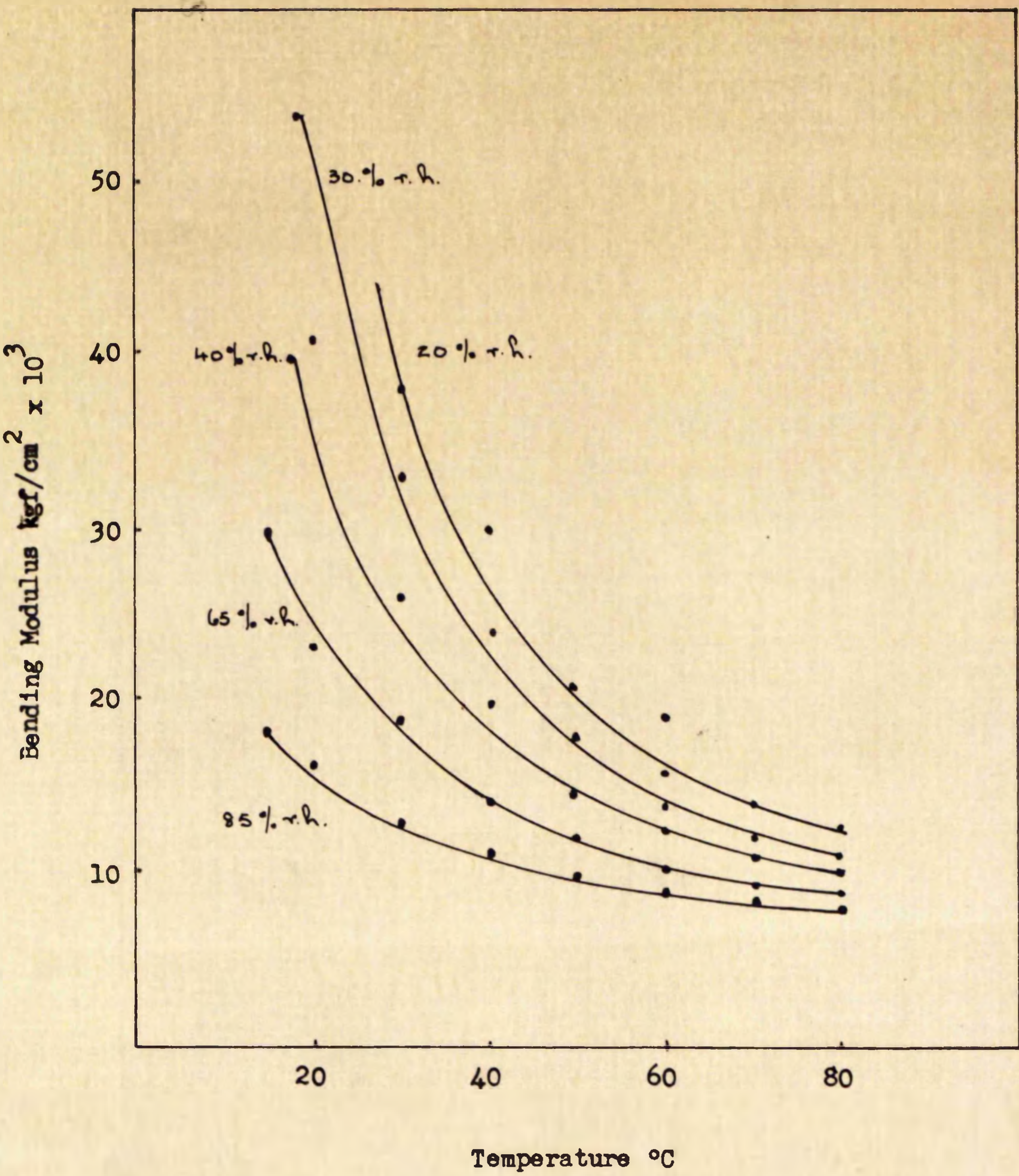


Figure 7(a) Effect of Temperature on the Bending Modulus of Nylon 6 at Different Humidities

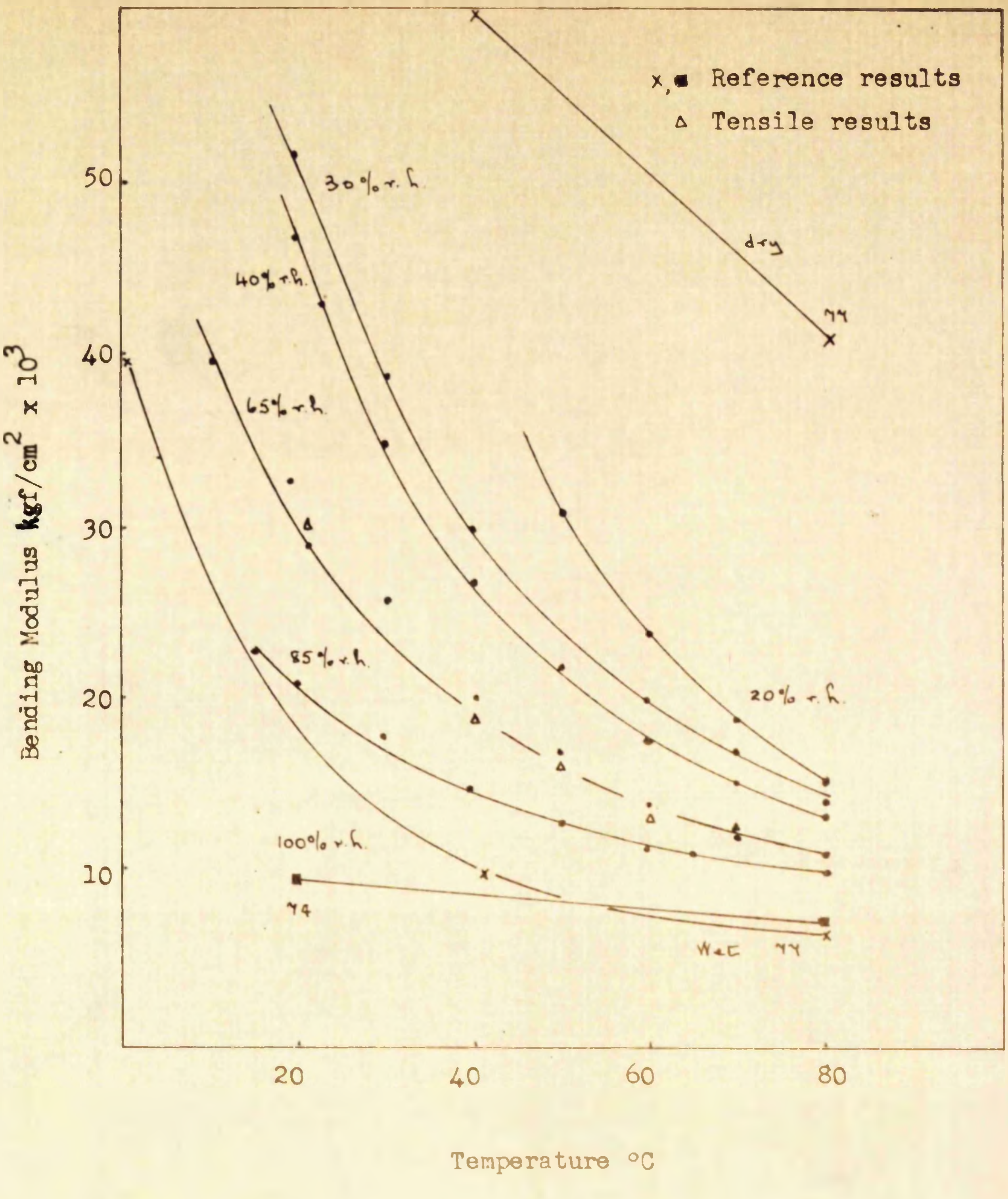


Figure 7(b) Effect of Temperature on the Bending Modulus of Nylon 66 at Different Humidities

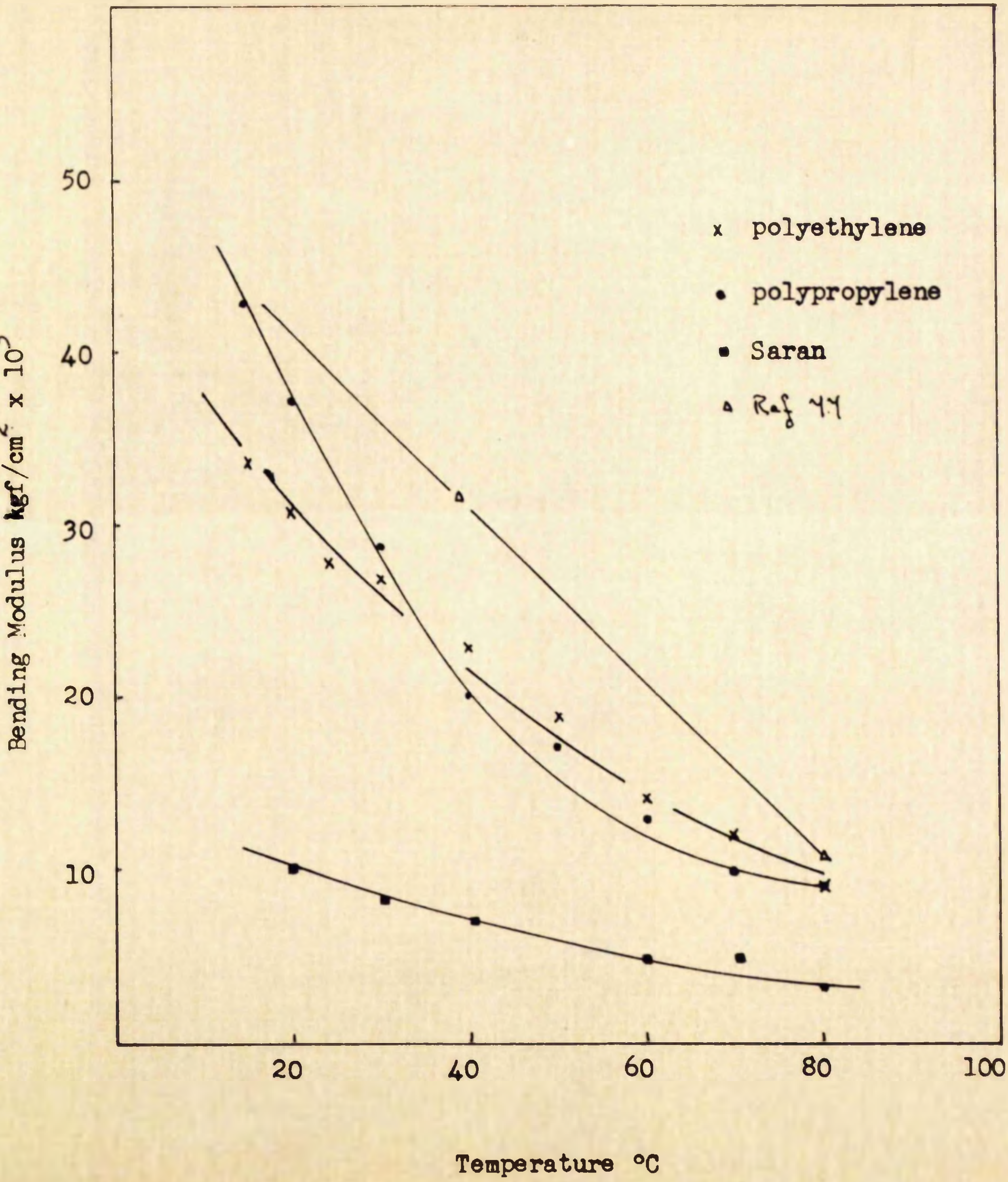


Figure 7(c) Effect of Temperature on the Bending Modulus of Polyethylene, Polypropylene, and Saran

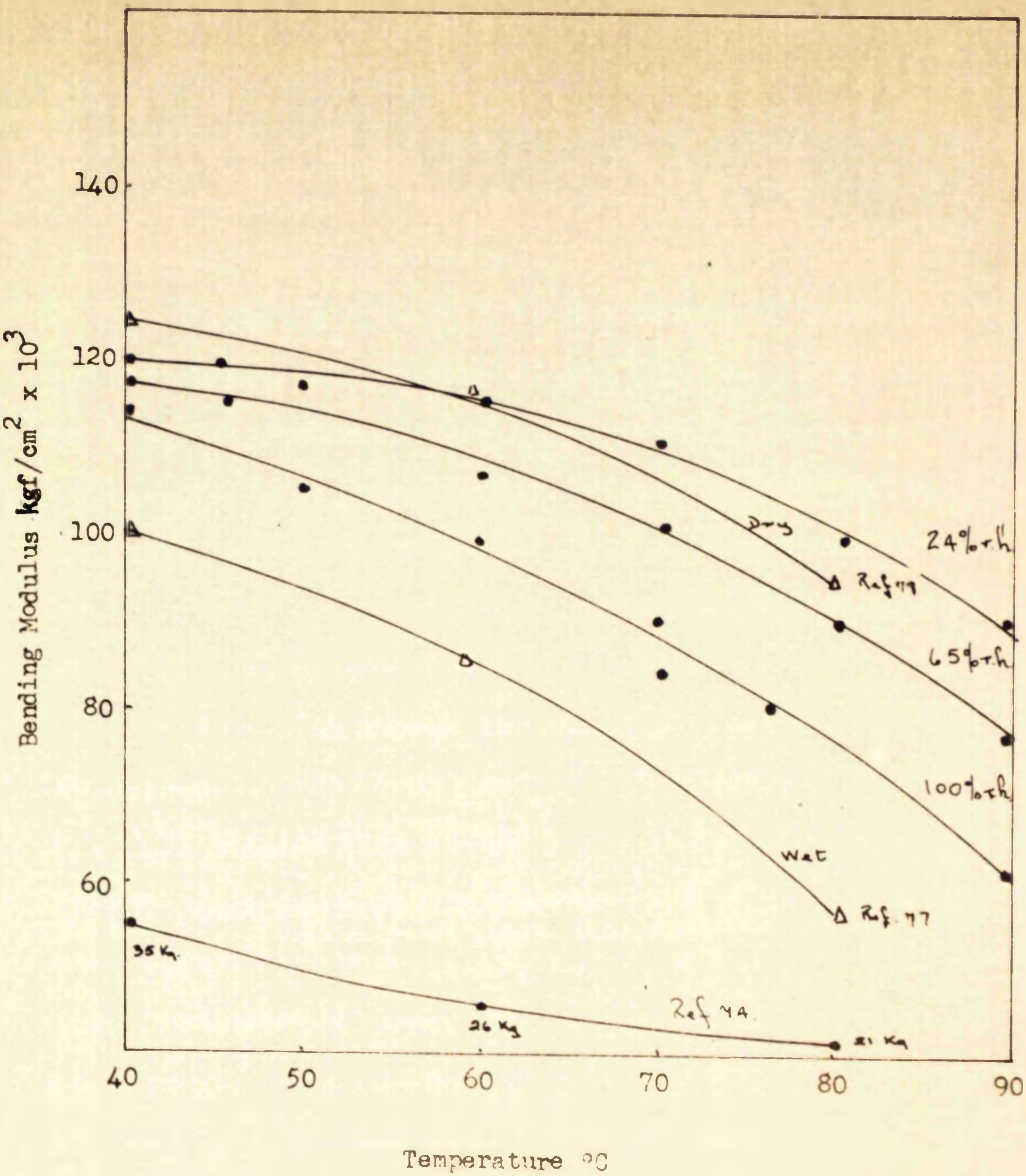


Figure 7(d) Effect of Temperature on the Bending Modulus of Terylene

It has been shown elsewhere that there was a drop in the value of the tensile modulus for nylon 6, nylon 66 and Terylene due to heating the sample in preparing test specimens but that this change was recoverable provided time was allowed for reconditioning.

Similarly comment was made that the tensile modulus of polyethylene, polypropylene, and Saran was very much reduced in value depending on the temperature used in straightening the sample, the change being irreversible. It was found that the bending modulus was similarly affected and the importance of the change is that some of it occurs within the general range of atmospheric temperatures.

Brown[76] measured the stiffness temperature behaviour of Dacron, nylon, Orlon and Saran, stiffness being taken as the load required to extend the fibre by one per cent and the result being expressed as grammes per denier. The results were plotted as the log,(stiffness)against temperature but were replotted by Eeg-Olofsson[180] on linear coordinates. No mention was made of the humidity at the time of test so that it has to be assumed that the value of humidity would fall with each increase in temperature. Inspection of the results showed that the general shape of the curves is similar to that shown for the bending experiments while the magnitude of the change in modulus was also similar being about a drop of 50% over the range of temperature, 20°C. - 80°C. for nylon, and Terylene, and 70% for Saran.

Beg-Olofsson questioned the use of a logarithm scale and doubted whether initial tensile measurements would reflect second order transition temperatures. Brown suggested the use of such a scale gave equal sensitivity to all values of stiffness whereas a linear scale tended to compress stiffness values, particularly below 2 grammes per denier to the point of insignificance. Brown went on to relate the resilience of the fibre to the transition temperature, resilience in this instance being the degree of elastic recovery from stretching.

The two methods of expression, logarithmic or linear, offer an interesting example of the way in which a property may be presented and it certainly seemed as though the method chosen by Brown did show convincing correlation particularly with resilience. It is known that time dependant properties of fibres often do correlate on a logarithm basis.

Bueche[78] measured the effect of temperature on the Young's modulus of two samples of polyethylene, one highly crystalline and the other possessing a lower degree of crystallinity. In this case the polyethylene was in the form of a sheet or strip and the value of the modulus was very much lower than in the case with the material in fibre form. However inspection of his results showed that the effect of temperature was similar to that found in the present experiments. The value of the modulus was highest in the structure of greatest crystallinity but dropped in both cases by almost 75% over the range of temperature from 20°C. to 80°C.

Bueche also commented that his values obtained by a static method were lower than those found by another author working on a similar material but using an oscillation method to measure the modulus. The reason for this difference was explained as being due to the time dependance of the property in question.

Measurements of the initial modulus of wet fibres at temperatures between 20°C. and 100°C. were made by Guthrie [74] and his results for nylon have been included in Figure 7(b) where it would appear that they fit into sequence remarkably well. The results for Terylene showed a drop of about 50% in modulus over the test range. These have been incorporated into Figure 7(d) where it will be seen that while there is similarity in the percentage loss of modulus value there is a difference in the actual modulus value and in the shape of the curve the present experimental results being concave to the coordinate axis while Guthrie's results were slightly convex. However Brown[76] showed some results where there was a wide divergence in the shape of the tensile curves and in the modulus values and these were attributed to differences in the degree of stretching of the original fibre.

Further work on the effect of temperature on fibres was carried out by Bryant and Walter[77] who quoted results for stiffness, stretching modulus at 1% extension, and shrinkage for air dry and wet fibres. The values for stiffness were plotted on a logarithmic basis as grammes per denier but they have been replotted on a linear scale as kgf/cm^2 and shown in Figures 7(b), 7(c) and 7(d). It will be seen that the general outline of the curves are very close to the present experimental work.

It has been shown that the value of the modulus may change with temperature and humidity and that the value was also time dependent in relation to creep and stress decay.

Clark and Preston[66] have commented on the tension temperature length relations of nylon and Terylene while Eckstein[125] showed that for nylon at constant temperature, but exposed to changes in relative humidity, and held at constant lengths, the tension in the yarn was inversely proportional to the logarithms of relative humidity. At constant tension the logarithms of the length was directly proportional to the relative humidity. At low strains he found that stress was proportional to strain and thereafter over a limited range a linear relationship existed between log stress and log strain.

Finally a paper that dealt with the effect of temperature humidity and effect of preparation condition was that of Farrow [72]. Of specific interest are the results for the initial modulus of a number of fibres taken at 20°C., 65% r.h. at 20°C. in water, at 95°C. in water, and at 20°C. 65% r.h. after treatment with hot water. The results at normal conditions agree with the general observations on the values of both the tensile and bending modulus. Terylene, Saran, and polyethylene were shown to be unaffected by a change in condition to that of water at 20°C. while nylon 66 lost 40% of its value supporting the result shown in the present work. On the other hand Farrow showed nylon 6 to be unaffected under these conditions whereas a drop in value similar to that of nylon 66 was found in this work. The results at 95°C. in water showed that the values dropped by 80% (75%) for nylon 66, 65% (70%) for nylon 6, 55% (50%) for Terylene, 80% (85%) for Saran and by virtually 100% (90%) for polyethylene. The values in brackets represent the predicted values from the present work.

The results of Farrow showed the following changes in modulus after pretreatment with hot water before testing. There was a drop in value of 70% for nylon 66, 50% for nylon 6, and 30% for Terylene. A similar order of change was recorded in the present work where the exposure conditions were not so severe but it was found that the change was reversible with time, a factor that does not appear to have been commented on by Farrow.

The reduction of 50% for Saran finds a parallel in this work but, a value of 90% for polyethylene was reported compared with 50% but this could be due to the higher temperature and time of immersion allowing greater contraction to take place.

Considering the differences in experimental technique it is felt that there is considerable agreement between the two sets of results.

It was noted that there might be a change in the diameter of a fibre with temperature or humidity but as it had been shown that the order of such a change was less than 2% until 90% r.h. no correction was made because of the general variability of the materials. The change may be of the order of 5% at 100% r.h. or at high temperatures when it might become important.[233, 234, 235]

At the beginning of this section it was suggested that consideration of the effects of changes in atmospheric conditions on the elastic tensile and bending properties of fibres would be helpful. It is suggested that the evidence points to the fact that any error will be small if a change in bending property is forecast from a knowledge of a change in tensile property.

CHAPTER 6. STRAIN MODULI OF FIBRES.

1. Tensile Strain Moduli.

2. Bending Strain Moduli.

3. Results and Discussion.

CHAPTER 6. STRAIN MODULI OF FIBRES.

Most references to the stress-strain relationship of textile fibres will be found to contain information either on the initial modulus or on the modulus at break, although some reference to what might be called in-between values have been made e.g. compliance [87], secant modulus [124]. The purpose of this section is to obtain strain moduli in tension and bending, to compare the results to see how far they are in agreement with each other, and to consider the application of such results.

1. Tensile Strain Moduli.

In previous work on tensile moduli attention was restricted to strains 1%, the regions usually described as being truly elastic. If the strain is allowed to continue then a normal stress-strain curve will be obtained up to the breaking point of the material, from which, knowing the stress at each unit of strain, a number of tensile strain moduli could be calculated.

These would be useful in two ways; in any attempt to correlate tensile and bending properties, and as an indication of the behaviour of the material in addition to those properties previously mentioned.

Figure 2 (60) showed the complete stress-strain curves of a number of fibres. If it is assumed at the moment that deductions about stiffness may be made from tensile measurements then inspection will show a number of interesting changes take place depending on the stress or strain involved.

Thus nylon becomes less stiff after about 1% strain but increases in stiffness again at about the 10% strain level, while Saran after a slight drop in stiffness remains unchanged until dropping again about the 15% strain level.

Again the ranking of stiffness may change depending on strain, and stress. At 1% strain nylon 66 is stiffer than nylon 6 but about 12% strain they would appear to have the same stiffness value. When considered on a cross sectional area Terylene is markedly stiffer than polypropylene but both have about the same behaviour when stiffness is related to count. More will be made of this aspect in a later section, attention at the moment being rather confined to establishing the relationship between tensile and bending strain moduli.

The method of test remained as described previously, and the modulus was calculated at successive strain intervals being expressed as stress over strain to that point. The modulus was also calculated as the ratio of stress per preceding one per cent strain to strain.

2. Bending Strain Moduli.

In a previous section comment was made on the calculations involved in finding the percentage strain after a certain deformation, or deflection, of the sample. The samples were tested in the same way as previously, in both beam and loop form, but the test was continued past the region of low strain giving a stress-strain curve of the fibre under bending strain, the deflection equivalent to an appropriate strain value being found by calculation. The amount of deflection is governed by the dimensions of the specimen but for higher strain values it was usually necessary to reduce the test length, this also having the advantage that the errors involved in consideration of effective length were also reduced at least in magnitude.

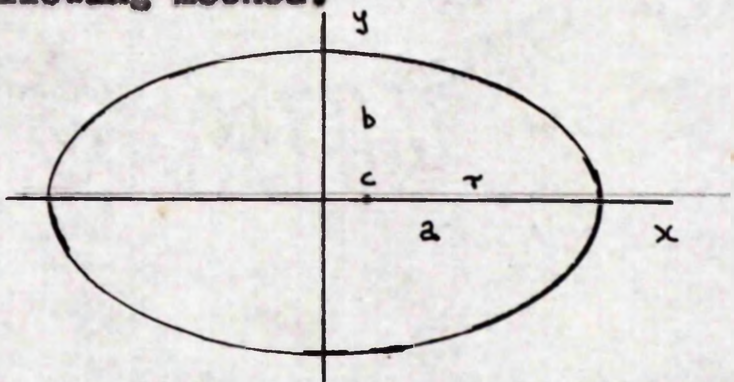
There were limiting factors present in the bending tests that were not found in tensile tests. The fibre was not held, at least in the present tests, and hence slippage occurred in a beam test when the restraining frictional force was overcome, while in the loop test there is a rapid change in sample dimension. As was pointed out in the beginning the formula for bending modulus or flexural rigidity is strictly only applicable to homogeneous elastic bodies and covers small deformations.

Despite this it was considered worth while to continue the measurement past the elastic strain limit, this being prompted in part by the observations already made on the similarity between tensile and bending stress-strain curves.

It was found that it was possible to get up to a level of 5% strain in the beam bending test provided the beam level was reduced to 0.4 inches and it may be possible to get above that level with a still shorter beam length. Comment has been made that a lateral compression of the monofilament had been noted and it was found that the use of the corrected value of diameter brought the value of the (beam) bending modulus into line with that of the tensile modulus at the same level of strain.

It will be appreciated that it was not possible to superimpose a tensile and bending curve on each other under actual test conditions because of the scale differences particularly in the strain coordinate. It was possible to obtain 1% strain in both stretching and bending in the same time and with the load scales adjusted in proportion and the extension scale suitably magnified. An almost exact superimposition of the two graphs was obtained and it was also possible to get close agreement at any specific strain level although the slope of the curves might differ before and after this point.

In order to calculate the strain imposed on the loop at the support inspection suggested that the form of the loop changed from a circle to an ellipse, and that there was a linear relationship between log strain and log r , the radius of curvature. An exact definition would require a calculation in which the periphery of the circle and the ellipse remained constant and that the loop behaved as a true elastica. It was hoped however that to a first approximation the strain on the sample could be calculated by the following method.



Let the figure represent an ellipse with x the major axis and direction of deflecting force, y the minor axis, a the major radius and b the minor radius.

The equation of the ellipse is given by

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

where $\quad x = a \text{ Cos } \theta$

and $\quad y = b \text{ Sin } \theta$

Let C be a point on the major axis such that r is the radius of curvature at a point of intersection of the ellipse and the major axis, where $\theta = 0$

Then
$$\frac{1}{r} = \frac{\frac{d^2y}{dx^2}}{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{\frac{3}{2}}}$$

and $\quad \frac{dx}{d\theta} = -a \text{ Sin } \theta, \quad \frac{dy}{d\theta} = b \text{ Cos } \theta$

Then
$$\frac{dy}{dx} = -\frac{b}{a} \text{ Cot } \theta$$

$$\frac{d^2y}{dx^2} = +\frac{b}{a} \text{ Cosec}^2 \theta \quad \frac{1}{-a \text{ Sin } \theta}$$

$$= \frac{-b}{a^2 \text{ Sin}^3 \theta}$$

Hence
$$r = \frac{\left[1 + \frac{b^2}{a^2} \frac{\text{Cos}^2 \theta}{\text{Sin}^2 \theta}\right]^{\frac{3}{2}} a^2 \text{ Sin}^3 \theta}{-b}$$

$$= \frac{(a^2 \text{ Sin}^2 \theta + b^2 \text{ Cos}^2 \theta)^{\frac{3}{2}}}{-a b}$$

At $= 0$, $r = \frac{-b^2}{a}$

$$= \frac{b^2}{a} \text{ ignoring sign.}$$

Thus for a circle where $b = a$

$r = a = b$, which is correct.

The values of a and b for loops of different diameter undergoing depression were measured by means of a cathetometer, and the resultant radii of curvature and strain values were calculated. Measurements of load against depression were already available hence the values of bending modulus with depression and strain could be compared. A complicating feature was the presence of residual stress and strain in the loop on formation. This was allowed for by letting the loop relax or condition before test. The rigidity of loop might be 20% lower immediately on formation, the bulk of recovery being obtained within ten minutes of loop formation.

There was a parallel with tensile tests in that values of tensile modulus showed a comparable drop in value if taken on a sample that had just been strained to equivalent bending strain. A recovery of modulus was obtained if these samples were held at the strain level for ten minutes before test.

A converse agreement that was found to be generally applicable was that the value of the bending modulus of a fibre possessing inherent strain was that of the tensile strain modulus at the same level of strain. Thus the immediate bending modulus of nylon 6, as a 3.2 cm. and 1.7 cm.

loop, was 19,200 and 15,200 kgf/cm^2 respectively compared with tensile values of 19,800 and 15,900 kgf/cm^2.

The amount of inherent strain was greatest with the smallest loop and a very small amount of deflection increased the strain by 1.0%. Conversely the amount of inherent strain was slight with the large loops and considerable deflection was required before the 1% strain level was passed.

The significance of this was that depending on the stiffness of the material the larger loop allowed a more accurate reading of deflection.

3. Strain Moduli : Results and Discussion.

Table 16 shows the values for the tensile and bending moduli of nylon 6, nylon 66, polyethylene and Terylene at unit intervals of strain. It will be seen that there is agreement between the stretching and bending values, at least up to 5% strain which was the limit of bending strain attempted in the present experiments.

Strain moduli of this order represent values outwith the truly elastic region and past the yield point and it is felt that such agreement may be of some importance in consideration of theoretical aspects of bending. There certainly can be no doubt as to the value of such information in considering the practical changes in processing and handling.

Strain. %	Fibre (Table 4) Strain Modulus $kgf/cm^2 \times 10^2$	Nylon 6 Tensile	Nylon 6 Bending	Nylon 66 Tensile	Nylon 66 Bending	Polypropylene Tensile	Polypropylene Bending	Terylene Tensile	Terylene Bending
1.0		204	(a) 208	262	(a) 258	460	(a) 451	1270	(a) 1280
			(b) 198		(b) 268				(b) 1270
2.0		178	(a) 176	214	(a) 213	360	(a) 369	900	(a) 900
			(b) 185		(b) 220				(b) 900
3.0		163	(a) 173	175	(a) 176	315	(a) 300	760	(a) 770
			(b) 157		(b) 186				(b) 780
4.0		141	(a)	161	(a)	283	(a) 281	710	(a) 700
			(b) 146		(b) 170				(b) 660
5.0		136	(a) 142	152	(a) 153	261	(a) 250	630	(a) 630
			(b) 138		(b) 159				(b) 620

(a) Beam. (b) Loop.

Table 16. Tensile and Bending Strain Moduli.

On the basis of these results it is argued that the value of the tensile modulus can be taken as indicative of the value of the bending modulus of a fibre, and that this holds at least up to, and perhaps past, the 5% level of strain.

Figure 8 (shows the change in modulus with strain, the values being calculated as the modulus per consecutive one per cent extension, and the curve can be used to forecast the probable bending behaviour, an increase or decrease in the gradient reflecting an increase or decrease in stiffness.

This is the actual gradient at each strain unit and is a close representation, albeit a reciprocal, of the original curve. The values show the expected degree of stiffness of a material for unit increase in strain from one strain level to another provided the effects of creep or stress decay can be ignored.

The values in Figure 8 (b) also show a cumulative strain modulus at a specific strain, or the average gradient of the stress-strain curve and will if carried to their conclusion eventually give a ratio that has been widely used to denote stiffness namely breaking stress to breaking strain.

It is felt that this method of expression of cumulative strain modulus is useful if the extent of applied strain is, or will be, known. The application of the strain must be

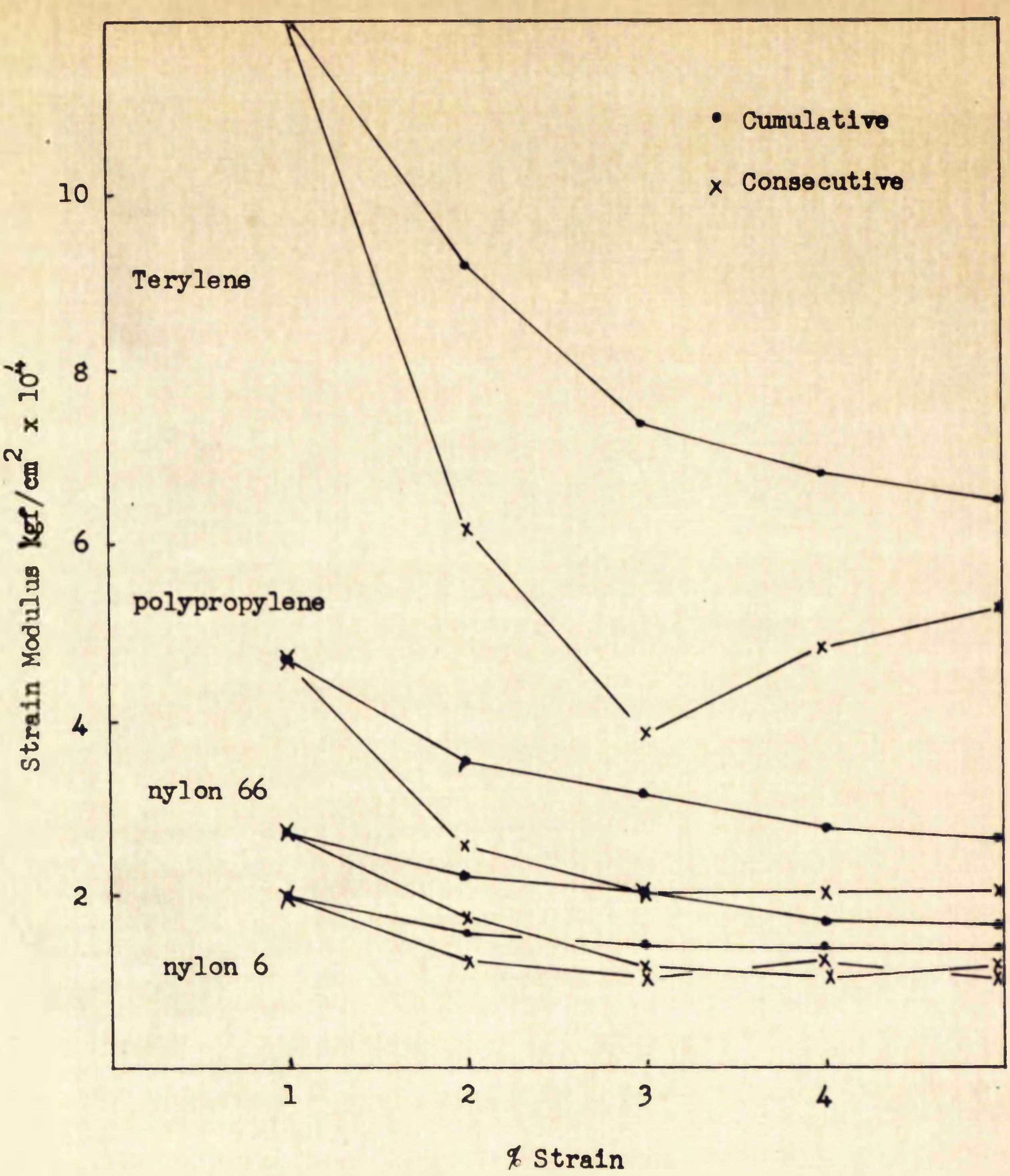


Figure 8 Cumulative and Consecutive Strain Moduli

continuous or else the value(s) will alter due to creep and stress decay.

It is considered likely that in practice the cumulative strain value will be the most useful. It is the easiest to obtain and at least likely to be nearer the practical value, the usual observation in this work being that the value of the modulus tended to increase with time of strain.

Yet another comparison would be that of the gradient of the load deflection curve itself. Figure 9 shows typical curves obtained by the beam and the loop method. Inspection of (a) would rank Terylene, nylon 66 (23 mil.) and nylon 6 in descending order of stiffness, (b) ranks Terylene, nylon 66, and nylon 6, and (c) Terylene and nylon 66, all in agreement with the known values of bending modulus. It will be noted that the general shape of the curves are similar to those of a tensile extension curve and comment has been made that coincidence of the bending and stretching curve can be obtained if the respective scales are suitably adjusted.

It follows that in any case where it is desired to check the comparative stiffness of two, or more, fibres irrespective of count, or diameter, inspection of the load

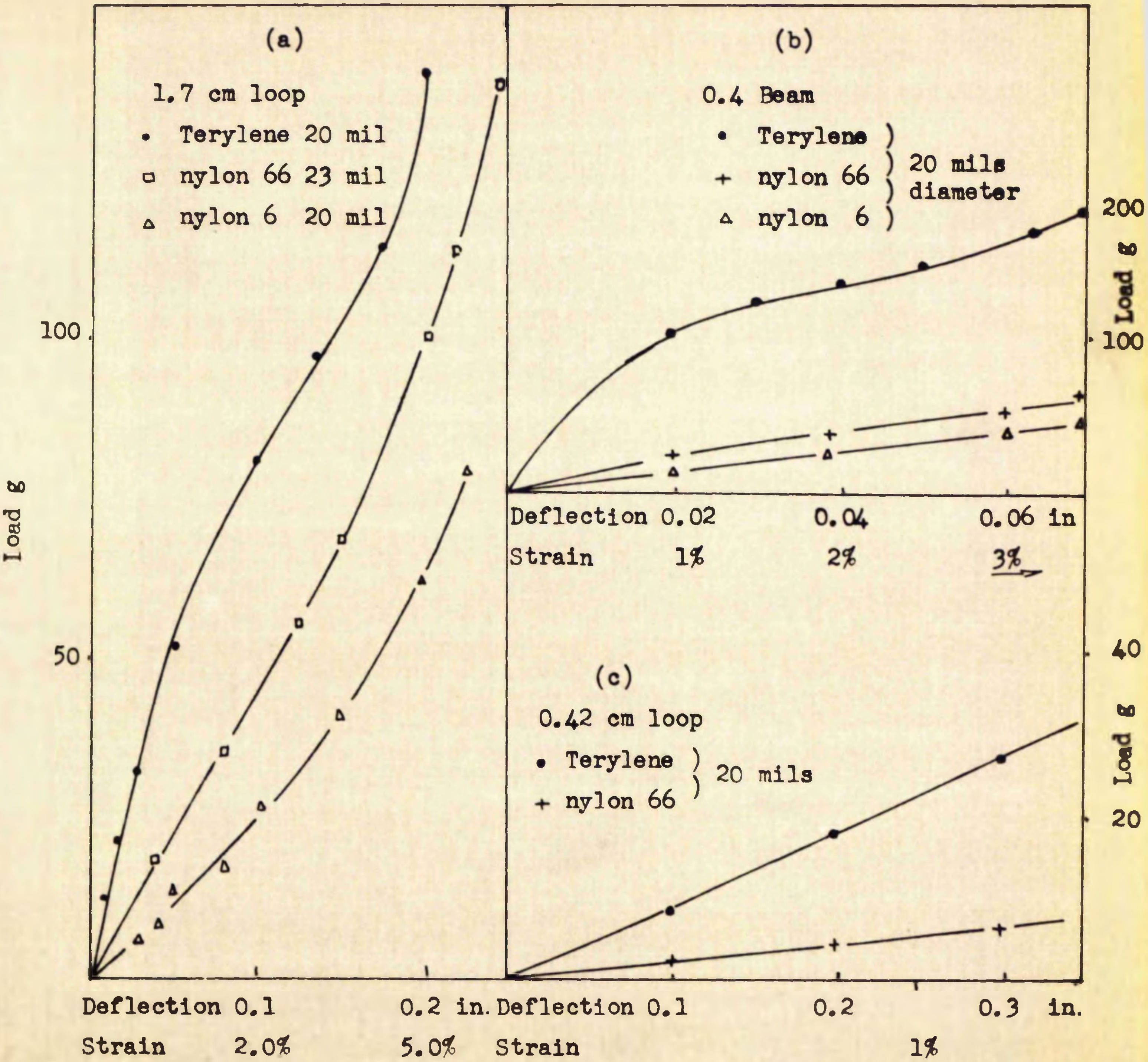


Figure 9 Load Deflection Curves for Beam and Loop Methods

extension curves should provide an answer. It will be seen that depending on the strain involved the stiffness of a material may change considerably, a drop of 50% being recorded for Terylene and only slightly less for nylon 66, while above 4% strain the stiffness of nylon 66 and nylon 6 has become virtually the same. On the premise that there is a correlation between tensile and bending strain moduli Figure 10 has been prepared from literature [16, 20, 72, 89] the values of the cumulative strain moduli, obtained by inspection and calculation, being plotted against the degree of strain.

It was considered that interests would be best served by selecting extremes of various types of fibres so that some information was available on the stiffest and least stiff fibre, and the range of stiffness within any particular family of fibres.

Inspection will show that while in general the value of the strain modulus will decrease with strain this is not always the case as is shown by a representative of nylon 66 and Orlon, Type 81.

No case was found where the modulus increased at low strain although examples were found where the value remained substantially unchanged. It is interesting to look ahead

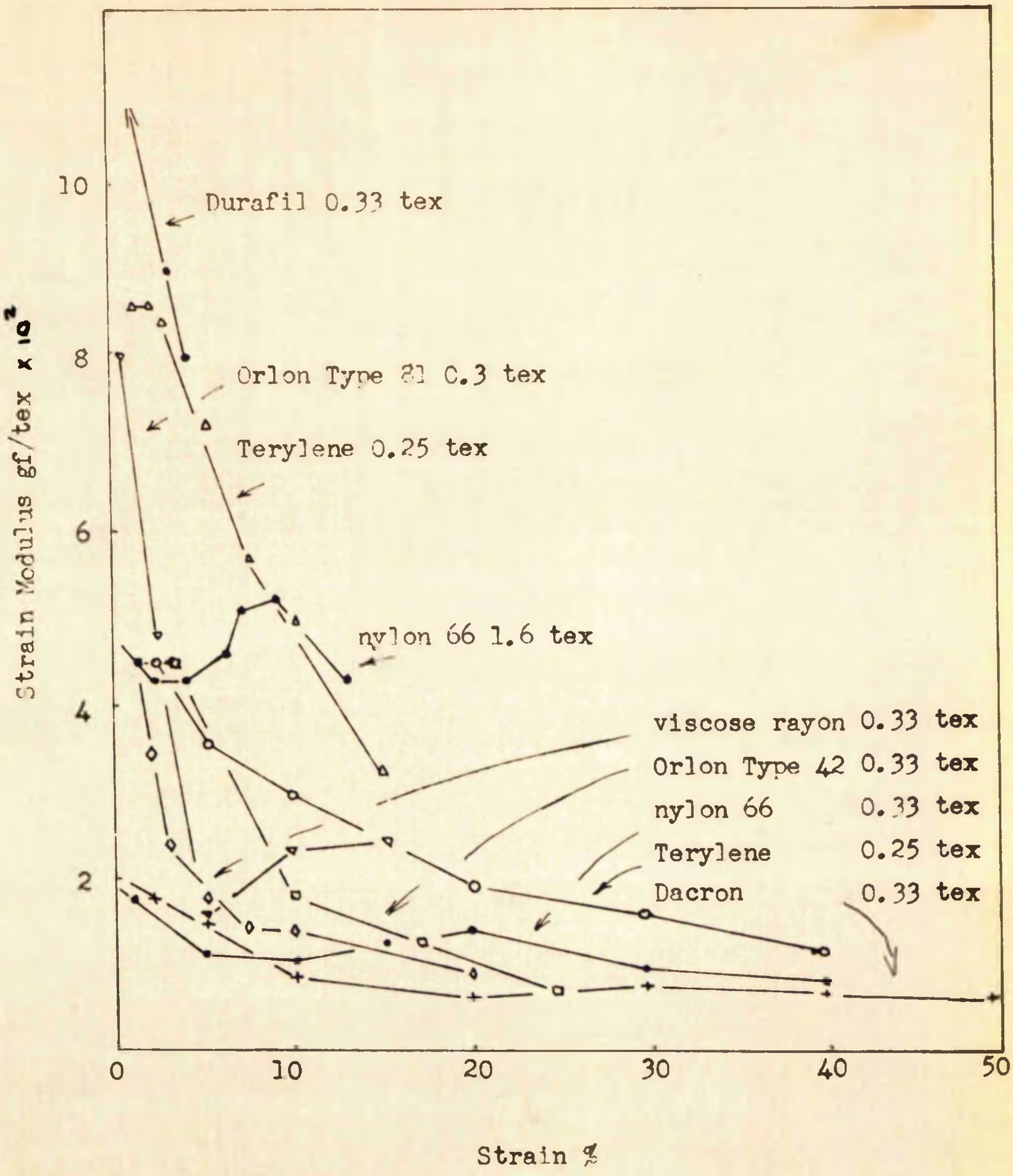


Figure 10 (Reference) Strain Moduli for Various Fibres

to yarn and fabric and to realise that all of these stress-strain results start with a taut fibre (presumably) with an immediate increase in stress relative to strain, whereas it may be found that under the influence of such items as crimp, there is an initial increase in strain relative to stress, and a sensation of limpness changing to stiffness.

Inspection of any set of values for initial modulus will show that there is a wide divergence between fibres. The present results show a range from 2000 gf/tex/ per cent extension for a Durafil fibre to 200 gf/tex/ per cent extension for nylon, a possible tenfold change in stiffness. The range narrows slightly with strain reaching five-fold at the 10% strain level and possibly as low as a two-fold range at 20% strain.

At the present time it seems unlikely that interest as far as handle and drape were concerned would involve strains above 10% so that irrespective of choice of tex, the designer has a large range with which to work. Again it is unlikely that stiffness would be the sole criterion governing choice of fibre, extremes excepted, but the results show the degree with which a specific stiffness can be obtained with any family of fibres, it being possible to virtually duplicate behaviour in this respect with rayon, polyamide, polyester, or an acrylic fibre. The reverse of this statement is also thought to be true and differences in handle, response etc. easily obtained.

It will be shown later that the term stiffness often relates to the relationship between breaking load and extension. The values for such stiffness of the monofilament fibres have been given in Table 17 and the results will be found to be in keeping with the previous comments on the relative bending properties of the materials. Further reference will be made to these values in the appropriate section. Mention has also been made that the term stiffness has also been used based on low strain values of tensile moduli. One reference with a particular bearing on this point is that of Hoffman[102] in an article dealing with the concept of a "diminishing modulus", in which it was stated that the stiffness of wool decreased with load, elongation, and with the deviation of the load. The effect of time and degree of stretch on the stiffness was illustrated by the following table in which the stiffness in grammes per denier per 100 per cent elongation was calculated for a wool fibre from creep data.

Fibre*	Breaking Load	Breaking Extension	Stiffness at Break	
	Kg.	%	Ratio	gf/tex/%Ext.
Nylon 6	8.1	28	29	113
Nylon 66	7.8	31	25	100
Polyethylene	5.2	48	11	54
Polypropylene	7.6	22	34	212
Saran	5.2	26	20	57
Terylene	10.5	16	64	235

* Table 4.

Table 17. Breaking Load, Extension, and Stiffness of Certain Monofilament Materials.

	Strain		
Time	1%	2%	5%
min.			
0.1	49	37	18
10.0	40	32	16
1000.0	31	26	14

Table 18. Stiffness of a Wool Fibre at Various Elongations and Loading Times.

The potential change in stiffness value is of interest in the light of earlier comments relating to the similarity of tensile and bending results under different conditions. It was also interesting to note that the modulus of wool, determined by the velocity of sound and involving much shorter times (1×10^{-6} minutes) and elongations was given as 56 grammes per denier per 100 per cent elongation.

Hamburger et al[68] discussed, some aspects of elastic behaviour at low strains and commented that although a fibre might have a breaking strain of 4%, it was capable of being bent in yarn form through 180° representing a theoretical strain of 100%. The fact that the fibre was not broken by such treatment suggested that considerable freedom of movement must be present. This has been taken out of sequence partly because it illustrates how knowledge of a fibre property may not always find correlation in yarn or fabric form, and partly because it would be useful if the argument could be used in reverse and measurement of the fibre (property) from the fabric prove something about the actual strain. It may be shown that the strain at the outermost portion of a monofil is slightly more than twice the average strain on the tensile side of the monofil when that monofil is bent through 180° over a rod. The size of the relative strains will depend on the respective diameters, being 50% and 33% at the outside when the monofilament is bent over a rod of equal diameter, and double diameter, respectively.

The corresponding figures for the average strain would be 21% and 14%. Similarly if the ratio of the diameter of the rod to the diameter of the monofilament was 19 to 1, then the relative strains would be 5% and 2%. A monofilament was bent over suitable rods in order to check these assumptions, being held in position for five minutes and then the tensile modulus of the fibre compared with the strain moduli of the fibre including the modulus obtained by holding the fibre at the above (stretching) strains for an equivalent period. The results showed that the tensile values of the bent fibres corresponded, taking polypropylene as an example the initial modulus of a sample strained and held at 50 per cent of the average strain was 450 gf/tex while that of a sample which had been bent over itself ranged from 375 to 510 gf/tex. The problem is complex being dependant on duplicating test conditions, and straining the entire length of the bent fibre and it has only been mentioned because the author considers that some correlation will eventually be found.

Comment might also be made that it had been noted that the surface of a number of monofilaments became opaque just before breaking strain. The change was usually rapid and the entire test length was affected although the effect seemed to travel from the centre to the jaws.

It was possible to produce this phenomenon by (lateral) compression and it could be used as check on undue strain at the jaws. It was also noticed on bending and particularly in loop and knot tests and its relevance at this point is that its appearance offers further evidence of high surface strain at the point(s) of bending, while it was noted that it formed on the outer (stretched) and inner (compressed) periphery suggesting equal strain.

CHAPTER V. STRETCHING AND BENDING RELATIONSHIPS.

Mention has been made on several occasions that a particular relationship, or proportionality, should exist between a property of a fibre and a particular parameter and that such a relationship could be used to check on the accuracy of an answer, or on the degree of departure from linearity. Thus in tensile experiments the load required to stretch a fibre should be directly proportional to the square of the diameter, or to the denier. Similarly in beam bending the load should be inversely proportional to the cube of the bending length and directly proportional to the fourth power of the diameter, or square of the denier. These relationships were always carefully checked.

One interesting point that follows from a comparison of the formula for the tensile and bending moduli, is that there should be a ratio between the load required to extend a fibre, and the load required to bend a fibre. Thus for 1 per cent strain the ratio of W_t to W_b was 25:1, where W_t is the load required to extend the fibre by 1 per cent, W_b is the load required to bend the fibre by 1 per cent, and the sample was a 20 mil. fibre test length 0.4 inches. Similar ratios can be calculated for any set of conditions and serve as a check on experimental accuracy. They were successfully applied over a range of beam lengths, and to strains up to 5 per cent. and it is considered that the reasonable preservation of this ratio outwith the elastic region serves as confirmation that there is a similar mechanism involved in stretching and in bending a fibre, even though the latter involves compression as well as stretching.

The relationship in the bending of a loop are more complex and involve angular functions. Although values may be substituted individually the usual procedure was to obtain the value of $\frac{W}{\mathrm{Tan}\theta/\mathrm{Cos}\theta}$ from the gradient obtained by plotting the load against the function of the angle. It has been shown that the stress-strain relationship was sensitive to the dimensions, and changes in dimensions, of the loop and this in turn was reflected in the relationship between the load and the angular displacement. Table 19 shows an example of the proportionality between load, tex, and diameter while Figure 11 shows the forms of the curve of load against angular function for loop displacement. The formula used allowed the calculation of the value of flexural rigidity from which, knowing the value of the moment of inertia, subsequent calculation gave the value of the bending modulus.

Assuming the constant k , it was possible to check the proportionality of G, flexural rigidity, with load,

Fibre. **Nylon 66.**

Diameter	Diameter^2	Diameter^4	Tex	Tex^2	Load for 1% Extension	Flexural Rigidity G.
cm x 10^{-3}	cm^2 x 10^{-7}	cm^4 x 10^{-16}		x 10^2	g.	g.cm^2 x 10^2
13	17	2.9	16	2.6	38	0.4
30	90	81.0	86	74.0	180	11
44	194	376.0	173	300.0	360	44
57	325	1050.0	326	1080.0	680	147

Table 19. Diameter and Tex Proportionality of Nylon 66 Fibres.

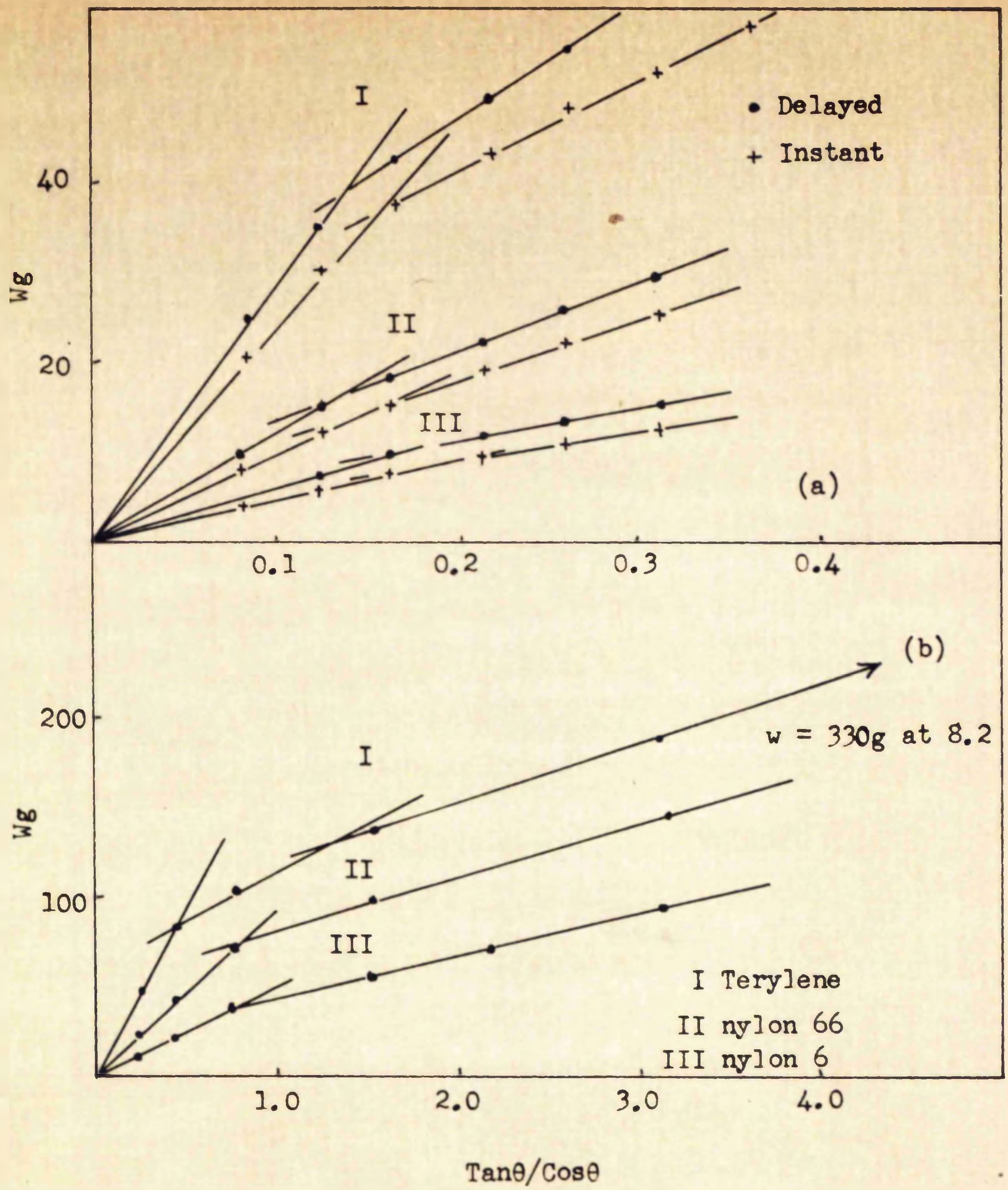


Figure 11 Change of Proportionality of $\frac{W}{\text{Tan}\theta/\text{Cos}\theta}$ with Deflection

(loop length)^2 (diameter)^4 and (tex)^2 and it was usually found that failure of these pointed to an error of measurement, provided that the system was not unduly strained.

The value of the constant was shown by Peirce [6] to be 0.0047 and this value was taken by Carlene [7] and has been used in the present experimental work. The value was based on the formula which Pierce derived for the bending of a hanging loop. It was stated that the form of a ring under tension may differ from that due to distortion by weight only. Inspection of a graph of k against $\tan\theta/\cos\theta$ showed that the curve was hyperbolic and that, depending on θ, the value of k could alternate by about 4% over the range of deflection used in these experiments. The derivation of the value of rigidity depends on the deflection of the loop under load, both variables may be measured and the value of θ may be calculated. The value of θ for the three sizes of loop most frequently used are given in the following Table 20, along with the value of kl^2.

<u>Loop Diameter</u>

cm.	kl^2	θ
1.7	0.134	23.4 y
4.2	0.820	95.0 y
8.7	3.53	46.4 y

y = deflection of Loop (in.)

Table 20. Values of Loop Factors.

Although the ultimate rigidity units were in the c.g.s. system it was found expedient to record the deflection in inches because of the instrument settings. It follows that the value of θ depends on the value of the deflection which in turn affects the amount of strain imposed on the fibre. The value of $\frac{\tan\theta}{\cos\theta}$ is not constant but the initial rise is not steep so that it is not considered that large errors will result in taking values of below 30° but the curve rises sharply to infinity above the 60° value. Before this point however the change in shape of the circle will be considerable so that in any case the geometry will be in error, the system changing from one of bending short lengths to that of the tensile performance of a loop. Thus unless there is a compensating change in the value of the load then departure from linearity may be expected. The immediate strain in the three loops using the 0.5 mm. diameter monofilaments was of the order of 3.0%, 1.2% and 0.6% respectively. If the stress at these strains is not allowed to decay before test then the value of rigidity obtained is lower than that of the unstrained filament. If the sample is allowed to relax then the value approaches that of the normal fibre. In either case the strain imposed varies with the diameter of the loop and with the smallest diameter the deflection necessary to bring the value of Θ above 30° also brings the fibre outwith the truly elastic region as evidenced by the slope of the stress-strain curve and the change in the gradient of the load, W, against $\tan\Theta/\cos\Theta$. The results shown in Figure 11 were typical and show that the change in proportionality was dependant on the fibre, the history of the fibre, and the amount of loop deflection. The change seems to take the form of a gradual curve such that it is possible to produce several regions of linearity, as shown, with the change in slope in itself an indication of a change of stiffness. No attempt has been made to investigate this point further, but it should be noted that linearity in itself is not an absolute indication that the performance of the loop is within the elastic region. It is important in any attempt at correlation with initial modulus that the correct slope is chosen.

It is interesting to consider the loop acting as a (relaxed) beam such that the effective length of the beam was equal to the diameter of the loop. The load at constant (linear) deflection of the loop should be in proportion to the cube of the loop diameter, while for constant strain the load should be constant. Reference to Table 21 will show that such was the case.

Loop Diameter D in.	D^3 Cu.in.	Load for Constant Deflection g.	Deflection for 1% Strain	Load for 1% strain g.
0.67	0.3	12.50	0.06	44.5
1.65	4.5	0.85	0.44	45.0
3.42	40.4	0.08	1.70	44.8

Table 21. Loop Load Deflection Diameter Proportionality.

Finally on a general point of relationship it had been hoped that some correlation might have been found between bending stiffness, and energy or work, either at low or high strain values.

It has been shown that the strain modulus is proportional to the ratio of stress over strain while as a first approximation the work involved is proportional to half the product of stress and strain. It follows that work should be proportional to half the product of the modulus and the square of the strain for constant strain, and to half the product of the ratio of the square of stress over the modulus for constant load. These relationships have not been posed experimentally because the necessary calculation of work from the respective stress-strain curves has not been completed.

CHAPTER 8. GENERAL CONCLUSIONS FROM FIBRE EXPERIMENTS.

It was hoped that the experimental work would produce some answers to the problems of bending and it is considered that some answers have been found and substantiated.

A survey of literature had shown that opinions differed on the relative standing of tensile and bending moduli and it was considered that one of the main factors would be the relationship of the tensile and compressive moduli on the argument that bending involved both of these latter items.

Experiment has shown both to be equal at small strains but that the problem of buckling will be encountered at higher strains and that this is linked to the dimensions of the test specimen. It is to be expected that buckling will occur when a yarn or fabric is being bent.

One reason for a reduction in modulus value with short test lengths was found to be failure to record actual strain.

Having established this point about the tensile and compressive moduli it was considered that if bending occurred about the central axis of a fibre then the bending modulus should be equal to tensile modulus. Bending tests were carried out, and the results, checked within the present tests and with published results, suggested that the value of the initial tensile modulus was the same as the value of the initial bending modulus with both properties showing similar characteristics with regard to the effects of time, temperature, and humidity. It was also suggested that the equality of the relationship extended to strains outwith the region of initial elasticity. The stiffness of a fibre at a specific strain, or as a result of a previous strain history, may be estimated by a knowledge of the value of the appropriate strain modulus.

The rigidity of a fibre may be expressed in terms of the cross-sectional area of a fibre, the weight per unit length of the fibre, or in units of flexural rigidity G. This term has been widely used as a measure of the stiffness of a material. It is largely a numerical term, the larger the number, the stiffer the material, although often expressed in units of gf cm^2. It has the advantage that it can be used to compare unlike structures as no knowledge of diameter, shape factor etc. is required. Equally this is a disadvantage if it is desired to compare the probable performance of materials similar in form but of different count or diameter, although it is known that the value of flexural rigidity increases as the square of tex, or fourth power of diameter. It is also known that the value increases in a linear way with an increase in the number of fibres being bent provided all samples are being bent to the same extent. At this stage the use of an expression such as stress, or specific stress, would appear tidier but as it would be helpful to have the value of the bending resistance of fibre, yarn, and fabric expressed in the same units the use of this term cannot be discounted.

One method of measuring the bending property of a fibre may be that used to measure the strength of a fibre and this would obviate the need for apparatus of the necessary sensitivity to deal with the very small loads and deflections in bending a fibre. Such apparatus might be necessary at high strains in which case the loop test would be needed as the present (unfixed) beam would slip. At low strains there was little to choose between the beam and loop method, both of which gave similar results. It follows that the beam method can be used to measure the flexural rigidity of a material.

Finally, the order of change of resistance to bending has been shown to vary considerably depending on the history of the material, and conditions at the time of bending. These changes, and the effect of the diameter of the material, may outweigh differences in the original moduli of fibres and should be considered in any evaluation of yarn and fabric.

PART II. TENSILE AND BENDING PROPERTIES OF YARNS AND FABRICS.

The foregoing sections have shown that for a fibre the valuesof the tensile, compressive and bending modulus were similar, and that there was close agreement between the tensile strain and bending strain moduli even above the region of truly elastic strain. With this in mind it should follow that the knowledge of a tensile strain modulus of a material is sufficient to be able to forecast some of the bending properties of that material. In these sectionsthe work is extended to see whether this hypothesis can be applied to yarns and fabrics.

The tensile moduli of a number of yarns and fabrics have been obtained, the ranking of ease of bending forecast, and then this ranking compared with that obtained by measurement of the bending modulus, flexural rigidity and bending length. Measurements were initially restricted to strains within the elastic limit of the material but consideration has been given to some values outwith the elastic limit.

CHAPTER 9. GENERAL COMMENT ON TEST METHODS FOR YARNS AND FABRICS.

1. Tensile Moduli.

2. Bending Properties.

3. Factors Affecting the Value of a Modulus or Other Property.

CHAPTER 9. GENERAL COMMENT ON TEST METHODS FOR YARNS AND FABRICS.

1. Tensile Moduli.

The methods used to determine the strain moduli were similar to those already used (42,95), a test length of ten inches being chosen for accuracy and ease of measurement of strain.

Care was taken that in cases of comparative testing the samples had been prepared in a similar manner and were in a similar condition, while in cases dealing with the comparison of fibre, yarn, and fabric properties, the yarns and fibres were taken from the fabric in question, due consideration being given to the question of effective sampling. The speed of test was dependant on the range of strain involved being usually 10 per cent extension per minute for strains below 5 per cent, and 20 per cent extension per minute for strains above 5 per cent and up to breaking strain.

Where tests were being made on a fabric, warp and weft strips were cut and frayed to one inch width. This width was chosen to correspond with the width of the Instron jaws and so that the same strips could be used beforehand for measurement of the bending length. One difficulty in measuring the modulus of a yarn lies in accurately defining the strain imposed. Strain could consist of true (tensile) elongation, be representative of the take-up of the slackness or fullness of the material, evident, say, in a loosely twisted yarn, or be the result of the removal of crimp. In practice it may well be the composite of all three factors, and the term has been used in this sense.

When the aim of a test is to establish the value of the breaking strength the usual practice is to pretension the yarn sample before clamping. The value of the load so applied may be obtained by measuring the load required to remove crimp and straighten the yarn, or it may be determined from inspection of the initial stress-strain curves, or it may be an arbitary decision to apply a load such as 0.1 g/tex.

It was felt however that the behaviour of the sample during such straightening might be symptomatic of the initial bending resistance and tests were carried out on each sample over a range of tension from slack to taut, taut being defined as the condition of the sample where sufficient load had been applied to straighten the fibre content of the sample.

A similar difficulty was encountered with the measurement of the stress-strain properties of a fabric. The degree of fabric assistance was measured in warp and weft direction by comparing relative yarn and fabric strengths in ratio form.

The tensile modulus of a fibre was expressed in terms of stress or specific stress. It may be argued that there are difficulties with regard to accuracy with either method due to the dimensions involved but both systems are in general use.

If it is desired to express the modulus of a yarn in terms of stress, either reference has to be made to the area of one filament and the total area calculated,the number of filaments involved being known, or the area of the yarn can be calculated on the assumption that the yarn is a cylinder whose diameter can be measured.

In the case of a yarn it is common textile practice to refer to the weight per unit length as an item of routine nomenclature,so that it follows that it is usually a straightforward step to refer to the strength modulus in similar terms, the initial load, or the breaking load, being divided by the weight per unit length. Such a value can then be directly translated in terms of individual filament strength, or allow yarn comparison, as the case may be.

Thus the use of specific stress measurement can be applied to either filament,or fibre,yarn and allows direct comparison of the property of individual filament and yarn. The use of stress measurement can be applied most easily to filament yarns in the present state of experimental methods, and does not permit such direct translation of filament and yarn property. Either term has been used in the following section wherever relevant, and use has also been made of the relationship

$$gf/tex \times density = kgf/mm^2$$

to check the order of the value of the diameter used in calculation. It was assumed that the accuracy of tex measurement exceeded the accuracy of diameter measurement, and the value of the stress of yarn and fabric has been calculated and errors checked by tex conversion.

The question of units was again encountered when dealing with the strain moduli of fabrics. If the fabric were a solid sheet then a case could be made for employing stress units, and in fact there may be occasions when such a procedure would be justified. These units might be employed if the question of a packing factor was being dealt with, or any other factor which would express the degree of solidity of the section of the fabric.

It is rather anomalous that a very common method of describing a fabric is to give the weight per square yard of the fabric, so that there may be a case for rationalising both items and measuring the strength and the weight per unit volume, but the procedure adopted was to reduce the strength of the fabric to the stress per thread in the direction of test.

The use of specific stress is again attractive as it allows direct comparison of filament, yarn, and fabric property provided the number of filaments and number of yarns involved are known. Each term has been used in the following section where relevant.

Other than the problems of accurately measuring initial strain and calculating the modulus mentioned in the preceding section, the general accuracy and risk of error is considered to be similar to that already discussed when dealing with fibre property.

The question of a jaw effect has to be remembered. This could take the form of undue compression leading to the occurrence of an undue number of "jaw breaks", or it could be that because of uneven mounting the strain was not thrown evenly on each component of the material under test.

The problem of jaw breaks was dealt with by discarding any result where the break occurred within half an inch of either jaw, but the only solution to uneven mounting was to exercise as much care in mounting as possible.

2. Bending Properties.

Bending modulus of a yarn

This was obtained from beam and loop experiments using the same techniques as were described for fibre measurement, The yarns were treated as cylindrical bodies and the value of the mean diameter obtained from microscopic inspection was used. It was realised that these assumptions might be in error at large deformations but it was hoped that the errors under small strain would be within the general experimental conditions. Such was not the case and the modulus was calculated as being the result of the bending of a number of rods whose diameters were known. All the fibres were taken as being cylindrical for the purposes of calculation. This assumption was probably justified for nylon and Terylene but viscose rayon is likely to be irregular in section. The use of shape factors[40,83] was considered and microscopic examination of filaments from the viscose yarns showed that the outline was in fact irregular both between and along the filaments.

It was decided that as the problem involved the behaviour of a number of such filaments, it might be argued that sufficient accuracy would result by taking a number of readings of diameter and taking a mean value. Such results suggested that the error in taking the moment of inertia as $\frac{\pi d^4}{64}$, where d is the mean diameter compared with taking the value given by $\frac{\pi d_1{}^3 d_2}{64}$, where d_1 is the mean value of the minimum diameter of the ellipse and d_2 was the maximum value, was less than 10 per cent or near the shape factor correction of 0.93. The modulus values would tend to be higher if the correction were applied and lower if the mean diameter method were used. While the need for the correction when dealing with a single fibre freely mounted is admitted, it is difficult to visualise that every fibre in a yarn will bend in this manner or direction, so that the error in taking a mean value may not be as large as suggested.

As the problem cannot be reduced so simply to fibre terms with staple yarns, some measurements of yarn diameter were made to see if any empirical solution could be obtained.

The immediate problem was to define the diameter of a fibrous yarn. It is not necessary to go into detail on this point as any calculations based on diameter measured by the microscope, or the diameter of the yarn measured under compression on a thickness guage showed a wide discrepancy in result from the order of expected modulus.

One method that seemed to give some consistent results of the correct order was to calculate the theoretical diameter of a solid yarn of equivalent tex to that of the yarn in question, take approximately half this value and use this to calculate the moment of inertia. The only logic in such a method could lie in the existence of a packing factor[114].

Flexural rigidity of a yarn.

This was measured by the loop test and beam test in a similar manner to that already described for a fibre. The size of loop chosen was dependant on the stiffness of the yarn which was in turn dependant on the denier, number of filaments, and material involved. The length of the beam was also governed by these factors. A short length, 0.2 inches, was usually required and even then the load required was often only just within the range of instrument sensitivity.

The graph of load against the ratio of tan θ to cos θ could be inspected to ensure that results were being taken within the elastic region, unless strains outwith this were being investigated. The deflection was kept to a minimum with both methods as correlation with initial strain values was being sought. This not only avoided the risk of over-straining the fibres, but also ensured that the degree of interference of one fibre with another was kept to a minimum.

No reference was found to the use of the beam method for yarns.

Bending moduli of a fabric

As at present defined these must not be compared with the use of the term made by Peirce[8], although the use of his term will be considered.

Strips of fabric one inch wide were treated as a beam so that the value of their bending modulus could be obtained. The experimental details were similar to those already described care being taken that comparative test details were always the same.

The results may either be expressed in terms of the width of the strip, or reduced to equivalent yarn, or fibre, state. The units may be those of stress, or specific stress. No reference was found to the use of beam test for fabrics.

Values for the bending moduli of a fabric may also be obtained by conversion of the values of the flexural rigidity from loop tests.

Flexural rigidity of a fabric

One inch wide strips of fabric were treated as loops and the value of their flexural rigidity established by the appropriate method. The ends of the strips were held in position by a very fine ribbon of adhesive tape, and care was taken to position the join between one o'clock and two o'clock in relation to the test loop. Values within the first linear relationship of W/(tan θ / cos θ) have been taken as being within the initial elastic region. Values of flexural rigidity were also obtained by the beam method. The results were reduced from gf cm^2 units to gf cm units to enable comparison with the value of flexural rigidity obtained by the Peirce[8] method where the bending of a fabric strip of unit width is considered.

Bending Length c, Flexural Rigidity G, and Bending Modulus q.

Values for these properties of a fabric were obtained so that a comparison could be made with those properties already discussed. The test method was that given by Peirce[8] and now available in standard form[140]. Bending length and flexural rigidity results have been widely used to denote the stiffness of a fabric while this connotation of bending modulus has been used with reference to the handle of a fabric.

3. Factors Affecting the Value of a Modulus or Other Property.

Some of the problems affecting accuracy remain as before, and the comments made in previous sections apply to the measurement of the bending properties of yarn and fabric. There are some new factors and these will now be considered under the headings of moment of inertia, test dimensions, and percentage strain.

Moment of Inertia

There are two factors which affect the estimation of this item namely, the general shape of the material and the change in this shape under strain conditions. The shape of the fibres in the preceding section was taken as circular so that the moment of inertia was $\frac{\pi d^4}{64}$ where d was the diameter of the fibre. It was suggested that under bending compression the shape might alter to that of an ellipse with a corresponding change in the moment of inertia, $\frac{\pi a^3 b}{4}$ where a is the smaller radius and b the larger radius.

Inspection of any yarn will show that it may, or may not, be circular in cross-section, and that whatever its section, that shape will probably alter due to fibre movement during bending.

The problem becomes more involved when items of fabric geometry are added. One solution would be to treat the fabric as a rigid beam so that the area of its cross-section would be that of the diameter and breadth of the beam and the moment of inertia would be given by $\frac{bd^3}{12}$.

Alternatively it might be argued that the fabric was made up of a number of yarns in the plane of bending, the yarns in the cross-direction being ignored, and the diameter involved being that of the bending yarns.

Thus one reason for any failure to obtain correlation between tensile and bending properties might well be failure to use or modify the appropriate moment of inertia. It was decided to use values calculated from the diameter of the yarn in the test direction, and the compressed fabric diameter, where the compressed diameter was the diameter measured under a pressure of $1 lb/in^2$ this being the pressure used in the standard test for thickness.

Test dimensions.

The tex of the individual fibre and of the resultant yarn partly determined the choice of method. A fine count implied the need for increased sensitivity in measurement and yet it required decreased sample size whether loop or beam, it being impossible in some cases to form a loop successfully. For very fine measurement recourse had to be made to a static test whereby very small increments of load were applied by hand and the resultant displacement of the sample measured by means of a cathetometer. A 1.7 cm. diameter loop and a 0.2 inch beam length were the most usual test dimensions for yarns and fabrics. 4.2 cm. loop diameter and 0.4 inch beam lengths were used with stiffer materials.

There will be an increased risk of flattening of the sample, with consequent effect on the moment of inertia, where a number of fine filaments are involved or the amount of twist in the yarn is small. The likelihood of correlation is expected to be less with a fibre yarn than with a filament yarn.

The sett and structure of the fabric, the count, twist and crimp of the yarns, and the diameter and number of fibres, are factors that might be expected to influence the bending properties of a fabric.

The resistance to bending is proportional to the number of threads in the strip and a one inch width was chosen partly because of the magnification of load achieved, partly because it was a convenient width for tensile strength testing, and partly because of its use in the cantilever test.

The length of the strip depended on the stiffness of the material. At one extreme, a very stiff material could be tested by either method and with whatever length was most suitable for general convenience; at the other extreme, a very limp material could not be formed into a perfect loop, and even with the beam method required a very short test length.

One experimental point that might be useful in any future assessment of the effect of fabric geometry on the bending of a fabric could be mentioned. It was found with the beam method that the load deflection curve of a fabric strip could be obtained, the traverse threads removed, and the corresponding load deflection curve of the remaining set of yarns obtained. Any difference between the two results may be attributed to fabric assistance.

Percentage strain.

In previous cases the strain was calculated on the basis of a known diameter and radius of curvature.

In the present context neither can be assumed to remain constant with a yarn if indeed they can be accurately measured in the first place. Examples will therefore be taken in which full freedom of movement is considered, this will represent one extreme but will allow calculation of the possible strain on a single component, and the possible degree of movement will be considered in the light of results.

Comment has already been made that the amount of strain has been restricted to allow comparison of stretching and bending on a equal basis.

CHAPTER 10. TENSILE AND BENDING PROPERTIES OF YARNS.

CHAPTER 10. TENSILE AND BENDING PROPERTIES OF YARNS.

1. Yarn and Test Details.

Details have been given in Table 22 of the yarns that were examined and the results of the various experiments may be found in Tables 23 to 26. All the yarns were commercial samples and they were chosen to cover a range of count, diameters, number of fibres present, and materials.

Details of test procedure were as follows:-

Instrument. Instron.

Strain Moduli. Rate of extension 10 per cent per minute, with a 10 inch test length. Extension magnified twice.

Breaking Load and Extension. Rate of extension 20 per cent per minute with a 10 inch test length. Extension not magnified.

Flexural Rigidity and Bending Modulus.

1.7 cm. loop and 0.4 inch beam. Rate of traverse 0.5 inches per minute, chart speed 20 inches per minute. 0.2 inch beam. Rate of traverse 0.2 inches per minute, chart speed 10 inches per minute.

Calibration in all tests was the lowest load possible set at half scale.

All tests were carried out under standard conditions on relaxed samples which had been exposed for 24 hours to those conditions. The minimum number of tests per sample per experiment was ten.

Yarn	Tex	σ	Number of Filaments	Yarn Twist Turns per Inch
Viscose Rayon	196	3.3	750	3.9Z
	55.5	1.2	50	2.6S
	27.8	0.6	50	2.3S
	16.6	0.3	27	2.5S
	100	2.2	Fibre	6.7S
Nylon	16.6	0.3	50	0.9Z
	11.0	0.2	1	-
	4.41	0.1	13	0.7Z
	4.28	0.1	34	0.8Z
Tery-lene	16.6	0.2	72	0.5S
	8.30	0.2	36	0.5S
	8.32	0.2	48	0.4S

Table 22. Details of Viscose Rayon, Nylon and Terylene Yarns.

Yarn	Tex	Number of Filaments	1% Strain Modulus kgf/cm^2 x 10^3	σ	Bending Modulus kgf/cm^2 x 10^3	σ
Viscose	196	750	62	2.0	-	
Rayon	55.5	50	84	1.5	112	2.1
	27.8	50	88	1.7	110	3.3
	16.8	27	92	1.7	108	2.8
	100	fibre	29	2.6	-	-
nylon	16.6	50	45	1.4	49	2.0
	11.0	1	31	1.3	32	1.8
	4.41	13	42	1.5	49	2.2
	4.28	34	44	2.0	52	2.6
Terylene	16.6	72	140	1.9	151	2.2
	8.30	36	142	1.7	154	2.7
	8.32	48	139	1.8	156	3.1

Table 23. Tensile and Bending Moduli of Viscose Rayon, Nylon and Terylene Yarns.

Fibre	Tex	Mean Diameter	Strain Modulus			
			0.5% Strain		1.0% Strain	
	x10^{-2}	μ	kgf/cm^2 x 10^3			
				σ		σ
Viscose	25	15	108	3.3	81	2.9
Rayon	111	31	104	2.8	88	2.6
	56	21	101	2.8	89	3.1
	62	23	103	3.6	90	3.1
Nylon	33	19	47	2.1	44	2.1
	13	12	46	2.7	42	2.8
Terylene	23	14	150	2.4	143	2.6
	17	12	146	3.4	136	2.9

Table 24. Strain Moduli Values of Viscose Rayon, Nylon, and Terylene Filaments.

Yarn	Tex	Number of Filaments	Load for 1% Strain g (1)	1% Strain Modulus gf/tex/% strain (2)	Load at Break g (3)	Extension at Break % (4)	Stiffness at Break g/% strain (5)	Stiffness at Break g/tex (6)	Stiffness at Break g/tex % strain (7)
Viscose Rayon	196	790	800	408	5000	24	24100	29	123
	55.5	90	300	550	860	16	5350	15	97
	27.8	90	160	500	390	17	2160	14	83
	16.8	27	100	604	250	14	2780	15	108
	100	fibre	190	190	1400	16	8800	14	88
Nylon	16.6	50	65	390	770	19	3900	46	235
	11.0	1	30	270	320	34	900	28	82
	4.42	13	17	390	220	20	1050	48	240
	4.28	34	17	400	210	16	1300	48	300
Terylene	16.6	72	170	1080	600	16	3660	36	220
	8.30	36	85	1030	330	16	2060	40	250
	8.32	48	83	1000	320	24	2300	38	270

Table 25. Tensile Properties of Viscose Rayon, Nylon and Terylene Yarns.

Yarn	Tex	Number of Filaments	Flexural Rigidity: Yarn gf.cm² x 10⁻³ (1)	(2)	Filament gf.cm² x 10⁻⁴ (3)	(4)
Viscose Rayon	196	750	32.1	12.8	0.43	0.28
	95.5	50	25.6	21.7	5.10	5.29
	27.8	50	6.42	6.74	1.29	1.31
	16.8	27	4.24	3.94	1.56	1.57
	100	fibre	12.8	-	-	
Nylon	16.6	50	2.14	1.88	0.43	0.45
	11.0	1	23.4	21.0	-	
	* 4.42	13	* 0.56	0.49	0.43	0.45
	* 4.28	34	* 0.21	0.20	0.06	0.06
Tery-lene	16.6	72	2.80	2.70	0.39	0.39
	* 8.30	36	* 1.38	1.38	0.38	0.39
	* 8.32	48	* 1.21	1.22	0.25	0.23

* Checked by cathetometer reading

Table 26. Flexural Rigidity of Viscose Rayon, Nylon and Terylene Yarns.

NOTE Column (1) experimental results from beam and loop methods.

(2) calculated results using equation on page 240.

(3) column (1) results divided by appropriate number of filaments.

(4) calculated results based on tex or diameter of filament.

2. Initial Strain Moduli in Tension and Bending.

1% Strain moduli

The values shown in Table 23 are of a similar order to the values for the initial moduli of nylon 66, Terylene, and viscose rayon quoted by Morton and Hearle[18], Cook[22], Carroll-Porczynski[23], and other authors[16, 30, 39].

Comment has been made that the initial stress-strain response of a yarn will depend on the structure of that yarn. A fibre yarn might be expected to undergo a period of longitudinal straightening and lateral compression while the components of a filament yarn required less adjustment before taking their share of the applied load. Inspection of the stress at 1% extension taken in the slack state with the value in the taut state would show the truth of these remarks,and it is felt that the initial behaviour may offer some evidence in deciding whether the handle of a yarn is soft or stiff in addition to the effect of denier and initial modulus.

It will be noted that the value of the modulus diminishes as the count or number of fibre components is increased. It was previously argued that the ease of bending of fibres could be forecast from a knowledge of their strain moduli valuesand it would appear that this is also the case with the present yarns. Thus the three yarns of equivalent tex (16.6) should show the ranking in descending stiffness of Terylene, viscose rayon, and nylon if of equivalent construction. The lower modulus of viscose rayon relative to Terylene may be offset by the higher filament tex and diameter and scrutiny of later results will show that this was the case.

It was noted that the viscose rayon filament yarns showed a very sharp change in strain modulus between 1% and 2% strain and it is considered that this is a contributory cause to the limpness that such yarns may show in service.

A monofilament nylon yarn was included for comparison: it has a lower modulus value than the other nylon yarns, the value being similar to that shown in a previous section for other nylon monofilaments.

Bending modulus

The results of bending tests given in Table 23 show strong agreement with the results for 1% strain modulus. It will be noted that they are generally higher particularly with the more complex yarns. The reason for this was believed to be that the tensile results were low because of the effects of yarn geometry, there being a time and strain lag which would reduce the value of the strain modulus. It was noticed that the effect most predominant in the viscose and then the

Terylene yarn, that is in order of sensitivity of change of stress-strain ratio at low strains.

The strain modulus of individual filaments was obtained (Table 24) and it will be seen that those values at 0.5% are nearer the values quoted for the bending modulus, whereas the values at 1.0% are similar to the values of the strain moduli of the yarns.

It is concluded therefore that, under the conditions of low strain used in these tests, the filaments have had complete freedom and yarn bending has been the free bending of each component fibre, and that the tensile strain values at less than 0.5% strain would show a further increase in value. It was also noted that the values were approaching moduli values quoted by workers using dynamic methods[12,28,30]. It is appreciated that the time element in this case is different but low strain is a common factor. In cases where the tensile strain is directly transmitted to the fibre components the strain modulus value is the same as the value of the bending modulus. In other cases the structure of the yarn may cause the strain modulus to be lower in value. This reduction in value may have some significance in assessing the handle, loft, or fullness of a yarn but this has not been fully investigated at this time. The order of result will be found to be comparable with values for initial moduli quoted in literature. For fibres of equivalent diameter the order of ranking of diminishing stiffness would be Terylene, viscose rayon and nylon. The difference in value between fibres of similar chemical composition is again shown.

No attempt was made to measure the moduli at higher strains except with viscose rayon, apart from stiffness tests which will be discussed in the next section. Comment was made that the tensile strain modulus of viscose rayon changed abruptly just above the 1% strain level and it would be expected from previous filament experiments, that the value of the bending modulus would also drop. In another context it had been noted that the recovery of the viscose rayon loops from deformation was very poor at anything other than the lowest deflections. It was suspected that the change in modulus, and elastic recovery might be the same in both bending and stretching and experiments where the yield point was exceeded, and cases where the yarn was held at high strain for some time, tended to confirm this, both values being reduced.

3. Comparison of Expressions for Yarn Stiffness.

The stiffness of a yarn may be expressed in various ways and some of these have been considered on the basis of the present experiments.

Bending modulus.

The initial resistance to bending may be expressed as bending stress in which case materials of any equivalent diameter may be compared. Thus from the results (Table 23) a Terylene filament would be stiffer than a viscose filament which in turn would be stiffer than a nylon filament. Given the same number of filaments, yarns would rank in the same order but this ranking could be upset if either the diameter of the filaments, or number of filaments were changed in a dissimilar manner. In the present case, and with additional reference to Table 22, the 55 Tex viscose rayon yarn would be expected to be stiffer than the 28 Tex yarn because of the greater filament diameter, although both yarns have 50 filaments. The 28 Tex viscose rayon yarn would be expected to be stiffer than the 17 Tex viscose rayon yarn. The small difference in filament diameter in favour of the 17 Tex yarn is offset by the very much larger difference in the number of filaments in the 28 Tex yarn compared with the 17 Tex yarn. Similar arguments can be advanced for the nylon and Terylene yarns. The ranking of the three yarns, viscose rayon, nylon, and Terylene, of comparable Tex value, 17, is complicated by the other differences in modulus, diameter, and number of filaments. Consideration of each factor in proportion leads to the forecast that the order of descending stiffness would be viscose rayon, Terylene, and nylon, the difference in filament diameter of the viscose rayon offsetting the greater number of filaments and higher modulus of the Terylene yarn.

Load for 1% strain.

Inspection of Table 25, column (1) will show that the values of the load for 1% strain have been given for each yarn. Assuming that the highest loads reflect the stiffest materials then it is possible to rank the yarns within their material group, the order of descending stiffness for the viscose rayon yarns being 196, 56, 100, 28 and 17 tex yarns respectively.

The nylon yarns would be ranked as 17, 11, and 4 tex with no difference between the two 4 tex yarns with such different structure. Similarly the Terylene yarns were separated into 17 tex as the stiffest but with no obvious difference between the two 8 tex yarns. The method would rank the yarns of equivalent tex (17) in descending order of stiffness as Terylene, viscose rayon, and nylon.

1% strain modulus ; specific stress.

Column (2) Table 25 shows the 1% strain moduli of the yarns expressed in terms of yarn count. The viscose yarns have been split into three groups. The 56, 28, and 17 tex yarns may be considered together with a common modulus and their stiffness will be directly proportional to the square of their filament tex and to the number of filaments. The 196 yex yarn which experiment has shown to have the same specific stress per tex filament has a different strain modulus value so that other factors besides tex and the number of filaments may be involved. The 100 tex fibre yarn has the lowest strain modulus value, a result expected because the modulus of viscose rayon fibre is usually lower than a filament value, and because of the openness of a fibre yarn permitting strain at a lower stress than the compact filament yarns. The order of ranking in descending stiffness is 196, 56, 100, 28, and 17 tex, respectively.

The nylon and Terylene multifilament yarns may be ranked in descending order of count. The monofilament nylon yarn has a different modulus value suggesting that it represents a different family although of the same chemical type as the other nylon yarns.

It should be possible to forecast the values of the flexural rigidity of a yarn from a knowledge of the tensile property of the yarn by use of the following equation.

$$\text{Flexural rigidity} = \frac{F \times n \times N^2}{4\pi \rho}$$

where F = force required to produce 1% extension, (or initial modulus value)

n = number of filaments

N = count of filaments

ρ = density of filaments

If F is expressed in terms of specific stress, N as tex count, and ρ as grammes per cubic centimetre then the equation is satisfied with the units being gm cm^2 on both sides of the equation. The appropriate values from Table 25 have been substituted and the values of flexural rigidity have been shown in Table 26, column (2). The agreement between the results obtained by tensile and bending experiments is taken as verification of theory and experiment. (column (1), bending results).

The values used for specific stress were those obtained from yarn tests, the argument at this stage being that bending results can be obtained from such tests but closer agreement would be reached by the use of filament specific stress values.

Stiffness at break.

The term stiffness has been used to denote the stress-strain relationship at breaking strain, the most usual form being specific stress at this point. Values of breaking strength and breaking extension have been given in Table 25, columns (3) and (4), and specific stress in column (6).

The 56, 28, and 17 tex viscose yarns are obviously of the same family and their strength is proportional to their count. The result for the 196 tex yarn is higher than would have been expected, had the only difference lain in structure, but in fact the filaments were known to be Tenasco and hence the higher breaking tenacity is explained. The breaking strength and tenacities of the nylon and Terylene yarns reflect the gross tex and any difference in family but do not distinguish between yarns of the same family and gross tex but with different constructions. The use of breaking strength and tenacity can indicate stiffness but give no indication of strain values whereas the corresponding initial values were at unit strain.

Strain may be incorporated by direct divisions of load by extension, or by dividing specific stress by strain, and both results have been given in Table 25. (Columns (5) and (7))

The ranking of the yarns in descending order of stiffness by load over extension gives 196, 100, 56, 28, and 17 tex viscose rayon: 17, 4, and 11 tex nylon; and 17, 8 tex Terylene within material classes. Comparison of yarns of different materials but comparable count would give nylon as the stiffest, closely followed by Terylene, with viscose rayon having approximately half the value of either of the others. It is important to remember that this is ranking materials by what might be called final stiffness and attention has been drawn to the changes in slope that may occur in a stress-strain relationship, viscose rayon being a particular example.

Inspection of the comparable results for the monofilament forms of nylon and Terylene (Table 17) will show that the position has been reversed. This is due to the greater extension of the monofilament nylon, the difference in initial modulus of the two forms suggesting a difference in molecular orientation.

It has been shown that the breaking tenacity of a material is dependant on the class or family of the material, that it would be expected to be similar for members of one family, but that it might be affected by structural features of a yarn. There was a difference of some ten per cent in the tenacity values of three viscose rayon yarns, 56, 28, and 17 tex and there was a difference of almost twenty per cent in their extension figures. Values for nylon and Terylene yarns also known to belong to a particular class also show divergence although to a smaller extent. If a general mean were taken in each class then the value of specific stress at break can be used in the same way as with the initial value and the final or gross value of flexural rigidity obtained. Thus the value of the flexural rigidity of the 17 tex viscose rayon would change from 4×10^{-3} gf.cm^2 to 0.7×10^{-3} gf.cm^2, that of the 17 tex nylon from 2×10^{-3} gf.cm^2 to 1.3×10^{-3} gf.cm^2, and the value of the 17 tex Terylene from 2.8×10^{-3} gf.cm^2 to 0.7×10^{-3} gf.cm^2. Expressed on a percentage basis the flexural rigidity of viscose rayon decreased to 17%. nylon to 65%, and Terylene to 25% of their original value. This approach could be made at any strain value up to breaking point and a series of values of flexural rigidity could be calculated giving a pattern of the change of stiffness of a yarn with strain which should be similar to the pattern produced by considering the change of stiffness as shown by bending and tensile moduli.

Experience has shown that the handle and stiffness of viscose rayon materials changed with usage very much more noticeably than with nylon materials. In the present context it is considered that the stiffness of a yarn expressed as specific stress at breaking strain has a valid significance in the assessment of the properties of that yarn.

Graphical representation of yarn stiffness.

It may be argued that inspection of the stress-strain curves of yarns should allow their relative ranking of stiffness to be decided and the load-extension curves for a number of yarns have been given in Figure 12.

If these curves do reflect the change in stiffness of the yarns the change in stiffness with strain for any yarn is clearly shown, while they are easily ranked in order of stiffness with each other. As these are simply graphs, whose moduli have already been discussed, the subject need not be repeated as the comments are as before. The yarns

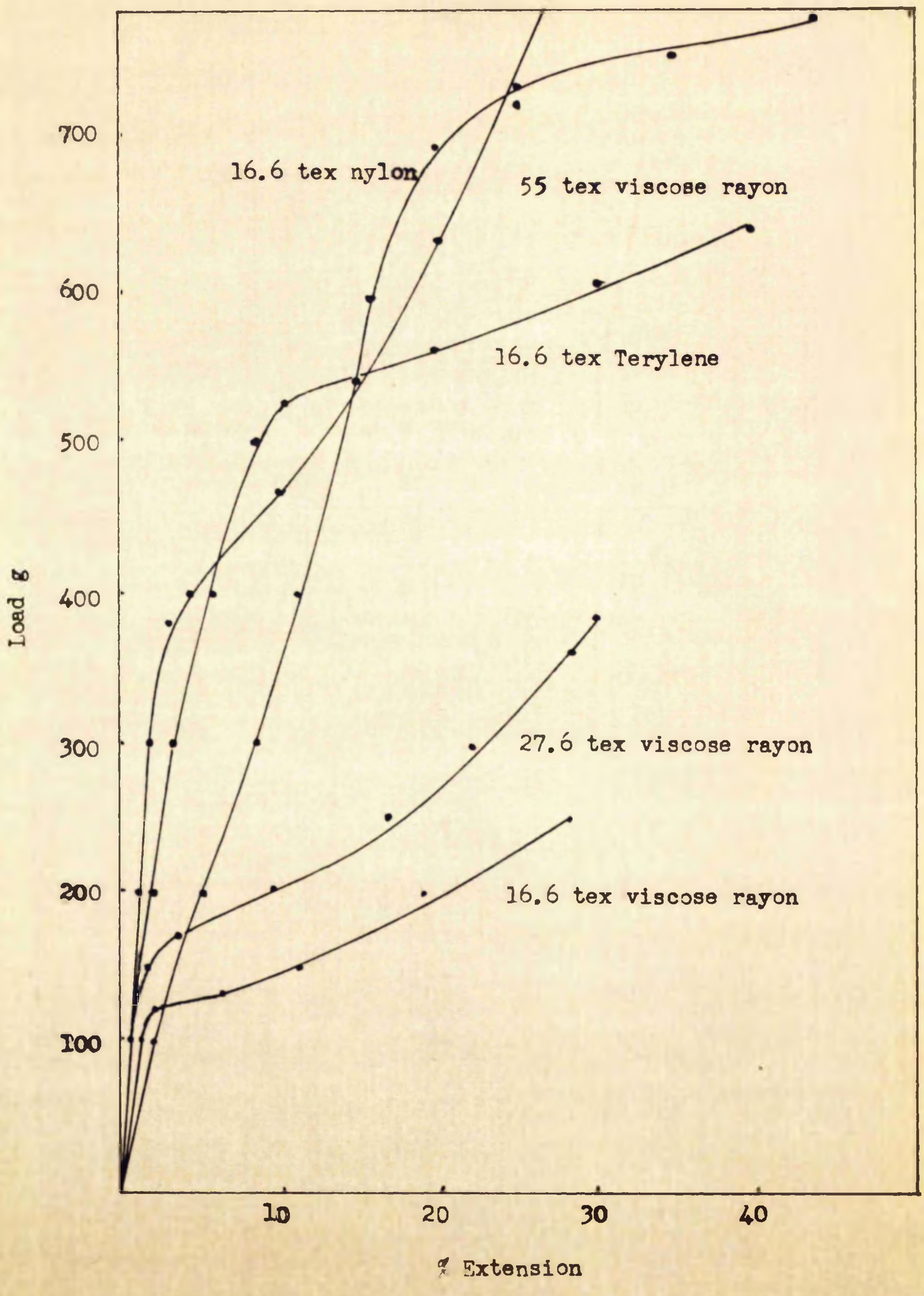


Figure 12 Load Extension Curves for Some Filament Yarns

are correctly ranked taking their flexural rigidity value as a criterion except for the relative position of the Terylene and 28 tex viscose rayon yarns which would be ranked of equivalent stiffness by sample inspection whereas the rayon yarn has a much higher rigidity. The position would be rectified when considered on a filament basis.

Flexural rigidity.

This property of a yarn is the one that has been most widely reported whenever stiffness rankings were required. It is usually reported in terms of m.gm.cm.^{2} units because of the extremely small values of load required to deflect a specimen. The property should be directly proportional to the fourth power of the diameter of the fibre, and to the second power of the denier or tex.

Carlene[7] showed that the flexural rigidity of a filament yarn was the sum of the flexural rigidities of the individual filaments and this was verified in the present experiments, while the present result for 150 denier 27 filament viscose rayon was also similar to the value quoted by Carlene.

Inspection of the results in Table 26 will show that the flexural rigidities of the yarns generally bear the expected relationship with filament tex and diameter and this was taken as proof of the experimental accuracy, (columns (1) and (3)).

The flexural rigidity value of the heaviest viscose yarn, 196 tex, was an exception. The experimental result was 32.1×10^{-3} gf.cm.^{2} compared with the expected result of 21.2×10^{-3} gf.cm.^{2} based on a filament stiffness of 0.28×10^{-4} gf.cm.^{2}, or 12.8×10^{-3} gf.cm^2 from specific stress.

This would suggest that the number of filaments have affected the freedom of movement such that some filaments have acted together, instead of independantly, with a consequent increase in total stiffness. The effect is in keeping with the forecast by Platt et al[119] regarding an increase in rigidity with a decrease in freedom. The rigidity of the staple yarn was 12.8×10^{-3} gf.cm.^{2} which is of the same order as the comparative filament yarns.

The writer has commented that the readings of flexural rigidity obtained by loop tests where θ lies between 10^{o} and 25^{o} have shown the best correlation with results obtained by beam experiments and with modulus values. The present experiments confirmed this and it is considered that this may be one reason why Carlene[7] failed in some cases to obtain correlation between yarn and filament results as the writer found that values of yarn flexural rigidity increased with higher values of θ . It was noticed during the beam tests that the graph of load against deflection sometimes showed an initial sharp rise as the test was started. It was considered that this was not representative of individual filament bending and was due to the initial inertia and friction of the system. The effect was most noticeable in Terylene and nylon, which have a higher coefficient of friction than viscose rayon.

The results in column (1) Table 26 were obtained by experiment and they show the ranking of descending stiffness of the viscose rayon yarns to be 196, 56, 100, 28, and 17 tex respectively, the 56 tex yarn being stiffer than the 100 tex yarn because of the rigidity of the filaments. The multifilament nylon and Terylene yarns have been ranked as might have been expected and in both cases there was a difference between the rigidity of the two yarns where the count was the same but the number of component filaments differed. The viscose rayon yarn was the stiffest of the three 17 tex yarns, followed by the Terylene and nylon yarns. The viscose rayon had the heaviest filament tex but the higher initial stiffness of the Terylene filaments presumably outweighed the effect of the nylon filament tex. The difference in result between the 17 tex multifilament nylon yarn and the 11 tex monofilament nylon yarn shows how the structure of the yarn can offset the gross tex values.

Comment has been made on the method of obtaining the results in column (2) Table 26. The general ranking remains as above with the exception that the 196 tex yarn would be displaced as the stiffest viscose yarn. A reason for the higher value of rigidity has been given. The results in column (3) Table 26 were obtained from the results in column (1) by division by the number of filaments in each yarn while the results in column (4) were obtained by calculation based on a knowledge of material tex and diameter. The two results should be the same, within experimental error, as long as the filaments being compared are of the same family and have complete freedom. Such proved to be the case, with the 196 tex viscose rayon yarn discrepancy referred to in a previous section again showing, the effective filament rigidity being higher than the calculated value. The rigidity of one filament of the 17 tex yarn is almost four times that of the Terylene filament and slightly more than three times that of the nylon filament, while the nylon filament is only slightly more rigid than the Terylene filament, so that allowing for the number of filaments the ranking of 17 tex yarn stiffness in descending order as viscose rayon, Terylene, and nylon is explained.

Effect of yarn twist on the flexural rigidity of a filament yarn.

In the preceding discussion the effect of twist on the properties of a yarn has been neglected.

According to Carlene[7] and Cooper[29] there is little effect of twist at the usual levels of twist associated with many filament yarns. This was checked by inserting 1,2,4,6,8, and 10 turns per inch into a filament yarn. The yarn was 16.6 tex, 50 filament, nylon and the twisted yarn was clamped, relaxed in water, and then dried and conditioned. No significant difference in value of the rigidity was noted.

Further tests were carried out on yarn containing 15, and 20 turns per inch inserted as above, when a difference was noted values of 1.58×10^{-3} gf.cm^2 and 1.46×10^{-3} gf.cm^2 being obtained respectively. The inference is that increasing twist in a filament yarn will decrease the value of the flexural rigidity. Carlene stated that the rigidity of a yarn will not be a simple sum of individual filament flexural rigidity at high twist but gave no values. The result seems to be in agreement with the comment by Platt et al[119] although inhibition of filament movement would have been expected about the upper level of twist.

Conclusions.

Scrutiny of the preceeding pages will show that attempts to rank the respective yarns in order of stiffness have met with with reasonable success. The most important conclusion is that it is possible to forecast the resistance to bending of a filament yarn from a knowledge of the initial tensile strain modulus of that yarn, the units being either those of stress or specific stress. Initial stiffness might be used as a name for the term when bending is implied. The value of such a modulus is very similar to the value of the bending modulus of the yarn assuming complete freedom, and the values of the flexural rigidity obtained by the two methods are similar. The stiffness of a filament yarn obtained from a knowledge of the breaking strength and extension of that yarn, and expressed in terms of specific stress, may serve as a guide to possible changes in the stiffness characteristics of a yarn under strain. The use of a stress-strain relationship is preferable to that of stress, tenacity, or extensibility by themselves although there will be circumstances when a knowledge of such properties will allow a correct forecast to be made.

The problem of restricted filament movement, and the question of fibre yarns has not been considered in detail. Experiment has shown that the value of the actual flexural rigidity can be obtained and that an estimate of stiffness can be made from tensile data.

CHAPTER 11. TENSILE AND BENDING PROPERTIES OF SOME FABRICS.

1. Fabric and Test Details.

2. Results and Discussion.

3. Moment of Inertia.

4. General Conclusions.

CHAPTER 11. TENSILE AND BENDING PROPERTIES OF SOME FABRICS.

1. Fabric and Test Details.

A number of fabrics were analysed and their tensile and bending properties were obtained. The fabrics have been considered separately because of the number of observations and relevant yarn details have also been included.

It was hoped that these experiments would prove of assistance in considering some aspects of fabric bending.

(a) If it could be shown that the agreement between tensile and bending property still held, then the resistance to bending of a fabric could be measured by a tensile test. It follows that this would require agreement between tensile and bending strain moduli, and also with the flexural rigidity of the material. The question of units would require consideration.

(b) The order of strain is known to vary in a bent fabric depending on the freedom of movement of the component yarns and fibres, and hence the value of the strain modulus may also vary.

(c) The possibility of correlation between an initial strain modulus, bending modulus q, and the handle of a fabric.

(d) Opportunity will be taken to measure the stiffness at tensile breaking strain. This term is widely used and is one which is conveniently measured in many routine tests. It would appear that this value might give some useful information in the ultimate bending strain characteristics of a material but the author has not been able to find the origin and justification of the term.

(e) It should be possible to forecast the probable bending behaviour of a fabric from a knowledge of the construction of the fabric. Such a forecast will be made and then reviewed after the experiment.

(f) The effect of finishing treatment should cause a similar change in the tensile and bending behaviour of the material if the two items are linked as has been suggested.

(g) The programme will require the comparison of test methods for fabric and should offer further evidence of yarn and fibre properties.

Details of test procedure for fabrics have been given below while these for yarns have been previously described.

Instrument Instron.

Strain Moduli Rate of extension 10 per cent per minute with 5 inch or 10 inch test lengths. Extension magnified twice.

Breaking Load and Extension Rate of extension 20 per cent per minute with 10 inch test length. Extension not magnified.

Flexural Rigidity and Bending Modulus 1.7 cm loop and 6.4 inch beam. Rate of traverse 0.5 inches per minute chart speed 20 inches per minute

0.2 inch beam. Rate of traverse 0.2 invhes per minute chart speed, 10 inches per minute.

0.6 inch beam. Rate of traverse 1.0 inch per minute chart speed 20 inches per minute.

4.2 cm loop. Rate of traverse 5.0 inch per minute chart speed 20 inches per minute.

Calibration in all tests was the lowest load possible set at half scale.

All tests were carried out under standard conditions on relaxed samples which had been exposed for 24 hours to those conditions. The minimum number of tests per sample per experiment was five.

Woven fabrics of simple construction were chosen with some change in detail from fabric to fabric. It seemed logical to start with fabrics with monofilament yarns so that some of the fabric geometry would be simplified, thence to fabrics with multifilament yarns, and finally to fabrics with fibre yarns. Details of each fabric have been given in Table 27 and reference should be made to these values as required throughout the subsequent script.

The results of tensile and bending tests have been given in Table 28 to 35 and these will be discussed separately. There were some explanatory notes that were common and these have been listed below.

Tensile tests.

(a) With both yarn and fabric the extreme values of strain modulus have been quoted. The value of the modulus was lowest when the sample was mounted under minimum tension, or slack. The load in this instance reflected any change in property due to crimp or bulk.
The value of the modulus was highest when the sample was mounted under moderate tension, or taut. It might be expected to correspond to the value of a specimen in which the fibre and yarn in the direction of test were straight, and to provide the best correlation between fibre,yarn, and fabric moduli.

(b) The value of the strain modulus, or stiffness, at breaking strain has been calculated.

FABRIC	One	Two	Three	Four	Five	Six	Seven	Eight
Material	Saran	Polypropylene	Polyethylene	Nylon	Terylene	Viscose Rayon	Nylon	Viscose Rayon
Ends per Inch	56	49	156	100	104	118	76	70
Picks per Inch	31	42	75	100	80	74	70	66
Yarn Count and Twist								
Warp tex	130	27	15.4	7.1	16.5	16.6	16.6	30.0
turns per inch	-	-	-	1.12	4.35	2.68	6.18	14.12
Weft tex	118	25	18.0	7.0	16.5	16.6	20.0	30.1
Turns per inch	-	-	-	0.92	1.03	2.58	8.92	12.92
Yarn Crimp %								
Warp	4	4	11	5	4	4	6	22
Weft	8	2	4	9	2	3	9	15
Yarn Diameter cm x 10^{-2}								
Warp normal	3.0	1.8	1.4	0.81	1.3	1.1	1.4	1.6
pressure	2.8	1.4	1.3	0.40	0.6	0.8	0.7	1.2
Weft normal	3.0	1.8	1.4	0.80	1.3	1.1	1.5	1.6
pressure	2.8	1.6	1.3	0.41	0.6	0.8	0.8	1.2
Fabric Thickness cm x 10^{-2}	7.6	4.0	3.7	1.2	1.7	2.2	2.2	3.7
Cover Factor Warp	637	234	610	266	425	430	312	382
Cover Factor Weft	335	210	318	264	324	302	314	362
Fabric Weight g/m^2	446	92	152	42	126	118	113	204
Fabric Tex	4460	930	1520	480	1260	1280	1130	2040
Weave	2/2 Twill	1/1	2/1 Twill	1/1	2/2 Twill	2/1 Twill	1/1	1/1

Table 27. Analysis of Fabrics used in Bending Experiments.

(c) The specific stress and stress have been calculated for yarn and fabric, the values for the fabric being reduced to a single thread basis.

(d) Specific stress has also been expressed in relation to fabric tex. The tex of a fabric is defined as the weight in grammes of a strip of fabric 1000 metres long and 1 cm wide, equivalent to ten times the weight of the fabric when expressed as grammes per square metre.

Bending tests.

(a) The value of the bending modulus of a yarn has been obtained by direct experiment using beam and loop methods. In some cases a number of yarns had to be tested together to bring the deflection load within the sensitivity range of the instrument.

(b) The value of the flexural rigidity of a fabric has been obtained by direct experiment using both the beam and loop methods. The value of the bending modulus obtained by beam or loop experiment has been reduced to a single thread basis. In some cases the transverse threads of the fabric were removed enabling comparison between complete fabric and test direction threads. Readings were taken at the lowest possible deflection.

(c) As the table of results was already fairly full only the most appropriate results for the bending modulus have been given. The problem has been discussed at a later stage. It was stated in the section dealing with yarns that the value of the flexural rigidity of a sample could be obtained fairly readily but that obtaining a value for the bending modulus was complicated by the structure of the yarn. Some success attended the method of treating the yarn as a series of rods, but was limited to cases where the number of filaments per yarn and their count, or diameter, was known and where the filaments were free to act individually. A search for a method based on the dimensions of a yarn had shown that taking the moment of inertia as $\frac{k\pi d^4}{64}$ where k was a packing factor, and d was the diameter of the (solid) tex yarn gave results of the right order but with the possibility of considerable scatter due to the power involved. When fabric properties were being investigated, moments of inertia based on the yarn thickness, the fabric thickness, and proportions of these values were calculated and the results substituted in the appropriate equations. It would be expected that the flexural rigidity of the fabric might be greater than n times the yarn value with the freedom of movement of filament inhibited by traverse threads, n being the number of threads in the direction of test, while in turn the rigidity of the yarn would no longer be a simple magnification of the flexural rigidity of the filament.

(d) The value of the flexural rigidity of the fabric has been calculated as g f.cm, and the values of bending length, flexural rigidity, and bending modulus obtained by the cantilever test have been included for comparison.

2. Results and Discussion.

Fabric One. Monofilament Saran.

The results of an analysis of this fabric have been given in Table 27, tensile properties in Table 28(a), and bending properties in Table 28(b).

It would be expected that the fabric would require a greater force to bend a warp strip compared with a weft strip of the same dimensions, because of the greater number of warp threads per inch.

The breaking strength and stiffness of the warp and weft yarns were similar, as would be expected because of the similarity of yarn details. There was a difference in crimp

FABRIC ONE Monofilament Screen.

Strain Moduli

Yarn	Extension	Load		Stiffness	Specific Stress				Stress	
	%	g		Kgf / % Ext	gf/tex		gf/fabric tex		Kgf/cm^2 x 10^2	
		(a)	(b)		(a)	(b)	(a)	(b)	(a)	(b)
Warp	1	45	96		35	59			57	107
Weft	1	21	75		18	63			30	106
Warp	27	1700			50				86	
Weft	27	1700			53				89	
Fabric		Kg								
Warp	1	2.6	3.1		36	43	50	70	59	78
Weft	1	1.0	1.9		27	52	22	43	45	84
Warp	27	85		310	45		70		74	
Weft	30	46		160	44		36		72	

C.S.R. Warp 0.9 Weft 0.9

(a) Slack (b) Taut

Table 10(a) Tensile Properties of Fabric One.

Fabric One   Monfilament Saran

Yarn	Flexural Rigidity $gfcm^2$	Flexural Rigidity G gfcm	Bending Modulus E_{b_2} $kgf/cm^2 \times 10^2$ Beam	 Loop	Bending Length c cm	Flexural Rigidity G gfcm	Bending Modulus q kgf/cm^2
Warp	0.47		100	96			
Weft	0.46		98	107			
Fabric							
Warp	27	10.6	(a) 106 (b) 50	-	6.3	11.2	292
Weft	17	6.7	(a) 140 (b) 37	-	5.5	7.2	196

(a) $I = \frac{\pi d^4}{64}$ (b) $I = \frac{bd^3}{12}$

Table 28(b). Bending Properties of Fabric One.

and this would be expected to render the weft less stiff on initial unstretching. The low strain moduli were shown to vary from 3,000 to 10,600 kgf/cm^2 depending on the initial tautness of the sample. The monofilament structure and the high count of the yarns enabled the crimp to be retained when the samples were mounted, to a degree dependent on the mounting tension. It was possible to calculate two extremes of initial strain modulus for comparison with fabric values. The greater degree of weft crimp was reflected in the lower limit of modulus value of the weft yarn, while the upper limits of both yarns were of comparable magnitude.

The initial strain modulus of the fabric in the warp and weft direction showed the effect of the difference in crimp referred to above, the lower value being in the weft direction. The high warp sett would be expected to make the fabric stronger per cent extension in this direction and this has been supported by the results, but when expressed on a per thread basis it will be seen that once the effect of crimp has been overcome, the stiffness is again comparable. The breaking strength was naturally higher in the warp direction so that the fabric stiffness at break would also be higher even though the extension in the weft direction is slightly higher presumably due to yarn crimp, while the strain modulus expressed per thread was the same in both directions. Finally the ratio of load per cent extension for warp and weft is repeated in the values of specific stress per fabric tex but the stiffness ratio is slightly lower.

The bending property of both warp and weft yarn would appear to be similar. This would be expected as the two yarns were virtually the same tex but it will be noticed that the results are comparable with the tensile modulus of the taut yarns and that the difference in crimp did not affect the result, a point confirmed by both loop and beam methods.

The bending modulus of the fabric was calculated on a per thread basis treating the bending of the sample as being the bending on a number of rods of known diameter, the number being the appropriate threads per inch of the sample. The modulus was also expressed on a different basis from a calculation taking the sample as a beam of specific width and thickness. In both cases tests were carried out on sample of three different test lengths as a check on result, and in case any point arose through coincidence of test length and the float length of the bending yarn. No such effect was noticed.

Considering the results as the bending of a number of rods, the bending moduli of warp yarn and warp fabric were the same suggesting that the weft yarn played no part in offering resistance to bending at least in the early stages. The results were in keeping with those for the moduli of a single yarn but were much higher than the initial strain modulus of the fabric. The fact that the result for the bending of a crimped yarn was also high suggests that in initial bending in this case the yarn in the fabric has bent without attempting to straighten. The better tensile fabric modulus is that after crimp has been removed, although this is still low possibly due to failure to straighten completely and perhaps to time effects involving stress decay.

In the weft direction the resistance to bending of weft yarn and fabric were not the same, that of the fabric being greater than the resistance of the yarn sheet itself. There was a difference between the amount of warp and weft crimp but as the crimp of the weft yarn has been shown to have little effect on the bending of the yarn itself it might be concluded that the reason for the difference must be due to the effect of the difference in the sett of the fabric with consequent effect on thread spacing and freedom of movement. The difference in result was constant whether the test length was 0.2, 0.4, or 0.6 inches. The result for the bending modulus of the yarn calculated from the sheet result was seen to be similar to that of the yarn itself, and comparable with the tensile modulus of the taut yarn. The value of the bending modulus of the weft-way fabric will be seen to be higher than any tensile result which would suggest that the high result may be due to a restriction of bending length and not to a constriction of yarn under direct load. It can be commented that the tensile modulus of the weft fabric was greater than the warp once the crimp had been removed while the cover factor was much higher in the warp direction.

The order of results from treating the fabric as a rectangular beam were such that this method of expression cannot be discounted but the agreement between the bending of the fabric and the sheet of yarn would suggest that the correct bending diameter is that of the yarn rather than the fabric.

Finally there was general agreement between the flexural rigidity of yarn and fabric. The yarns were practically identical allowing for the slight difference in yarn diameter, while the rigidity of the warp fabric was n times that of the yarn with n the number of threads involved. The weft fabric was stiffer than would have been expected from a similar calculation supporting the findings of the beam tests.

The following conclusions were drawn in respect of Fabric One:

(1) For a yarn out of a fabric the tensile and bending moduli were similar provided that crimp was removed before the tensile tests. The presence of some crimp in a bending specimen did not affect the result.

(2) Because the behaviour of warp yarn and fabric were similar the yarn tensile modulus, and fabric bending modulus were similar. The higher weft result determined by bending experiment was forecast by the higher fabric modulus after removal of crimp.

(3) The direct fabric tensile results indicated respective stiffness but moduli per yarn were low due to crimp.

(4) In this instance the breaking strain results gave a fair indication of warp and weft stiffness.

(5) Inspection of the stress-strain curves of warp and weft fabric placed the fabric as being stiffer in the warp direction.

(6) The results shown as gf/fabric tex show the respective stiffness of warp and weft fabric.

(7) There appeared to be better grounds for taking bending diameter for purposes of calculation as being yarn diameter rather than fabric, and treating the sample as a series of rods.

(8) There was reasonable agreement between the flexural rigidities calculated by the bending length test, and

from loop or beam tests. No direct relationship was expected between the respective bending moduli (E_b, or q) but it was noted that the ratio of warp to weft result was similar in both cases.

Fabric Two: Monofilament Polypropylene.

The results of an analysis of this fabric have been given in Table 27, the tensile properties in Table 29(a), and the bending properties in Table 29 (b). The structure is very similar in warp and weft direction so that the bending properties would be expected to be similar in both directions. The effect of retained crimp was again noticeable and a wide divergence in the result of the 1% strain modulus was possible. The value of the yarn bending modulus was in agreement with the taut value of the strain modulus, and the same was true for the respective fabric moduli.

The results suggested that while the tensile tests reflected the effect of yarn crimp, the bending tests showed that the modulus involved was that of a straight fibre. The stiffness of the fabric as reflected by the breaking strain moduli suggested that the stiffness of the fabric would decrease with strain or service.

FABRIC TWO **Monofilament Polypropylene.**

					Strain Moduli					
Yarn	**Extension**	**Load**		**Stiffness**	**Specific Stress**				**Stress**	
	%	g		Kgf	gf/tex		gf/fabric tex		$Kgf/cm^2 \times 10^2$	
		(a)	(b)	% Ext.	(a)	(b)	(a)	(b)	(a)	(b)
Warp	1	60	125		240	300	-	-	220	400
Weft	1	60	125		250	300	-	-	230	400
Warp	18	1060			244		-		225	
Weft	16	1020			262		-		204	
Fabric										
		Kg.								
Warp	1	3.0	4.0		257	394	326	436	260	360
Weft	1	3.5	5.0		340	408	302	526	304	459
Warp	18	45		290	248		271		224	
Weft	16	45		260	272		306		257	

C.S.R. Warp 0.99 Weft 1.05

(a) slack (b) taut

Table 29 (a). Tensile Properties of Fabric Two.

Fabric Two Monofilament Polypropylene.

Yarn	Flexural Rigidity	Flexural Rigidity	Bending Modulus		Bending Length	Flexural Rigidity	Bending Modulus
	G	G	E_b		c	G	q
	gfcm^2	gfcm	Kgf/cm^2 x 10^2		cm	gfcm	Kgf/cm^2
			Beam	Loop			
Warp	0.28	-	462	456			
Weft	0.26	-	-	-			
Fabric							
Warp	12.0	4.7	(a) 525	-	8.1	4.86	910
			(b) 253				
Weft	10.8	4.3	(a) 516	-	8.0	4.76	884
			(b) 249				

(a) $\frac{\pi d^4}{64}$ (b) $\frac{bd^3}{12}$

Table 29(b). Bending Properties of Fabric Two

The bending tests showed that the fabric was slightly stiffer in the warp direction with the rigidity values being confirmed by bending length and modulus tests. The discrepancy between tensile and bending forecast may be explained, the bending results reflecting the slightly higher tex and sett of the warp, whereas the warp tensile tests tended to be lowered by the effect of yarn crimp. A forecast built up from yarn property would give an accurate answer, and it was noted that the cover factor of warp and weft was similar in value.

The general conclusions were similar to those quoted for Fabric One and have not been repeated. Conclusions were given so that subsequent details could be inspected with certain points in mind, but it was felt that unnecessary repetition could be avoided by leaving further comment on conclusions until a number of fabrics had been examined.

Fabric Three. Monofilament Polyethylene.

The results of an analysis of this fabric have been given in Table 27, the tensile properties in Table 30(a), and the bending properties in Table 30 (b).

Sett would be expected to be the dominant feature the count of the yarns being almost equal. The higher warp crimp could offset the effect of sett at low strains.

FABRIC THREE Monofilament Polyethylene

Yarn	Extension %	Load g (a)	Load g (b)	Stiffness Kgf / % Tex	Strain Moduli: Specific Stress gf/tex (a)	gf/tex (b)	gf/fabric tex (a)	gf/fabric tex (b)	Stress Kgf/cm² x 10² (a)	Stress (b)
Warp	1	10	35		66	230			60	220
Weft	1	10	34		66	225			60	205
Warp	50	730			99				95	
Weft	48	760			101				104	
Fabric		Kg.								
Warp	1	1.0	1.4		40	102	66	156	40	99
Weft	1	1.4	2.0		120	180	92	132	118	174
Warp	50	89		178	76		118		69	
Weft	50	52		98	76		47		49	

C.S.R. Warp 0.76 Weft 0.90

(a) Slack (b) Taut

Table 30(a). Tensile Properties of Fabric Three.

Fabric Three   Monofilament Polyethylene.

Yarn	Flexural Rigidity G $gfcm^2$	Flexural Rigidity G gfcm	Bending Modulus E_b $kgf/cm^2 \times 10^2$ Beam.	Bending Modulus E_b $kgf/cm^2 \times 10^2$ Loop	Bending Length c cm	Flexural Rigidity G gfcm	Bending Modulus q kgf/cm^2
Warp	0.049	-	218	220	-	-	-
Weft	0.052	-	254	244	-	-	-
Fabric							
Warp	7.0	2.8	(a) 225	230	5.5	2.5	750
			(b) 160				
Weft	4.0	1.6	(a) 242	212	4.5	1.4	426
			(b) 81				

(a) $\frac{\pi d^4}{64}$ (b) $\frac{bd^3}{12}$

Table 30(b).   Bending Properties of Fabric Three.

Inspection of the stress-strain curve showed that the slope of the weft-way fabric could be steeper than the warp-way fabric but the position was reversed after one to two per cent extension and was dependant on the initial tension when the sample was clamped.

The strength of the warp and weft yarns was the same so that the breaking stiffness was also the same, but the value of the initial modulus could vary due to the crimp in the yarn. The value increased if the tension of the yarn was increased when the sample was mounted in the jaws.

The initial strain modulus of the fabric was greater in the warp direction after the first one per cent strain. The modulus in the weft direction only exceeded the warp value when the samples were mounted under a very low tension.

The initial strain modulus per thread was higher for the weft yarn and reflected the effect of yarn crimp at this stage; later values of strain modulus showed that both sets of yarn contributed in the proportion of the sett of the fabric.

This was also the case for the fabric breaking strain modulus per thread where the result was the same for the warp and weft direction, the difference in actual fabric strength being due to the difference in sett.

The values of c, G, and q obtained from the bending length stiffness test show the influence of the warp sett and these are supported by the values of G obtained from the loop and beam bending test.

The value of the bending modulus per thread of fabric was found to be similar to the value of the initial bending moduli of the yarn, the moment of inertia being calculated using the yarn diameter. The cover factor was again higher in the warp direction as was the case with Fabric One.

Fabric Four: Multifilament Nylon.

The results of an analysis of this fabric have been given in Table 27, the tensile properties in Table 31(a) and the bending properties in Table 31(b).

With a square sett and equal count the bending properties should depend on the effect of yarn crimp. It was noted that equal count extended to individual filament as well as yarn. The yarn strength tests showed that the warp and weft yarns were similar once crimp was removed, the greater amount of crimp in the weft yarn was reflected in the generally lower load per unit strain and by the slope of the stress strain curve.

The same applied to the fabric strength tests but the values of the modulus, even with the taut fabric, remained

FABRIC FOUR **Multifilament Nylon**

Tangent Moduli

Yarn	Extension %	Load g (a)	Load g (b)	Stiffness kgf / % tex	Specific Stress gf/tex (a)	Specific Stress gf/tex (b)	Specific Stress gf/fabric tex (a)	Specific Stress gf/fabric tex (b)	Stress kgf/cm² x 10² (a)	Stress kgf/cm² x 10² (b)
Warp	1	10	15		140	215			149	268
Weft	1	8	15		234	215			160	272
Warp	20	300			215				270	
Weft	17	270			230				286	
Fabric		kg.								
Warp	1	0.7	0.8		100	134	147	188	134	145
Weft	1	0.4	0.6		57	86	96	148	70	105
Warp	26	29.2		111	162		268		196	
Weft	23	26.0		113	160		269		195	

C.S.R. Warp 0.95 Weft 0.96

(a) Slack (b) Taut

Table 31(a). Tensile Properties of Fabric Four.

Fabric Four. Multifilament Nylon.

Fabric	Flexural Rigidity	Flexural Rigidity	Bending Modulus		Bending Length	Flexural Rigidity	Bending Modulus
	G	G	E_b		c	G	q
	$gfcm^2$	mgfcm	$kgf/cm^2 \times 10^2$		cm	mgfcm	kgf/cm^2
			Beam	Loop			
Warp	0.33	130	(a) 165	172	2.72	120	1373
			(b) 280	–			
Weft	0.15	59	(a) 82	91	2.25	68	806
			(b) 179				

(a) $\frac{\pi d^4}{64}$ (b) $\frac{bd^3}{12}$

Table 31(b) Bending Properties of Fabric Four.

well below the potential value as shown by the taut yarn. The specific stress and stress results at low strain placed the warp fabric as being stiffer than the weft but the ranking of stiffness at breaking strain was shown to be equal for warp and weft direction however expressed.

The value of the bending modulus per thread of fabric calculated by taking the moment of inertia of the fabric based on half the diameter of the fabric was of the same order as the initial tensile strain modulus of the fabric.

The value of the bending modulus of the fabric calculated by taking the moment of inertia of a rectangular beam was of the same order as the tensile strain modulus of the fabric when the depth taken was half the diameter of the fabric, and as the modulus of the yarn when the depth was one third the diameter of the fabric.

The results of the various bending tests placed the warp direction of the fabric as stiffer than the weft with the values of flexural rigidity supported by bending length and modulus tests. Consideration of the results of the possible methods of calculating the values of the bending modulus have been deferred until all the fabrics have been examined but it will be noted that on this occasion the value of the modulus was not the same for warp and weft as might have been expected, but echoed the actual difference in bending resistance. Values for the cover factor were equal despite the difference in rigidity.

Fabric Five. Multifilament Terylene.

The results of an analysis of this fabric have been given in Table 27, the tensile properties in Table 32(a) and the bending properties in Table 32(b).

The count of the yarn is the same in warp and weft yarn as are the number of filaments. It would be expected that the higher warp sett would make the fabric stiffer in the warp direction unless this was upset by the crimp effect which on this occasion should tend to make the weft stiffer than the warp.

The yarn strength tests showed that the warp and weft yarns were similar on characteristics, that the initial strain modulus value could alter considerably depending on the tension of mounting, and that the stiffness of the yarn might be expected to decrease with strain from the high potential initial stiffness. The initial strain moduli values of the fabric showed a similar pattern with a tendency for the weft to have a higher value due to the lower crimp in this direction. At the other extreme the weft may still be expected to be stiffer than the warp although the level of stiffness will have decreased in both directions.

FABRIC FIVE Multifilament Terylene.

Yarn	Extension %	Load g (a)	Load g (b)	Stiffness Kgf/% Ext.	Specific Stress gf/tex (a)	Specific Stress gf/tex (b)	Specific Stress gf/fab.tex (a)	Specific Stress gf/fab.tex (b)	Strain Moduli Stress Kgf/cm² x 10² (a)	Strain Moduli Stress Kgf/cm² x 10² (b)
Warp	1	30	90		180	540			236	680
Weft	1	30	90		180	540			236	680
Warp	21	700			202				256	
Weft	19	680			214				290	
Fabric		Kg.								
Warp	1	1.4	5.8		85	335	115	440	118	465
Weft	1	2.8	6.2		210	470	222	490	290	646
Warp	25	63		85	148		200		210	
Weft	19	54		28	220		230		305	

C.S.R. Warp 0.80 Weft 0.99

(a) Slack (b) Taut

Table 32(a). Tensile Properties of Fabric Five.

Fabric Five **Multifilament Terylene**

Fabric	Flexural Rigidity G $gfcm^2$	Flexural Rigidity G mgfcm	Bending Modulus E_b $kgf/cm^2 \times 10^2$ Beam	Bending Modulus E_b $kgf/cm^2 \times 10^2$ Loop	Bending Length c cm	Flexural Rigidity G mgfcm	Bending Modulus q kg/cm^2
Warp	0.56	220	(a)460 (b)130	450	2.60	222	586
Weft	0.60	236	(a)630 (b)164	800	2.68	243	645

(a) $\frac{\pi d^4}{64}$ (b) $\frac{bd^3}{12}$

Table 32(b). Bending Properties of Fabric Five.

The strength of the warp fabric was numerically greater than the weft as would be expected from a knowledge of the higher warp sett but not in the proportion that might be expected. The values for fabric assistance show clearly the assistance to be much higher in the weft direction. The results of the bending tests placed the weft direction of the fabric as slightly stiffer than the warp, this being confirmed by bending length, rigidity, and modulus tests.

Values of the bending modulus expressed on a thread basis corresponded to the values of the taut tensile modulus, whereas expressed on a beam basis the value was nearer that of the slack moduli. Both ranked the weft direction as stiffer than the warp direction. It will be noted that the values of cover factor were contrary to the direction of greatest stiffness on this occasion.

Fabric Six. Multifilament Viscose Rayon.

The results of an analysis of this fabric have been given in Table 27, the tensile properties in Table 33(a) and the bending properties in Table 33(b).

In this fabric the high warp sett should clearly influence the bending behaviour, there being no difference in yarn count and the crimp values being almost equal. The yarn strength figures showed the warp and weft yarn to have

FABRIC SIX   Multifilament Viscose Rayon.

Yarn	Extension	Load		Stiffness	Specific Stress				Strain Moduli: Stress	
	%	g		Kgf / % Ext.	gf/tex		gf/Fabric tex		$Kgf/cm^2 \times 10^2$	
		(a)	(b)		(a)	(b)	(a)	(b)	(a)	(b)
Warp	1	3.5	45		21	270			31	470
Weft	1	15	45		90	270			130	470
Warp	13	300			139				250	
Weft	19	300			95				170	
Fabric		Kg.								
Warp	1	0.7	3.5		36	176	94	272	70	310
Weft	1	0.5	2.7		31	220	40	210	60	380
Warp	19	36		19	96		147		170	
Weft	24	25		10	85		81		150	

C.S.R.   Warp 1.08   Weft 1.12

(a) Slack   (b) Taut

Table 33(a).   Tensile Properties of Fabric Six

Fabric Six Multifilament Viscose Rayon.

Fabric	Flexural Rigidity	Flexural Rigidity	Bending Modulus		Bending Length	Flexural Rigidity	Bending Modulus
	G	G	E_b		c	G	q
	gf/cm^2	mgfcm	$kgf/cm^2 x10^2$		cm	mgfcm	kgf/cm^2
			Beam	Loop			
Warp	2.84	1140	(a) 265	-	4.56	1120	1280
			(b) 180	-			
Weft	0.87	342	(a) 161	166	2.95	327	350
			(b) 111				

(a) $\frac{\pi d^4}{64}$ (b) $\frac{bd^3}{12}$

Table 33(b) Bending Properties of Fabric Six.

a similar initial strain modulus but with an extremely wide range from slack to taut yarn, despite the fact that the yarn crimp value was not unduly high. The higher extension of the weft yarn was carefully checked and seemed real despite the similarity of the yarns. The weft yarn also had a lower and more pronounced yield point so that the difference was presumably due to the previous histories of the yarns.

The load per unit strain for the warp fabric was numerically higher than the weft value but reduced to proportional yarn value it will be seen that the weft value could be higher than the warp. A similar effect had been noted previously when it was found that there was a difference in the degree of fabric assistance. Inspection of the values of the cloth strength ratio will show that there was a gain in the weft direction. The breaking strain values naturally reflect this but the warp fabric is still stiffer, particularly as given by the numerical stiffness value and the value of specific stress per fabric tex.

The results of the bending tests showed that the fabric was considerably stiffer in the warp direction, the value of the flexural rigidity of the fabric being supported by the bending length and loop and beam tests. The values of the bending modulus were of the right order but tended to be low when expressed on a thread basis, while the highest cover factor was in the warp.

Fabric Seven. Multifilament Warp, Fibre Weft, Nylon.

The results of an analysis of this fabric have been given in Table 27, the tensile properties in Table 34(a) and the bending properties in Table 34(b).

The main difference between warp and weft direction should be the result of using a filament and a fibre yarn. On the basis of sett the warp should be stiffer than the weft while on the basis of count as such, the weft might be stiffer than the warp but it must be remembered that this yarn contained finer fibres. The amount of crimp is greater in the weft direction and from previous experience this should mean that the weft yarn possesses a lower potential strain modulus.

The yarn strength results showed the warp yarn to be considerably stronger, although with similar extension than the weft yarn, and this was reflected in the values of stress, and specific stress, at break. Inspection of the results of the initial strain moduli also suggested that the warp yarn was stiffer than the weft yarn although a considerable spread of result was possible due to the effects of yarn crimp. The strength of the fabric confirmed the yarn strength results and the numerical results were maintained in stress and specific stress values. The values of the initial strain

FABRIC SEVEN   Filament/Fibre Nylon

Strain Moduli

Yarn	Extension	Load		Stiffness	Specific Stress				Stress	
	%	G		Kgf / % Ext	gf/tex		gf/Fabric tex		Kgf/cm^2 x 10^2	
		(a)	(b)		(a)	(b)	(a)	(b)	(a)	(b)
Warp	1	5	35		30	110			35	140
Weft	1	5	20		25	100			29	124
Warp	27	800			189				210	
Weft	26	460			89				100	
Fabric		Kg								
Warp	1	0.7	1.3		55	104	67	115	63	120
Weft	1	0.2	0.9		14	65	18	82	16	84
Warp	39	60		154	122		136		140	
Weft	33	29		68	62		76		79	

C.S.R.   Warp 0.98   Weft 0.90

(a) Slack   (b) Taut

Table 53(a). Tensile Properties of Fabric Seven.

Fabric Seven Filament/Fibre Nylon.

Fabric	Flexural Rigidity	Flexural Rigidity	Bending Modulus		Bending Length	Flexural Rigidity	Bendin Modulu
	G	G	E_b		c	G	q
	$gfcm^2$	mgfcm	$Kgf/cm^2 \times 10^2 cm$		cm	mgfcm	Kgf/cm^2
			Beam	Loop			
Warp	0.44	173	(a) 68	72	2.42	161	168
			(b) 31				
Weft	0.28	110	(a) 44	49	2.10	105	109
			(b) 18				

(a) $\frac{\pi d^4}{64}$ (b) $\frac{bd^3}{12}$

Table 34 (b). Bending Properties of Fabric Seven.

result also confirmed the general order of the yarn results with the warp being stiffer than the weft. The stiffness of the fabric would not appear to alter very much with strain judging from these results.

Beam, loop, and bending length tests showed that the warp direction of the fibre was considerably stiffer than the weft direction, but the values of the bending modulus were low compared with the tensile results while the difference between warp and weft was not reflected in the respective cover factors.

Fabric Eight. Fibre Viscose Rayon.

The results of an analysis of this fabric have been given in Table 27, the tensile properties in Table 35(a) and the bending properties in Table 35(b).

The warp and weft directions of this fabric might be expected to have equivalent bending properties as far as sett and yarn count were concerned. The most important feature would be expected to be the extremely high crimp in both yarns with the warp value being almost twice that of the weft.

The strength of the warp and weft yarns was similar supporting the assumption that they might be regarded as the same yarn. The initial strain moduli showed a wide range of possible results due to the effect of crimp. Given a

FABRIC EIGHT Fibre Viscose Rayon. **Strain Modulus**

Yarn	Extension	Load		Stiffness	Specific Stress				Stress	
	%	g		kgf / % ext	gf/tex		gf/fabric tex		$kgf/cm^2 \times 10^2$	
		(a)	(b)		(a)	(b)	(a)	(b)	(a)	(b)
Warp	1	1.8	40		6.0	130			9	200
Weft	1	2.6	42		6.7	140			13	210
Warp	30	420			47				71	
Weft	28	400			50				76	
Fabric		kg								
Warp	1	0.08	1.43		1	72	1	71	1.4	110
Weft	1	0.08	1.40		1	81	1	79	1.4	123
Warp	43	31		60	37		35		57	
Weft	37	30		61	40		30		61	

C.F.S. Warp 1.13 Weft 1.09

(a) [illegible] (b) [illegible]

Table 33(a). Tensile Properties of Fabric Eight.

Fabric Eight. **Fibre Viscose Rayon.**

Fabric	Flexural Rigidity	Flexural Rigidity	Bending Modulus	Bending Length	Flexural Rigidity	Bending Modulus
	G	G		c	G	q
	$gfcm^2$	mgfcm	$kgf/cm^2 \times 10^2$	cm	mgfcm	kgf/cm^2
Warp	0.100	39.0	(a) 6.0	1.23	37.8	91
			(b) 3.6			
Weft	0.088	35.6	(a) 5.4	1.19	34.6	84
			(b) 3.4			

(a) $\frac{\pi d^4}{64}$ (b) $\frac{bd^3}{12}$

Table 35(b) Bending Properties of Fabric Eight.

taut yarn the moduli would be similar, with the results suggesting that the weft yarn was slightly stiffer due to the lower crimp value. In view of earlier comments on the probable change of viscose rayon stiffness with strain it was interesting to note that the potential final strain modulus showed a considerable drop in value from the initial taut strain value.

The fabric results showed more clearly than any other so far the effect of yarn crimp on the value of the initial strain modulus, the value changing by more than fifty times depending on the initial tension. The final strain moduli results were strongly influenced by the high strain values, a difference of over twenty per cent being possible between the strain value of a slack fabric and the strain value of a taut fabric. As the slack fabric was considered to be more representative of the condition of the fabric in service, that value of extension was used. The numerical values showed that the final stiffness of warp and weft fabrics would be about equal.

Bending tests showed that the fabric was extremely limp and that the flexural rigidity was low. The results suggested that the fabric was slightly stiffer in the warp direction, this being confirmed by beam, loop, and bending tests. Values of the bending modulus were very low compared with tensile results, and the cover factors were of equal value.

3. <u>Moment of Inertia</u>.

In the preceeding tables the values that were shown for the bending moduli were those which appeared to be nearest to the order of the result of the initial tensile strain moduli. Values of the bending moduli were calculated on a thread basis from the equation

$$E_b = \frac{G}{nI}$$ where E_b was the

bending modulus, G the flexural rigidity of the fabric in the direction of test, n the number of threads in the direction of test and I the moment of inertia. The object was to find if any dimension of the fabric or yarn could be used as the value of d, the diameter, thus allowing the solution of a term such as $\frac{\pi d^4}{64}$ to give a value to I.

Values of yarn diameter and fabric thickness have been given in Table 27.

As some of the fabrics contained monofilament yarns an obvious value of d was that of the filament diameter obtained from microscopic measurement and checked by Tex, specific stress, and stress calculation. (I_1). The other values chosen were one half and one third the value of the fabric thickness, referred to as I_2 and I_3 respectively.

For a fibre or filament yarn the normal diameter was taken as the calculated diameter assuming a solid yarn of equivalent tex. The results shown under "pressure" were obtained on the thickness tester referred to elsewhere in this section. They show the maximum degree of flattening that might be expected.

Values of the bending moduli were also calculated from the equation $E_b = \frac{G}{I}$ where G was the flexural rigidity of the fabric in the direction of test and I the moment of inertia obtained by treating the problem as the bending of a rectangular beam in which case $I = \frac{bd^3}{12}$ with b the width of the beam and d the thickness. The moment of inertia was calculated using fabric thickness (I_4), one half (I_5), and one third (I_6) the value of thickness.

Fabric thickness referred to the thickness measured by a thickness guage under a pressure of 10 lb. per sq.in. on the measuring head.

With such a large number of results to evaluate it was felt that numerical presentation of the results would be confusing. Some results have been given in the preceding tables but a tabular presentation has been given in Table 36, where the general agreement of the bending moduli calculated from a specific value of I with tensile results has been

STRAIN MODULI in General Agreement with Value of Bending Modulus Calculated by

Moment of Inertia	I_1	I_2	I_3	I_4	I_5	I_6
		Thread Method		Beam Method		
Value of d	Yarn	Fabric Thickness / 2	Fabric Thickness / 3	Fabric Thickness / 1	Fabric Thickness / 2	Fabric Thickness / 3
Fabric						
One	Yarn Fabric	Slack Moduli	Values $> I_1$	Too low	Slack Moduli	Yarn Fabric
Two	Yarn Fabric	Slack Moduli	Values $> I_1$	Too low	Slack Moduli	Yarn Fabric
Three	Yarn Fabric	Slack Moduli	Values $> I_1$	Too low	Slack Moduli	Yarn Fabric
Four	Yarn Fabric	Values $> I_1$	Too high	Too low	Fabric	Yarn
Five	Yarn Fabric	Yarn Fabric	Too high	Too low	Low	Yarn Fabric
Six	Fabric	Yarn Fabric	Too high	Too low	Slack Moduli	Yarn Fabric
Seven	Yarn Fabric	Values $> I_1$	Too high	Too low	Low	Yarn Fabric
Eight	Yarn Fabric	Values $> I_1$	Too high	Too low	Low	Yarn Fabric

Table 3[illegible]. Comparison of Strain Moduli and Bending Moduli obtained from Specified Moment of Inertia.

shown for each fabric. The results for the three monofilament fabrics showed that the problem appeared to have been correctly solved by taking the bending of the fabric as being the bending of n yarns. It was noted that the results for d, half fabric diameter (I_2) tended to be too low, although within the range of slack strain modulus, while the results for d, third fabric diameter (I_3) tended to be too high so that a value based on d as five twelfths might be a compromise.

Similarly another solution would appear to be to take the bending of a rectangular beam whose diameter was one third (I_6) the thickness of the fabric. As in the previous instance the result of taking d, one half (I_5) the thickness of the fabric was to obtain an extremely low result but just within the order of general result.

It was not expected that the multifilament fabrics would behave in the same manner as the monofilament fabrics as far as the moment of inertia was concerned, but in the event there was a considerable amount of agreement. Taking the value of the diameter as that given by the equivalent tex and treating the problem as bending n rods produced results that were of the correct order although tending to be low in value.

Taking d as equivalent to one-third fabric thickness produced high results as was the case with the monofilament fabrics while the results were nearer the value of the yarn and fabric moduli when the value of d was one half fabric thickness. Thus taking d as five-twelfths the compressed fabric thickness would give a result of the correct order and value as was the case with the monofilament fabrics. Some difference will be noted after Fabric Three and reference to Table 27, and to previous comment, will show that with the monofilament fabrics, yarn $d < \frac{\text{fabric thickness}}{2} > \frac{\text{fabric thickness}}{3}$, whereas with multifilament and fibre fabrics, yarn $d \rightleftarrows \frac{\text{fabric thickness}}{2} > \frac{\text{fabric thickness}}{3}$.

Attempts were made to reduce the problem to single filaments by taking the value as $E_b = \frac{G}{n_1 n_2 I}$ where n_1 was the number of yarns per section, n_2 the number of filaments per yarn and $I = \frac{\pi d^4}{64}$ where d was the mean diameter of the filament material. The results have been shown in Table 37 and it was found that they were much higher than they should be if the fabric bent as an aggregate of filaments. Taking the values of flexural rigidity found by previous experiment on yarns similar in tex and construction to those in the fabrics under discussion, calculation showed that the results were out by the amount by which the practical value

FABRIC	FOUR	FIVE	SIX
Ends per Inch (n_1)	100	104	118
Picks per Inch (n_1)	100	80	74
Filaments per yarn (n_2)	30	78	87
G gm cm^2			
Practical, warp	0.33	0.56	2.04
Theoretical, warp	0.09	0.19	0.50
Practical, weft	0.15	0.60	0.87
Theoretical, weft	0.09	0.22	0.32
E_b, Kgf/cm^2 x 10^9			
Warp	21	29	63
Weft	9	42	30

TABLE 37. Fabric Flexural Rigidity and Filament Bending Strain Moduli of Nylon, Terylene, and Viscose Rayon Multifilament Fabrics.

of G exceeded the theoretical value obtained by assuming complete freedom. This was a not unexpected result following earlier comments that the flexural rigidity of a fabric containing n threads was higher than the flexural rigidity of n threads themselves. Inspection of the results will show that values of bending modulus calculated from the theoretical value of rigidity would be similar to the (expected) values of tensile modulus.

The multifilament fabrics were also treated as rectangular beams in a similar manner to monofilament materials. Taking d as the fabric thickness produced low results of the wrong order, d as half fabric thickness gave low results but approaching the correct order, while taking d as one-third fabric thickness gave results of the correct order and magnitude. Thus the results showed a similar trend to those of the monofilament fabrics.

Inspection will show that even fabrics Seven and Eight which might have been expected to diverge still further fitted the general scheme, the major change being that the results as a whole tended to be lower than the tensile strain results.

4. <u>General Conclusions</u>.

At the beginning of this Chapter some aspects of fabric bending were mentioned and it is considered that some progress has been made as a result of the detailed examination of eight fabrics. Although the number of fabrics was small, it was considered that they were representative of a wide range of woven fabric structures, and yet differed from each other in the points of construction that have been discussed.

The conclusions have been summarised as follows:-

a. Further work on yarns has shown that the initial tensile and bending moduli were again similar in value. The presence of crimp lowered the value of the tensile modulus but did not affect the value of the bending modulus provided the amount of crimp was not high.

b. The value of the initial moduli of yarn and fabric may be the same provided the strain has been equally taken up by the components in the tensile test and that complete freedom may be assumed in the bending test. Values for rigidity may be calculated from yarn and fabric data.

c. The use of the expression of fabric stiffness as grammes/fabric tex successfully differentiated between relative warp and weft stiffness.

d. Breaking strain moduli gave a fair indication of warp and weft stiffness.

e. Inspection of tensile stress-strain curves of warp and weft fabric requires care in interpretation. A steeper gradient may be the result of relative crimp and need not indicate the stiffest direction of the fabric.

f. The bending of a monofilament fabric may be taken as the bending of a number of rods in the direction of test and the modulus calculated accordingly.

g. Some success attended the measurement of the actual flexural rigidity of a fabric. It has been shown that similar values for a specific fabric direction may be obtained from beam experiments, loop experiments, and bending length experiments. It follows that it is possible to use the same method to test the bending property of a fibre, yarn, and fabric.

The following are considered to be among points on which further information is required.

Specific Stress and Flexural Rigidity.

In the chapter dealing with yarns it was shown that it was possible to forecast the flexural rigidity of a yarn from a knowledge of the specific stress of that yarn. In the same way it was felt that it should be possible to use the same relationship to obtain a value of the rigidity of a fabric.

Values of 24 and 14 gf.cm^2, 14 and 14 gf.cm^2, and 7.5 and 4.8 gf. cm^2 were obtained for the warp and weft flexural rigidities of Fabrics One, Two, and Three respectively. Inspection of the values obtained by experiment will show that the results are at least close enough to justify consideration.

Calculations and results on multifilament fabrics are complicated by the additional factors involved and it is felt that the results are inconclusive at this time.

Bending Modulus E_b.

The bending of a multifilament fabric might be taken as the bending of a number of rods provided complete freedom of filament movement were established. Yarn diameter was difficult to measure and it has been suggested that calculations for the modulus would require to be based on either the theoretical diameter of an assumed thread of equivalent tex, or the thickness of a fabric measured under a standard pressure. Some indications of the necessary proportions have been given but considerations of packing factors, cover factor, effect of crimp, and structure are required.

It has been shown that the resistance of a fabric to bending is influenced by fibre, yarn and fabric characteristics, which might be summarized by considering each point.

The initial modulus of the fibre may be regarded as the basic property. A fabric made from a fibre with a high modulus will be stiffer than a fabric made from a fibre with a low modulus everything else being constant. It is possible to increase the stiffness by increasing the tex and diameter of the fibre of one fabric relative to another, assuming circularity of the fibres, and the effect of such a change may outweigh any difference in moduli. The value of the tensile modulus of a fibre may be used.

The stiffness of the fabric will next depend on the tex of the yarns used which is in turn dependant on the tex, and number, of the component fibres. A fabric may be stiffer because of the greater tex of the yarn, or the greater tex of the fibre, but just as the effect of diameter could outweigh the effect of modulus, so the number of fibres per cross-section may outweigh gross yarn tex. The taut value of the tensile modulus of the yarn may be used provided it is remembered that the rigidity of the yarn may be altered by effects of packing or displacement. Cases have been shown where the flexural rigidity of a yarn was higher than the calculated value for these reasons. The effect of yarn twist within the present experiments has been judged to be slight, but it would be expected to play some part, particularly as twist was increased and in considering yarns within a fabric, because with low twist, yarns would be expected to flatten, freedom of relative fibre movement would be enhanced, and lower yarn cross-sectional moments of inertia would be obtained.

The number of yarns in a specific direction of the fabric and the manner of their interlacing with other (traverse) yarns will affect the stiffness of the fabric. It has been shown that in cases where the yarns remain circular in section the modulus of the fabric is that of the yarn but that crimp will tend to lower the value of the tensile modulus although not the bending modulus. With fibrous yarns the effects of flattening and ease of fibre movement will influence the fabric stiffness, and therefore in addition to yarn twist, the weave and the sett of the fabric will be important.

Stiffer fabrics will be produced by close weaves, such as plain weave, and high cover factors, whereas open weaves permitting greater yarn and fibre mobility will result in a limper fabric, while any increase in length of the floating yarn between intersections will also decrease rigidity.

In the case of the multifilament fabrics the value of the taut modulus gave a comparative ranking of stiffness and it has been shown that, because of the difficulties in calculating the correct value for the cross-sectional moment of inertia of the fabric, this value may be just as useful or accurate compared with the estimated value of the bending modulus, in the assessment of fabric stiffness.

Direct measurement of the bending length, the resultant calculated value of flexural rigidity, and the measured value of rigidity have been shown to be in agreement with each other. They represent the easiest methods of obtaining information on the actual stiffness of a fabric as values of moments of inertia do not require to be obtained or assumed. For the same reason correlation between these values and the bending modulus cannot be obtained but the order of the difference between calculated and practical results offers some information on the geometry of the fabric particularly if tests were carried out on a range of fabrics whose details were varied in a systematic manner.

From the information gained on stiffness as measured by the strength and extension of a material at break it would appear that there are grounds for using this parameter as a general indication of the average stiffness of a yarn or fabric. It is felt that the results support, and in turn are supported by, the work on cumulative strain moduli in an earlier chapter. It was argued then that there was agreement between tensile and bending moduli up to the 5 per cent level of strain and perhaps above, such that the change in slope of the stress-strain curve could be taken as an indication of the probable change of stiffness of the fibre. In this section only work on initial and final strain moduli has been carried out but in view of the general agreement of tensile and bending result the author would suggest that the use of final strain, or breaking strain, modulus to indicate average stiffness is justified. Further work on this aspect will be found in the next chapter.

Finally it has been suggested that the value of the slack tensile modulus of yarn and fabric may serve as a measurement of the handle of the material. A low value, assuming a constant Young's modulus of the fibre, is indicative of the presence of crimp and openness in a yarn, or crimp and bulk in a fabric. These factors tend to effect the thickness and compressibility of the material along with the inherent stiffness of the fibre and are one of the items sensed when a yarn or fabric is handled.

Comment has been made that the bending modulus, q , indicates handle, this term also takes stiffness, weight, and thickness into account and it has been suggested that some correlation between the terms might exist. It may be that the results of a slack tensile stress-strain test would be better expressed in terms of uncrimping energy, represented by the area under the curve up to a certain point such as the start of the linear section of the curve.

Inspection suggested that some correlation might also be expected between the values of q and the bending modulus obtained by treating the fabric as a rectangular beam.

CHAPTER 12. MODIFICATION OF FABRIC PROPERTIES BY RESIN OR OTHER TREATMENT.

1. Fabric Six.

2. Fabric Eight.

CHAPTER 12. MODIFICATION OF FABRIC PROPERTIES BY RESIN OR OTHER TREATMENT.

It was shown in an earlier section that any change in the value of a textile modulus due to the history of the fibre, or to the effect of temperature and humidity would be equally reflected in the value of the bending modulus, the value of flexural rigidity being also altered. It has also been shown that the relationship between fibre tensile and bending strain moduli continued in yarn and fabric forms, although subject to modification depending on the geometry of the system.

In this chapter an attempt has been made to see whether the physical and chemical changes produced in a fabric as a result of treatment were reflected in both tensile and bending properties.

Fabrics Six and Eight were given such post-treatment and their tensile and bending properties were reassessed. The results for Fabric Six have been given in Table 38 and those for Eight in Tables 39 to 44 some of the data from earlier tables being repeated for convenience.

1. The treatment given to Fabric Six consisted of a mild wash in 1% Teepol solution at 40°C for 15 minutes, similar in fact to a relaxation shrinkage test with the fabric being rinsed and dried without undue squeezing or distortion.

Fabric Six

	Before Treatment Warp	Before Treatment Weft	After Treatment Warp	After Treatment Weft
Threads per Inch	118	74	128	82
Yarn Crimp %	4	3	8	5
Bending Length c. cm.	4.6	2.9	2.4	1.9
Flexural Rigidity, G. gf.cm.	1.1	0.3	0.2	0.1
Bending Modulus, q. Kgf/cm^2	1280	350	104	54
Tensile Load (Slack) gf/1% Extension	700	500	75	50
Initial Strain Modulus gf/tex (Taut)	178	220	137	176
Stiffness at Break Kgf/% Extension	19	10	13	9
gf/fabric tex	147	81	91	62

Table 38. Tensile and Bending Properties of Fabric Six after Treatment.

Such shrinkage produced a change in the sett, crimp, and weight of the fabric. The handle of the fabric was changed from hard and stiff to soft and limp. The values for bending length and flexural rigidity (Table 38) show clearly the change in the bending properties of the fabric. The fabric was still stiffer in the warp direction but the difference between warp and weft has been reduced to nearer the proportion expected from the difference in sett.

It will be noticed that the largest change in value occurred in the value of the bending modulus q . Pierce[8] stated that this term was suitable as an expression of the handle of a fabric and these results are a good example of the validity of this statement.

The nearest approach to this order of change was the tensile load required to stretch the fabric and the author has previously stated his belief that there could be some correlation between q and this value, or something equivalent, which might be termed uncrimping force or energy depending on the method of expression. The taut value of the modulus does change but the effect does not seem to reflect the dramatic change in fabric property, better success may be noted for the stiffness at break expressed as either a ratio or as specific stress.

2. Lengths of Fabric Eight had been given a series of separate resin finishes through the good auspices of Messrs. Courtaulds Ltd., Bocking, Essex, and the types of resin have been listed in Table 39 along with the bending properties of the samples which had been tested by the bending length method. The add-on values represent resin only as the lengths were finished by request without the usual softeners or lubricants being included.

It will be noted that the value for crimp changes appreciably from fabric to fabric there being a general reduction from the control sample 1, pure finish, which was the sample under discussion in previous tests. The reduction in crimp was accompanied by a reduction in sett of the order of three to four threads suggesting that the fabric had been stretched in finishing. An interesting point arises as to how much of the change of property of a fabric attributed to the resin finish could be due to the changes brought about by differences in yarn crimp and fibre mobility. In the event much has been attributed to the finish, it being hoped to show elsewhere[181] that many of the changes attributed to the fabrics find a parallel in fibre form where the effect of crimp may be discounted. It may be an important point if such tests fail to show the expected correlation, and in any case, changes of fabric structure of the order shown are bound to produce some changes in property.

FABRIC EIGHT

Sample	Finish	Yarn Crimp %		Bending Length c. cm.		Flexural Rigidity G mgf. cm		Bending Modulus q Kgf/cm^2	
		Warp	Weft	Warp	Weft	Warp	Weft	Warp	Weft
1	Pure	12	13	1.23	1.19	37.8	34.6	91	83
2	10% Melamine-formaldehyde	16	8	1.31	1.29	42.4	40.3	118	113
3	15% Melamine-formaldehyde	16	7	1.37	1.30	50.8	44.0	132	106
4	10% Ethylene Urea-formaldehyde	12	8	1.37	1.26	39.4	36.2	130	117
5	15% Ethylene Urea-formaldehyde	14	10	1.32	1.30	46.0	44.0	128	122
6	10% Methylated Urea-formaldehyde	15	10	1.35	1.28	50.7	40.7	127	113
7	15% Methylated Urea-formaldehyde	12	9	1.41	1.27	54.3	39.8	154	113
8	15% Urea-formaldehyde	15	9	1.37	1.32	50.8	44.6	144	127
9	10% Urea-formaldehyde	17	10	1.28	1.25	40.7	37.8	111	109

Table 39. Bending Properties of Fabric Eight after Resin Treatment.

At this stage the author wanted to show that changes in bending property of a fabric were reflected in changes in tensile properties, and to this end strength tests were carried out and the results have been given in Table 40, while the samples have been ranked in descending order of bending and tensile property as shown in Tables 41 and 42. They have been grouped in each instance with a class interval whose limits were governed by the values involved. Generally there was a wider divergence of result in the warp direction. In both cases the scatter increased from bending length through rigidity to bending modulus as would be expected because of the magnifying effect of the powers involved.

It was not the purpose at the present time to evaluate the resins specifically but it will be noted that in every case the stiffness of the fabric has been increased, compared with the pure finished sample, that there was general correlation between placings by c and G and some difference in placing by q, and that the resin finish did not appear to affect warp and weft in an equal manner this being most noticeable in Samples 4 and 7 in which the warp and weft crimp values were nearer in value than in other cases. It will also be noticed that the 5% additional add-on has increased the warp stiffness on each occasion, and to a greater degree than the weft stiffness.

Fabric Eight

Sample	Initial Strain Modulus gf/tex				Breaking Strain Modulus					
	Slack		Taut		Kg/Extension		gf/tex		gf/fabric tex	
	Warp	Weft	Warp	Weft	Warp	Weft	Warp	Weft	Warp	Weft
1	0.7	1.3	62	80	80	81	37	40	38	39
2	0.9	1.7	86	104	98	119	49	65	52	63
3	1.1	1.7	92	112	103	134	52	71	51	67
4	1.3	2.0	88	104	113	122	57	66	59	64
5	1.4	2.3	94	108	127	136	64	76	64	68
6	1.3	2.0	92	100	103	114	52	61	52	58
7	1.3	2.0	100	104	130	113	64	60	67	58
8	1.7	2.9	100	108	122	137	61	73	63	70
9	0.9	1.4	72	96	90	106	45	57	46	55

Table 40. Tensile Properties of Fabric Eight after Resin Treatment.

Fabric Eight

Ranking of Stiffness of Samples
(descending order)

Bending Length		Flexural Rigidity		Bending Modulus	
Warp	Weft	Warp	Weft	Warp	Weft
3	3	3	3	7	5
6	5	6	5	8	8
7	8	7	8	5	2
8	2	8	2	6	4
2	4	5	6	3	6
5	6	2	4	4	7
4	7	9	7	2	3
9	9	4	9	9	9
1	1	1	1	1	1

Table 41. Resin Treated Samples of Fabric Eight Ranked in Stiffness from Bending Tests.

Fabric Eight

Ranking of Stiffness of Samples
(descending order)

Initial Strain Modulus				Breaking Strain Modulus					
Slack		Taut		Kg/ Extension		gf/tex		gf/fabric tex	
Warp	Weft	Warp	Weft	Warp	Weft	Warp	Weft	Warp	Weft
8	8	3	3	5	3	5	3	5	3
5	5	5	5	7	5	7	5	7	5
4	4	6	8	8	8	8	8	8	8
6	6	7	2	4	4	4	4	4	2
7	7	8	4	3	2	3	2	2	4
3	3	2	6	6	6	6	6	3	6
2	2	4	7	2	7	2	7	6	7
9	9	9	9	9	9	9	9	9	9
1	1	1	1	1	1	1	1	1	1

Table 43. Resin Treated Samples of Fabric Eight Ranked in Stiffness from Tensile Tests.

It would be expected that the best correlation would be obtained between the initial strain modulus (taut) and the flexural rigidity, and the initial strain modulus (slack) and the bending modulus, the latter again on the assumption that both properties measure a characteristic of the handle of a fabric.

Inspection of the respective tables will show that there was a marked similarity in the ranking of stiffness by descending order of flexural rigidity and by descending order of taut initial strain modulus this being particularly the case in the weft direction. There was general agreement with the ranking of stiffness (of handle) by bending modulus and slack initial strain modulus, a point of interest being that the tensile results ranked exactly in order with each sample while the bending results did not rank the warp and weft direction of a specifically finished fabric in an identical manner. There was not agreement between the ranking of warp and weft. The bending length method ranked the warp direction as equal to, or stiffer than,the weft direction in each case whereas the tensile method usually placed the weft as being stiffer than the warp.

As far as the tensile breaking strain stiffness results were concerned the ranking of the samples has not been altered by the method of expression suggesting that in a comparison of a basically similar fabric the factors affecting the breaking load and extension are greater than the small changes in sett, weight, or thickness of the samples. The general ranking of the weft samples was practically identical to that of the flexural rigidity, while the warp-way agreement was near enough to be able to say that with this fabric this expression of stiffness gave a useful indication of probable fabric bending stiffness. The obvious inference that perhaps warp and weft directions had been mixed between tensile and bending tests was checked as being without foundation so that the probable explanation is that the bending test reflects the slight difference in fabric construction, prinsipally sett, whereas the tensile results have been strongly influenced by the yarn crimp.

A measure of correlation for a small number of observations is the use of the Kendall rank correlation coefficient[227,228] The rank results in Tables 41 and 42 were compared and values for the coefficients have been given in Table 43.

With this coefficient values may range from minus one through zero to plus one, indicating opposite or inverse ranking, random relationship, and perfect correlation respectively.

Rank Comparison	Kendall Coefficient		t-test t^*	t_c^*	Ranking
Flexural Rigidity and Breaking Strain Modulus	Warp	0.50	1.6	2.36	Not Alike
	Weft	0.89	5.1	2.36	Alike
Flexural Rigidity and Taut Initial Modulus	Warp	0.78	3.3	2.36	Alike
	Weft	0.82	3.8	2.36	Alike
Bending Modulus, q and Slack Initial Modulus	Warp	0.67	2.6	2.36	Alike
	Weft	0.73	2.9	2.36	Alike

* t, value from calculation, t_c, critical value from tables

Table 43. Kendall Rank Correlation Significance Test for Stiffness Rankings of Fabric Eight Samples.

As well as establishing the probability of correlation it is possible to test the significance of a result by means of a t test[229]. In the present case seven degrees of freedom were assumed and the critical value of t at the 5% level of probability obtained from tables. If the value of t obtained by calculation knowing the value of the Kendall coefficient is greater than the critical value, then the correlation coefficient is statistically different from zero and the rankings are statistically alike. The results showed that the general correlation in ranking of stiffness by bending and tensile tests was good and the earlier comments have been supported.

Failure of correlation in the warp direction between flexural rigidity and breaking strain modulus may be due to the high crimp values in this fabric.

One way of separating fabric effects would be to take yarn tests, and similarly fibre tests would eliminate yarn problems. Fibre tests were not carried out in the present work, and the number of yarn tests were restricted (Table 44), but the results suggested that warp and weft yarns from the same fabric were similarly modified with a tendency to repeat the ranking shown by the weft fabric. Thus the initial strain moduli ranked 3, 5, 7 and 8 as the highest values and 1, and 9 as the lowest, the load per unit strain required being

Fabric Eight

	Warp and Weft Yarn		
Sample	Load per initial 5% Extension	Load at Break	Extension at Break
	g	g	%
1	155	360	18
2	190	450	15
3	210	560	16
4	190	440	13
5	205	500	14
6	185	500	16
7	210	555	15
8	200	565	14
9	175	475	17

Table 44. Tensile Properties of Yarns from Resin Treated Samples of Fabric Eight.

greater, or less, with both slack and taut yarns. A similar ranking was obtained when the results of the breaking strain moduli were assessed.

It seems reasonable to assume from these yarn tests that the change in fabric bending property is a result of chemical modification. The fact that the yarn tensile and fabric tensile tests ranked as they did would seem to suggest that whatever the effect on the loft and handle of a fabric the effect of yarn crimp is not a deciding factor in determining stiffness, but it still may explain the divergence between warp and weft ranking in any specific fabric.

A final point of some importance may be made with reference to all the tensile values. It has been noted that the effect of the additional 5% resin add-on was to increase the stiffness of the respective samples as measured by bending tests. Inspection of the respective tensile values will show that they also have been increased in value.

CHAPTER 13. GENERAL DISCUSSION OF TENSILE AND BENDING DATA.

1. Tensile Strain Moduli.

2. Bending Moduli.

3. Stiffness.

4. Effect of Time, Temperature, Humidity, and Strain.

5. Bending Length and Flexural Rigidity.

6. General Items.

7. Recovery from Deformation.

8. Modification of Properties by Resin or Other Treatment.

CHAPTER 13. GENERAL DISCUSSION OF TENSILE AND BENDING DATA.

In an earlier assessment an attempt was made to relate the findings of the experimental work with those of other workers. It was shown then that there were many confirmatory results for individual items which backed the experimental accuracy, and that when these items were taken together as a test entity then there was a strong case for the principal statement that the values of the tensile, bending, and compressive moduli were similar, and that the behaviour of a fibre to either form of strain could be forecast from a knowledge of one of these values. The effect of experimental conditions on the value of the result was shown to be similar as far as temperature and humidity were concerned, and the moduli also seemed to respond in a like manner as far as time dependance was concerned although experiments on this point were restricted. So also was the work on the level of strain at which such interchangeability ceased but it was shown that this was at a higher value than might have been expected.

Finally the possibility of, and use of, a strain modulus was discussed with the suggestion that a knowledge of the bending behaviour of a fibre at higher levels of strain would be useful.

Introduction of yarn and fabric form has immediately widened the scope of this work and considerable difficulty has been found in containing the information available without running the risk of leaving out something of interest. It was decided to concentrate on the main terms of reference, namely the inspection of tensile and bending data, and to consider the other implications of the subject in condensed form.

1. Tensile Strain Moduli.

Comment was made in the Introduction that comparatively little was available on methods[19,64] of obtaining this property of a fibre. This was also true for yarn and fabric[148, 182]. It has been shown that the value can vary widely, particularly with crimp, and some standardisation would be preferable. In the present context slack and taut measurements were made in order to obtain an idea of the possible range in result. As would be expected the taut result was the nearest to quoted values of this modulus for any particular material but even at this some variation could be obtained.

One solution would be to take results at a stated value of tension such as 0.1 gf/tex. This would normally suffice for a yarn in open form but would not necessarily be sufficient to remove the crimp in yarn from package, or the crimp in fabric form. If, as the author believes, both the taut and the slack moduli have a significance in assessing the bending characteristics of a material then it may be preferable to continue to quote the range of result.

A continuous method of measuring yarn modulus has been reported by Brown[183] and the results for the modulus between two given loads, or between two given elongations compared with the values obtained by measurement on an Instron. The results for the continuous method were lower than the others and the reason given for this is that each element of the yarn has been subjected to an immediate total force during the passage of the yarn through the instrument,compared with the conventional method where the load is steadily increased from zero. It may be that this lower modulus is a truer measure of the yarn property, the conditions bearing a closer resemblance to those which the yarn will encounter during manufacturing processes and service life.

Support for a general statement that the elastic properties of a yarn resemble the elastic properties of its composite fibre came from the work of Virgin and Wakeham[123] on cotton quality. They commented that yarn strength and elongation could be predicted from a knowledge of fibre properties and in particular that the elastic modulus was an important common parameter. Linear relationships between fibre elastic modulus, yarn strength, and yarn elongation were shown.

Hoffman and Beste[26] stated that the three basic fibre properties that have the most to do with fabric stiffness were the elastic modulus, the lateral dimensions and the cross-sectional shape. On the assumption of the equality of moduli then the bending stiffness of a circular rod is proportional to the modulus multiplied by the fourth power of the radius, or for a fibre the square of the tex.[illegible]. Work in the preceeding sections has shown that this product may be a criterion of relative fabric stiffness but only so long as other variables such as twist, filament shape, inter-fibre friction, and the structure of the fabric either remain constant or do not interfere.

Chu et al[148] also comment on the importance of Young's modulus as a factor affecting the drapeability of a fabric.

A point that has not been investigated is whether better correlation would be obtained with bending characteristics by the use of the modulus of a mechanically conditioned material thereby eliminating secondary creep effects. In the present work care was taken that all samples were tested under similar conditions but this would not fully eliminate the past history of the material.

Meredith and Pierce[208] dealing with the shape of stress-strain curves stated that convexity would be produced by mechanical conditioning, and by work hardening or stretch orientation, concavity would be produced by yield or plastic flow. The end slope was stated to be free from the effects of previous history and to pertain to the state of the material as it neared failure.

The change in modulus during a period of cyclic loading has been discussed by Wakeham and Honold[63]. At each of two load levels arbitarily chosen at the top and bottom of each loop the average of the percentage elongation was marked and a line drawn through these points to establish the slope of the (curve) loop. The value of the elastic modulus was calculated using the diameter of the yarn to calculate the area, permissible in this case presumably because of the density of the yarns. The value of the modulus, and the elongation was shown to increase while that of hysteresis, expressed as the area (energy) between the curves, decreased. The yarns were nylon and viscose rayon tire cords and the changes were expressed on a logarithmic basis.

Inspection of some results published by Krasny and Sookne[184] showed that there was a direct relationship between the change of tensile modulus of a viscose rayon filament with an increase of humidity and the change of fabric crease recovery, at corresponding humidities, both properties decreasing in value with an increase in humidity. This relationship was not observed with wool, and Vicara, fabrics.

Frick et al[185] reported that the crease recovery angles increased following treatment of cotton fabrics with dimethylol urea, dimethylol ethyleneurea and formaldehyde. Inspection of their results showed that as the crease recovery angles increased, the elastic modulus and stiffness at break also increased, so that comment might be offered that the effect is surely the result of the change in modulus value. Inspection of their results also suggested that the increase in average stiffness, as measured by the stress-strain relationship at break, agreed with the general trend of improved crease recovery. There was a drop in both strength and elongation with resin treatment which the authors have attributed to cellulose degradation caused by the acidic catalyst systems, rather than to the structure of the crosslinks.

Load-elongation curves and recovery angle curves for the fabrics in the wet state were also shown but no comment was offered. Inspection again suggested that the behaviour of the fabrics as indicated by the drop in modulus value was paralleled by the change, or drop, in crease recovery.

Gagliardi and Gruntfest[146] commented that the crease-recovery of a fabric made from 150/40 denier filament viscose yarn was improved following chemical modification by acid-formaldehyde treatment. They showed that the degree of tensile elastic recovery of the yarn was improved and attributed the improvement in fabric property to this factor. Scrutiny showed that the initial modulus of the yarn was also increased, the yarn becoming stiffer, so that it may be suggested that, provided such an increase is accompanied by an increase in elastic recovery, an increase in yarn stiffness should provide an increase in fabric crease recovery. The work of Mehta[181] would suggest that there is an increase in elastic recovery with an increase in modulus for the same yarn. Gagliardi and Gruntfest did in fact, offer further comment to the effect that the fabrics, the fibres of which have the higher modulus, were those which had the higher crease-recovery values. They would appear from the context to be using the term fibre stiffness to denote the stiffness of the fibres in the yarn as measured by yarn tests. Some results were offered for fabric crease-recovery and stiffness compared with yarn stiffness and elastic recovery, where these results had been obtained on viscose rayon fabric in the untreated, surface resin treated, and diffusible resin treated states. They offer one possible explanation why the forecasting of fabric stiffness from tensile measurements may break down and may be worthy of further study. Briefly, they demonstrated that if a finish is not essentially monomeric it would not diffuse through the cellulosic fibre with the result that the stress-strain properties of the fibre (yarn) are not modified, although the stiffness of the fabric is increased due to the surface deposition. On the other hand where the resin finish has penetrated the fibre both the stiffness of the yarn as recorded by a strength modulus, and the stiffness of the fabric are increased.

A method for measuring the plate and shell buckling of fabrics has been described by Dahlberg[186]. The instrument can also be used to measure extension-compression in the plane of the fabric. The instrument consists of an attachment to the Instron Tensile Tester and complete load-deformation curves are obtained. Inspection of his results showed that he adopted a similar technique to that used earlier in this thesis in that he subjected a sample to extension and compression, and recorded the results on the same chart by moving the point of zero load to the centre of the chart. No comment was offered in his paper but it would appear that the moduli of initial compression and tension were very similar provided that measurements were restricted to loads below the critical buckling value for the material. Comment was made on buckling in the section dealing with fibres but no experimental work has been carried out on yarns or fabrics although it was noted that Lindberg[187] discussed the problem of buckling under compression in a paper on the dimensional changes in multicomponent systems of fabrics. If two fabrics are joined together such that the length of A is slightly greater than the length of B and the fabrics are compressed in the direction of the plane of the fabrics, then fabric A will buckle if the force exceeds the critical buckling force.

Assuming that they behave as a completely elastic material then the critical buckling load was given as

$$P_{CR} = \frac{4\pi^2 b_A}{\ell^2_A}$$

where b_A is the bending stiffness of part A = $E_A \frac{t^3 h}{12}$

E_A is the modulus of bending of fabric A

t is the thickness of fabric A

ℓ is the length of fabric A under compression

and h is the width of fabric A

This comment has been included as an example of the need to know the modulus value of a material and the use to which such information can be put. It was also noted that in this instance the concept of a rectangular beam had been used.

Further work on this aspect including comments on the shearing properties of a fabric has been published,[188, 189, 190] and it is considered that interchangeability of tensile and bending information would have obvious advantages.

Mention has been made that the bending properties of a fabric have been investigated by tensile, compressional, and torsional methods. One further example that might be mentioned is the work on two-dimensional stress-strain properties of which Woo and Montgomery[211] is an example. Inspection of their results showed that the effect of two-dimensional loading (tensile) was to increase the value of stiffness due to a reduction in extension.

2. Bending Moduli.

There was a paucity of work available for reference which used the concept of a strain modulus, it being evident that most authors used flexural rigidity to express the stiffness characteristics of yarns and fabrics.

The reason for this lack of information undoubtedly lies in the difficulty of expressing the moment of inertia but considering the wide use of the tensile value with its versatility in terms of tex, or area, in covering fibres, yarns, and fabrics it is felt that knowledge of the bending value is important.

Theoretical values for yarn and fabric may be calculated from fibre data making certain assumptions regarding freedom of movement and relative shapes.[29, 68, 148, 155] Practical values may be obtained from beam or loop tests and the difference between theory and practice evaluated by a systematic change in conditions. Some success has attended the comparison and interchangeability of tensile and bending moduli.

Consideration of the modulus obtained by treating a fabric as a rectangular beam showed some limited success when values were compared with tensile results particularly with monofilament fabrics, and where the thickness of one third of the fabric was taken. One of the few references to the load-extension properties of knitted fabrics was that of Cook and Grosberg[154] and they suggested a possible equation for the bending modulus from the consideration of the loop in the warp knit structure as an elastica.

By contrast more was available on the use of the term bending modulus derived from bending length tests. Howorth and Oliver[191] used this notation as an objective measurement compared with a subjective assessment of handle. They reported that they obtained better correlation than with the use of flexural rigidity possibly due to the factor of the thickness of the fabric especially as this is taken as a third power. Cooper[29] repeated the assertion that such a modulus need not be expected to have any direct relationship with the apparent tensile modulus.

The results of the present work suggest that the initial slack strain modulus value of a yarn or fabric may be used as an indication of the handle of a material, some agreement in ranking between q and such moduli being shown.

3. Stiffness.

Comment has been made that some confusion can be caused by the use of this term which might imply (initial) tensile stiffness as measured by the Young's modulus of the material, tensile stiffness as measured by the load extension ratio at break, tensile stiffness at some intermediate strain, or bending resistance such as bending length and flexural rigidity. The present work has shown that the use of the tensile values may be justified and it is considered that such stiffness measured over the range of strain provides a useful guide in the evaluation of a material. The possible changes in stiffness have been shown for fibres, but only the initial and final strain values have been given for yarns and fabrics, although the author believes that the intermediate relationships will hold for yarns and fabrics as well.

Because many papers using this connotation usually contain references to other items which have not yet been considered some discussion will be deferred until the section dealing with general assessment.

Chu et al[148,182] have given a useful collection of methods of obtaining moduli and cross-sectional moments of inertia in fibre, yarn, and fabric. They also showed a good correlation between the stiffness of a fabric as measured by the fabric strength modulus and that measured by the values of the bending length.

Fiori et al[124,207] showed a linear relationship between fibre average stiffness and yarn average stiffness, stiffness on this occasion being defined as the secant modulus between the points of zero stress and breaking stress. The material was again cotton.

An example of the use of an intermediate value of modulus and Young's modulus is given by the work of Beste and Hoffman[27] in a quantitative study of resilience.

In considering the stiffness of a fabric it may be argued that any factor which reduces the strain in a fibre will reduce the measured stiffness. Freedom of movement leading to increased radius of curvature, buckling, low cover factor implying low sett, and distance from yarn intersection to intersection or float length, are factors which might result in lower stiffness. Differences between tensile and bending stiffness might be accounted for by differences in behaviour such as strain, torque, and shear. Two yarns, or fabrics, of similar construction and composed of fibres of equal numerical stiffness but different fineness would not have the same bending properties. It would also be possible to have cases where the fibre stiffness was not the same, and yet the yarn stiffness values were in agreement and cases can also be made for fabrics. Papers by Finlayson[25], Smith[83] and Meredith[98], are useful references on the effects of the shape of a fibre on bending properties.

4. Effect of Time, Temperature, Humidity, and Strain.

Factors affecting the order of tensile or bending moduli of a fibre were shown, and known, to be time, temperature, humidity, as well as the level of strain. These have not been examined specifically in the work on yarn and fabric except that care was taken to keep conditions of the respective tests as comparable and constant as possible.

It would be expected that the response would be controlled by the major factor of the material involved but a number of references were consulted. Papers dealing with time effects included those by Dent[47], Coleman[53], Meredith[60], and Brown[183]. Comment has been made on some of these in other sections while further information on the subject may be found in a number of textbooks[4, 18, 178].

There were a number of references dealing specifically with the effects of temperature and humidity on yarns. Coplan[69] measured the tensile properties of some yarns at -57°C, 21°C, 99°C, and 177°C. The condition of the yarn was given as wet, 65% r.h., or dry. His results showed a pattern of decreasing stiffness as both temperature and humidity were increased, shown by decreasing stress values and increasing strain values both at yield point and break, with a decrease in initial modulus of about 50% from 21°C to 99°C for nylon, and by about 70% for Dacron and 90% for Orlon.

Maginnis[84] reported a drop of over 50% in the elastic modulus of 150 denier, 40 filament, viscose rayon with humidity, and with increased twist, for yarns and component fibres. The results for dynamic modulus were higher than those from a static method. Guthrie[74] investigated the effect of temperature on the initial tensile modulus of wet nylon, Orlon, and Terylene fibres. Inspection of his results showed that there was a drop in value of some 50% with nylon and Terylene and 80% with Orlon as the temperature rose from 20°C to 90°C.

The effects of temperature and humidity on the physical properties of tire cords were discussed by Dillon and Prettyman[192]. Results are quoted for the breaking strength of cotton, viscose rayon, Fortisan, and nylon, with examples of the change in tenacity at 60°C, 100°C, and 150°C over a range of 0% - 60% r.h., and the change in tenacity at 1.6%, 30%, and 60% r.h. over a range of 20°C - 150°C. Examples were also given for changes in stretch under constant load under these conditions.

The effect of elevated temperatures (150°F - 400°F), and the time of application of load on the growth (extension) and apparent "tensile strength" of tire cord yarns was studied by Busse et al[127] by means of a fatigue test involving a constant average load and a superimposed cyclic stress. The change in life with temperature on this test was found to be much greater than the change in tensile strength with temperature. Over a considerable range the logarithm of the life under a given load was a linear function of the reciprocal of the absolute temperature, showing that failure depends on a viscous or plastic flow within the fibres. The construction of a fabric made from those yarns was found to affect the absolute life, but not the calculated activation energy.

The present work has shown that the bending resistance of a fibre under changes of temperature and humidity are very similar to the changes in the tensile strain values. It is argued that while there may be form changes in yarn and fabric that affect a specific result, information gained from fibre tests might usefully be employed. The finishing section of the textile industry is an obvious example and possibly many complaints relating to handle, stiffness, softness, and the like could be traced to failure to appreciate the effects of temperature and humidity.

Inspection showed that the order of the results quoted above was similar to those found by the author for fibres. No direct reference was found to the effect of temperature and humidity on the bending modulus of a fabric. One of the early lessons of this work was that for successful correlation it was imperative that tensile and bending moduli were obtained at the same strain value unless circumstances were such that readings were being taken where the stress strain relationship was linear, or that time had allowed decay to a constant value. It follows that for correlation between yarn, and fabric, properties the same is true, with the difficulties of obtaining identical conditions increased.

A number of authors have discussed the problem of strain measurement when a yarn or fabric is bent,[1, 29, 41, 173, 193] but there is no clear agreement in practice.

It has been shown[120] that the length of the fibre loop in a bent yarn equals, within limits, the length of the fibre loop in the yarn before bending. Expressions were derived for the calculation of local fibre tensile strain. It may be concluded that there is no strain on the fibres provided they have freedom to redistribute themselves, but if excessive friction, or packing, prevents the slightest redistribution of length within the loop, difference in path length must cause local tensile and compressive fibre strain. A parallel might be drawn with molecular movement in a bent fibre.

Holdaway and Laws[67] reported that the amount of fibre strain, ratio of the radius of fibre to radius of curvature, did not differ markedly from that calculated as due to yarn bending and was of the order of 3.0/4.0 per cent, but some results as high as 40/50 per cent were also reported.

Schiefer and Boyland[194] carried out some work on the measurement of the flexural fatigue of cotton, viscose rayon, and silk fabrics. They commented that for coated fabrics where the freedom of fibre and yarn movement is inhibited the strain imposed on bending may be of the order of 15 per cent, that is past the elastic limit, and often past the breaking extension of many fibres.

As the number of factors involved are numerous it is not surprising that opinions vary but it is important that in any comparison the properties involved are at least likely to be in the same strain region.

An important illustration of this will be found in a later comment on wear testing with another example where initial and final strain moduli are linked with durability.

5. <u>Bending Length and Flexural Rigidity</u>.

Ever since tests for these properties were devised by Pierce[8] and others they have been used to denote the stiffness of materials. Bending length is used principally with fabrics, although it must be used as almost a subconscious test for yarns whenever they are being handled, while flexural rigidity is used for both yarn and fabric. Bending length is expressed in centimetres while the units for rigidity are gf.cm. from the bending length test and gf.cm.^{2} from the beam or loop test.

The present work has shown that the values of rigidity obtained by beam and loop test were similar and that the values were also in agreement with the values obtained from the bending length. No reference was found to the use of the beam method of test for yarns and fabrics.

Experience having shown that the rigidity of a fabric was not necessarily the sum of the rigidities of the number of yarns in the direction of test it was to be expected that the correlation between fibre yarn and fabric property was not always perfect.

One problem is the order of stress and strain involved and the sensitivity of the Instron was not high enough to deal satisfactorily with fine fibres, yarns or fabrics. It is not considered that a new test method is required as much as increased load capacity at the millegramme-weight level, and a satisfactory system of damping to prevent undue oscillation.

There are a great number of references to bending length and rigidity results, and as with stiffness it is difficult to know where to place them without resorting to cross-indexing and repetition. Some results are left to the discussion on general properties or effect of finish.

Platt et al[119] considered that an increase in yarn twist should produce a decrease in yarn rigidity, that the yarn bending rigidity should be proportional to the ratio of yarn denier times fibre denier over the square of the fibre density, and that except for possible fibre modulus changes produced as a result of relaxation of fibre stress, yarn bending rigidity should only be slightly affected by yarn relaxation.

Early work in this thesis has shown the chance that fibre modulus changes may be produced by time, temperature, moisture, while proportionality has been covered. The comments on bending modulus being unaffected by crimp would seem to find support from their last statement although the rigidity could alter although the modulus per fibre, or yarn, did not. It is shown that as a result of inserting twist residual fibre torque increases yarn bending rigidity but the effect is small unless with a very high twist factor. The magnitude is functional with the ratio of fibre torsional stiffness to bending stiffness with the higher ratio producing the greatest increase in yarn stiffness. The decrease in yarn stiffness with increased twist was not reversed despite the presence of this counter-acting factor.

The foregoing assumed that in bending a yarn all the fibres were free to act independantly, so that there were no net tension, or compression, forces acting on them in situ.

Leading up to the opposite case of complete lack of freedom, the fibres may be assumed to act in clusters and Platt et al[119] showed the effect of this assumption. Thus for a cluster of two fibres the average value of the moment of inertia becomes <u>six</u> times that of a single fibre, and the resultant average bending rigidity of the yarn is <u>three</u>

times that of a yarn in which all the fibres acted individually. In the case of a yarn with no freedom of fibre movement the rigidity becomes N_f/p times that for complete freedom where N_f is the number of fibres and p is the packing factor of the yarn. Backer[120] suggested that, for

$$\frac{r}{R} = \frac{5}{2}$$

where r is the radius of curvature and R the radius of yarn at any point, any future twist supplies the length balance necessary for movement. Under conditions of no freedom, maximum strain will be given by $\frac{R}{r}$ whereas under complete freedom strain will be $\frac{a}{r}$ where a is the radius of the fibre. So far experimental work has suggested that there is little inhibition to complete freedom of motion of fibres at least at low strains. The rigidity of yarns was found to be inversely proportional to count i.e. directly proportional to the number of fibres present whereas for no freedom, it should have been found that the yarn rigidity was roughly proportional to the square of the number of fibres in the yarn.

A useful paper was that by Abbott et al [1] in which equations were given which would also prove useful in calculating the probable strains and extent of clustering in fibrous yarns under bending conditions.

Turning to fabrics the same authors considered that the flexural rigidity of a fabric should be affected by yarn crimp and the flexibility of the sections of which the fabric is composed. The maximum effect of yarn crimp is suggested as likely to reduce the rigidity by about 10/20%.

Equations connecting fibre, yarn, and fabric rigidity have been given, inspection of which would support the previous suggestions that some of the discrepancies in the present results may be due to the need for a correction factor based on the degree of packing, length of yarn segment and yarn twist. Their comment on crimp is contrary to that by Go et al[195], and partly contradicts that by Platt et al[119] which has already been discussed. Hamburger[68] stated that yarn flattening is functional with yarn twist, the greater the twist, the less the degree of flattening. Increases in yarn flattening result in increases in the radius of curvature of yarns when woven, and hence would tend to decrease the strains existing in a fabric prior to bending. The process of bending tends to recircularise the cross-yarns at the point of bend and thus may modify the advantage of a flattened yarn in producing a more crease-resistant fabric. The longitudinal yarns do not recircularise (and tend to flatten) and thus can be inhibited in lateral motion when the fabric is bent, by the decrease in available space for such motion. Increased yarn length between thread interlacings creates the opportunity for bending strains to be dissipated over a longer length of yarn. The localised crimp interchange in the region of bend can take place more readily for a more flexible yarn, achieved by a longer yarn span between interstices (low cover factor), but the opportunity for, and extent of, buckling of bent yarns increases as the yarn length between intersections increases. The radius of curvature of short floats will be less than that of long floats resulting in increased strain.

These aspects explain the relative stiffness of a plain cloth, twill, hopsack or satin in descending order of stiffness if all constructional features except weave were constant.

Cooper[29] suggested that as movement within the structure of a fabric is inhibited it will become increasingly difficult to estimate fabric stiffness from a knowledge of fibre or yarn properties but the relationship between fibre stiffness and fabric stiffness may be used to judge the extent of the restriction of fibre movement. This was illustrated by reference to fabrics in which the sett, denier, yarn twist etc. was altered, and the stiffness measured as bending length, with the recovery angle also given. The effect of crease-resist treatment was to render the fabric less stiff and the effect of change of fibre denier was more pronounced, both suggesting easier movement of fibres. Most crease-resist finishes increase fibre stiffness but the effect on the fabric stiffness is often nullified by the greater ease of fibre movement and possibly the additional help of softening agents; these being specifically omitted in the present series of rayon fabrics. One omission often noted seems to be the lack of any measurement of fibre, yarn, and fabric friction and this property is deemed important in this connection. It is hoped that some measurements now being made[181] will help on this point.

Inspection of the values of bending length and sett would support the contention that the increased stiffness would generally be reflected in an increased strength modulus both in respect to the alterations of sett, denier, and number of filaments. This is not always so and this may be because the degree of fabric assistance alters requiring measurements of the cloth strength ratio for clarification.

Chadwick et al[206] examined the relations between cloth, yarn, and fibre properties in a series of plain-weave cloths. They concluded that observed cloth stiffness was not much different from the corrected integral fibre stiffness for cover factors below 11, but for cover factors over this value increasing closeness was accompanied by rapidly increasing stiffness. Cover factor on this occasion referring to cotton yarns. It was stated that the resistance of a cloth to bending arose partly from the stiffness of the individual fibres. If all the fibres were free to move independantly, the cloth stiffness per thread would be equal to the sum of the stiffness of all the n fibres in a thread the "integral fibre stiffness".

A survey of the factors which influence the draping properties of cotton fabrics was made by Chu et al [148, 182]. The report dealt primarily with the F.R.L. Drapemeter and the correlation of the results obtained with this instrument with such fundamental properties as the bending length of a fabric, and with the subjective assessments of a panel of observers.

A reasonably good correlation was observed between the monoplanar bending characteristics measured by the strip bending length test and the multiplanar bending evaluated by the Drapemeter for those fabrics approximately square with respect to stiffness. The strip bending test does not assess the buckling and trellising of draped samples and would classify papers and fabrics as equivalent in drape whenever their stiffness in corresponding directions are equal, whereas their draping qualities as given by the drape coefficient and by subjective classification were significantly different. It may be commented that such differences might well be shown up by the results for the flexural rigidity and bending modulus, q , and that the bending length test cannot always be considered on its own.

An interesting application dealing with bending resistance was the paper by Cusick et al[222] in which the physical properties of some non-woven fabrics were dealt with, measurement of bending length, crease recovery, elastic recovery, shear modulus, and drape coefficient being included. It was reported that the drape coefficient increased as the bending lengths and shear modulus increased. Values of the bending modulus, not defined but assumed to be derived from the bending length, were shown to have a linear relationship on a log-log basis with initial modulus. Some agreement between elastic recovery, ease of creasing (180°-creasing angle), and yield strain was also shown.

Reverting to conventional fabrics, Steele[138] described a series of tests designed to study the stiffness, resilience, and crease recovery of fabrics. A fabric loop method was used and it is of interest that the loop was compressed during the test, whereas the loop was extended by the method used in this thesis. While both methods result in an elliptical pattern it could be argued that the method suggested by

Steele comes closer to portraying the actual conditions of creasing in service. The pattern of the load-deformation curves agrees with those found by the present method.

Some details had been made available concerning the properties of a series of plain woven cloths made from cotton/nylon blends. As eighty cloths were involved varying systematically in blend, sett, yarn count and twist, and cover factor while some ten different properties were measured the assessment of results is a subject in itself. However inspection showed the following agreement between flexural rigidity ranking and tensile breaking strain stiffness.

(1) In every fabric, whatever differences in construction, there was agreement between comparative warp and weft way stiffness.

(2) A linear relationship was noted between rigidity and stiffness with change in yarn count with a constant cover factor. This applied to warp and weft direction and to cotton and nylon fabrics. The stiffness of the fabric decreased with the use of finer yarns.

(3) There was an increase in stiffness and rigidity with an increase in sett, yarn count and twist factor being constant. While this also applied to warp and weft direction, and to cotton and nylon fabrics, there

were not enough examples within one class to be able to state whether this was also a linear relationship.

(4) Increasing nylon content led to decreased rigidity and stiffness. While this was always true the effects were not always proportional between rigidity and stiffness or to the change in fibre content.

(5) There was no constancy in the change of either value with an increasing twist factor. In many cases there was no appreciable change in value at all.

The general results for flexural rigidity were in keeping with accepted theory [8, 131, 148], with larger yarns and tighter weaves resulting in stiffer fabrics, heavier fabrics being more flexible where the constriction was such that there were a few heavy yarns rather than many light ones.

The lack of any apparent effect of twist on the rigidity of the fabrics is not unexpected following the present practical work, and the evidence of other papers. The paper by Chu et al [182] offered a useful comparison between the evaluation of the hand and stiffness of a fabric by bending length and F.R.L. Drapemeter tests. Fabric strength details were not given but one example was noted where the difference in stiffness between two cotton fabrics, of identical construction save the degree of fibre maturity, could have been forecast by the difference in yarn strain moduli. The yarn from mature fibre being stiffer than the yarn made from immature fibre. This was a case where the use of a direct strength extension ratio would have been just as successful as specific stress.

A group of filament viscose rayon cloths were tested for initial and final tensile strength, the stiffness at 5% extension and break being calculated as the ratio of strength to extension. As the work on these fabrics has not been completed it is not considered necessary to give full details, but it was found that the differences made in these cloths by way of alterations in sett, denier, weave, and finish were reflected in changes in tensile stiffness. Values of flexural rigidity were known and comparison showed the closest relationship in the weft direction, the direction in which the changes were made. The effect in the warp direction, which would be largely one of changes in yarn crimp and fibre freedom was not clearly marked, although in support of previous ideas there was better agreement at the lower levels of strain.

A search of literature showed many cases similar to Morton and Turner [214] where information on a strength was given, in this case changes in fabric strength following changes in fabric construction, but with no information on bending stiffness for comparison.

Some aspects of fabric stiffness were dealt with by Nabar and Tawde[196] in a paper dealing with some aspects of mechanical finishing of cotton textiles. They used a Gurley stiffness tester which measures the resistance to bending both with, and against, the curl of the sample, the numerical values obtained with this instrument being directly proportional to the rigidity as determined by the Pierce heart loop test. They found that the stiffness of the fabric increased with an increase in the moisture content, with an increase in the temperature and pressure of the calender bowl, and with an increase of the concentration of starch. A decrease in stiffness was observed on storage over a period of time, and with the addition of various softening agents to the size mix. The most interesting feature here would appear to be the stiffness reflecting the increase in elastic modulus with humidity, although the change in the diameter of the fibre (swelling) might also be responsible.

6. General Items.

The following references relate to a wide divergence of subjects and yet it is felt that stiffness in one form or another provides a connecting link between them.

Treloar and Riding[224] have developed a theory of the stress-strain properties of continuous-filament yarns and they stated that the major departure from existing theory[48] was that the stress-strain characteristics of the material over the whole range of extension were introduced, the method of analysis operating on the energy of the system rather than on the stresses directly. It was noted that the principal deviations between the experimental and calculated stress-strain curves occurred at low strains and were attributed to the presence of a small amount of crimp, or other irregularity in the filaments, giving a spuriously low initial stress.

The relationship between the extensional modulus of a fabric in any direction and the shear modulus[59] has been discussed by Kilby[226] in a paper on planar stress-strain relationships in woven fabric in which the concept of energy was also used. Some help from this might be expected in any attempt to extend the present idea of warp and weft-way stiffness and flexural rigidity to other directions to link up with the Drapeometer[131] test results.

It was noted that Kilby stated that the Young's modulus of a trellis in either warp or weft direction was identical with the Young's moduli of the individual trellis elements in the appropriate direction.

It has been shown in the present work that the strain modulus of a fabric in a specific direction was not necessarily the same as the modulus of a component yarn or fibre because of crimp and bulk effects. It was therefore interesting to note that Kilby suggested that, in specifying the elastic properties of a fabric, the moduli of the fabric in a specific direction should be taken as fundamental and not taken as the value of an individual thread tested out of the fabric.

It was also noted that G in this paper referred to the shear modulus of the trellis, and its value was stated to be usually much less than the tensile modulus in warp, or weft, direction, and that it was expected that G would be largely responsible for the magnitude of the fabric moduli in directions other than warp and weft and especially the 45° direction.

Finally a paper by Clulow and Taylor[225] dealt with the biaxial stress-strain relations in a plain-weave cloth and one important point made related to the effect of yarn stiffness. It was suggested that one reason for a difference between theoretical and experimental results could lie in the assumption made in theory that yarn were flexible and incompressible. On this occasion the experimental value of the flexural rigidity of a yarn was below the calculated theoretical value whereas present results based on a different theory have tended to be below the experimental values. Further work on the flexural rigidity of stressed yarns and fabrics would appear to be necessary.

Mention has already been made of the work on the shearing[189] and buckling[186] of fabrics but in the present context the load-deformation curves and the parameters given for 66 commercial fabrics by Lindberg et al[190] are of interest.

The formability of a fabric was defined as the maximum compression a fabric can take up before it buckles, it is dependant on fabric direction and integrated formability should be related to the product of buckling load and shear angle. It may also be expressed as a product of an anistropy ratio and the square of the fabric thickness. A combination of high formability and low shell buckling load can be attained by combining high thickness with low bending modulus. The bending stiffness and buckling load were found to be closely related.

A rheological model was used to show how friction and fibre stiffness may interact in a fabric, the stiffness value should be that obtained at infinitely slow loading of the fibre. Stiffness here referred to that obtained by a cantilever method and was expressed as g.cm.^{2}/cm. Practical illustrations of the work on bending, buckling, and shearing have been given by Behre[220] in a paper on testing tailorability, and Rosenberg[221] who discussed finishing conditions for fabrics.

Kilby[58] commented on the fact that a change in nylon fabric hand with heat setting was noticeable although there was little or no change in the bending length of the fabric, so that the change could not be attributed to a change in the flexural rigidity. Following measurement of the shear properties of the fabric (method [59]) it was shown that in all cases where there was a change in subjective stiffness there was a corresponding change in the shear properties. It was tentatively suggested that the change in shear property as a result of heat setting was due primarily to the relaxation of residual bending stresses with the concomitant reduction of the normal reaction acting on the monofilaments in the cross-over region; this resulting in diminution in the magnitude of the frictional forces which opposed the trellising of the monofilaments relative to one another. It can only be conjecture but it would have been interesting to know if such a difference would have been obtained if the stiffness of the fabrics had been measured by comparing their tensile strength moduli, it having been shown that the effect of temperatures of the order used by Kilby would result in a decrease in modulus due to tensional relaxation.

Another interesting reading in this connection would have been the respective values of the bending modulus q .

One form of shear may be considered as the bending of a very short length of material with a very small radius of curvature.

A similarity in ranking was noticed when the monofilament yarns were compared for knot strength, loop strength, and shear strength. It was also noticed that the question of relative strain did not appear to have been considered in some of the earlier work on knot strength[197, 213]. This was also the case with flexural fatique tests[11, 198].

The theory of fatique failure in textile materials was the subject of an article by Lyons[199], and Lefferdink and Briar[153] found that when single fibres were flexed over a rounded metal bar the flexural fatique of the fibre was approximately linearly related to the radius of curvature of the surface of the bar, and to the tension on the fibre during the test. This is in keeping with the concept of bending strain. The role of flex fatique in the abrasion resistance of fabrics was also discussed by these authors who found that the resistance of fibres to fracture due to fatique correlated with the wear life of socks. Present work[181] suggests that correlation will be found between the results of Accelerotor wear tests involving a rapid tumbling flexing action for a short space of time and the initial modulus of the yarns of the fabric. In another case with a B.F.T.Mk IV tester involving friction and strain for a longer period of time, and up to actual failure of the components of the fabric, correlation is likely with the extensibility of the yarns or the tensile stiffness at break.

The effect of the picks per inch and denier of viscose rayon on the fabric strength, crease recovery and abrasion resistance of a series of fabric was studied by Jameson et al[212] and inspection showed that their results offered some support for the last statement while the question of relative strain would be important.

In another form of test linked with flexing and wear Gintis and Mead[152] reported that the bending stiffness of a fibre affected the degree of fuzz formation and fibre entanglement leading to the formation of fibre pills on the surface of the fabric. This was also the subject of an article by Grunewold[200] who stated that the pilling tendency decreased with a decrease in the bending-breaking stress stability of the single fibre, the fibres being bent over another fibre or a wire of similar diameter. A correlation between bending-breaking-stress stability, fibre load, and single fibre denier was established. If there is some correlation with stiffness and performance as suggested then another property which would require investigation would be that of toughness. Kaswell[20], Meredith[16, 24], Coplan[69], and Smith[83] have all reported values for the toughness of a fibre and inspection would indicate some agreement in ranking different fibres, provided that stiffness is that at a comparable order of strain. There is of course a difference that stiffness is either high or low depending on the strength extension ratio whereas it would be possible to have the same value of toughness with combinations of high strength low extension and low strength high extension. As so much of the service life of a material depends on the ability of the material to absorb work it is obvious that the property should be measured in its own right.

7. Recovery from Deformation.

An extremely comprehensive survey of the factors affecting recovery from deformation has been given by Tovey[201], although the paper was specially directed to the wrinkle recovery of cotton, and a summary of some methods for testing wrinkle recovery of fabrics after creasing has been given by Bostwick[173]. The methods were compared with respect to sample dimensions, time in minutes under maximum pressure, pressure per square millimetre of folded cloth, the percentage bending strain, and the time of free recovery. Each of these items is known to affect the bending properties of a material and the survey provides a useful reference in any attempt to examine the correlation between the results of any specific methods. Equally it might explain why there was a lack of correlation between other fibre, yarn, or fabric properties if examination showed that differences in time or strain were involved.

An example of this may be found if the question of bending strain is examined. According to Bostwick the great majority of wrinkle recovery testers impart strains of the order of 30% to 100%, so that, even allowing for freedom of movement, any correlation with tensile strain moduli or recovery values, should probably be sought using values of moduli at strains greater than that given by the initial modulus, and in fact breaking strain stiffness would probably be suitable.

Schiefer[135] showed that crease-resistant finishing treatments increased the energy required to deform the cloth specimens and the stiffness of the cloths. Comparisons were made between crease recovery, assessments made by recovery angle method, flexometer, and compressometer and the results showed that the ranking where samples were compressed by a constant maximum load, regardless of cloth thickness or weight, differed from that where the degree of compression was governed by the thickness of the sample to give equal strain. Finally from what has been said it is obvious that the time element would require consideration.

At the beginning it was stated that because of the need to limit the terms of reference, work would be concerned with the problem of measuring and defining the resistance to bending of fibre, yarn and fabric.

During the course of the experimental work there were occasions when it was possible to measure the property of recovery from bending. This could not be done with every test because of the additional time required, because for the results to have much meaning the amount of fibre strain must be known, and because it was not always convenient to limit a test to a specific strain. It has been stated that the author believes that the tensile strain moduli and the bending strain moduli are similar in value, certainly within the 1% strain level and possibly up to strains of the order of 5% or above. It follows that if this were the case then it might be expected that other stress-strain-time dependant properties involving stretching and compression would show the same similarity. The properties of stress and strain decay would be one example and comment has been made on the performance of a 1.7 cm. diameter loop made from 0.5 mm. diameter fibre if the loop was tested immediately it was made, or after a lapse of time.

This same example could be used to illustrate the property of recovery from deformation, or elastic recovery as it is usually called, because the time conditioned loop showed perfect recovery from small deformation, whereas the immediately tested loop showed poor recovery. Methods of testing this property in a tensile test have not been standardised but have been adequately described by Meredith [24, 87] and others,[210] while Burte [217] discussed measurement of elastic recovery using an Instron. No reference to a test method for measuring the elastic recovery of a bent fibre or yarn has been found, and the methods for a fabric are largely those involved in the assessment of crease recovery [26,103,140].

The essential feature for the present purpose was to measure the amount of tensile and bending strain under as similar conditions as possible. This meant that the time of application of strain, duration of strain, and time of removal of strain had to be of the same order together with a similar chart speed-crosshead speed ratio or magnification. With the small deflections involved in bending, it was necessary to magnify the strain to be able to distinguish relative amounts. Finally the sample and the atmospheric conditions had also to be the same for each experiment.

A sample undergoing a tensile test is usually clamped and is fairly stable under conditions of test but this is not the case with a sample being bent, particularly by a beam method. For this reason the tensile method whereby the sample is stretched, held, relaxed, and then stretched again, the intervals of time being defined, was curtailed and measurements were made simply on one short cycle, load to 1% strain either tensile or bending in 6 seconds, with immediate recovery as soon as full strain was reached.

Samples being strained above 1% were treated in the same way with a similar time interval. Elastic recovery, or perhaps more correctly strain recovery, was defined as the amount of recovered strain as measured from the chart ordinate expressed as a percentage of the total strain. It was felt that while the results would tend to be lower than those obtained by methods where a longer interval of recovery was allowed, they would be comparable with each other provided that tensile and bending agreement held.

Results arising from work on monofilament yarns, where the amount of strain was known, have been shown in Table 45 and inspection will show that the immediate elasticity of the yarns after tensile strain was very similar to the recovery after bending strain, and it is considered that the results support the findings on the respective moduli. No results have been given for multifilament yarns and fabrics because of the lack of definite information on effective strain, but comment might be made that in those cases where the amount of strain would be expected to be very small, $< 1\%$, the

FIBRE **Percent Elastic Recovery From Strain.**

	% Strain							
	1.0		2.0		3.0		5.0	
	Tension	Bending	Tension	Bending	Tension	Bending	Tension	Bending
Nylon 6	92	92	91	90	89	90	88	88
Nylon 66	89	90	86	88	84	87	83	86
Polyethylene	79	82	78	-	77	76	73	-
Polypropylene	91	90	89	-	86	84	80	-
Terylene	91	89	78	80	73	75	62	65
Saran	85	86	85	85	84	-	84	-

Table 45. Elastic Recovery of Some Materials from Tensile and Bending Strain.

amount of recovery was always of the order of 95% or above for Terylene and nylon materials, and 90% or above for viscose rayon materials. Similarly yarns and fabrics that were bent such that a greater degree of fibre strain might be expected, showed poorer recovery on release of tension, this being more noticeable in the case of Terylene than nylon, and in the case of viscose rayon compared with Terylene, a ranking in agreement with known tensile recovery properties[87,210].

Thompson[216] quoted the following values for recovery from 1% bending strain for 6 minutes, but gave no further details. Polypropylene recovered 40/50% in 1 second increasing to 90/94% after 100 seconds, while Terylene values for the same time intervals were 83/86% and 93/96%. These are in agreement with the values just quoted and at the same time show clearly the importance of standardising, or at least knowing, the time scale in these experiments. Wilkinson and Stanley[218] discussed the empirical relations of crease recovery and time but dealt with one class of fabric although suggesting a linear relationship.

Finally it has been stated that no appreciable effect of yarn twist on rigidity became evident until the order of twist was increased considerably, and it was noted that Steele[219] found that the crease recovery of fabrics, whose fibres had a high intrinsic resilience and whose structure was not complicated, did not show any crease recovery effect attributable to yarn twist. Resilience is normally measured as a ratio of work recovered to work expended and is therefore also linked to stress-strain relations. It is again a subject in itself but the author would suggest that just as resistance to bending can be forecast from tensile information, so recovery from bending, and resilience will be found to be linked with tensile elasticity.

8. Modification of Properties by Resin or Other Treatment.

Many of the papers covering recovery contain references to effects of resin treatment and of course virtually an industry has been created to improve the properties of a fabric by such treatment. A number of these papers have been surveyed and the author has found a lack of detail of construction of material and of resistance to deformation, as opposed to recovery from deformation.

A paper by Cooke et al[149] would appear to offer a useful source for comparison with tensile elastic recovery, and the effect of resin finish on the stress-strain properties of fibre, yarn, and fabric. Among other points they suggested that the per cent elastic recovery of a fabric using the Instron Tester could be used as a measure of the wrinkle recovery of a fabric.

Hoffman and Beste[26] and Daniels[150] also showed some correlation between fibre tensile recovery and fabric crease recovery, but the results of Woo et al[158] following a discussion on tensile stiffness and elastic recovery, offer conflicting evidence for andagainst the hypothesis that an increase in stiffness implies increased recovery.

McLeary and Royer[44] measured the effect of melamine resins on the torsional rigidity and elastic properties of wool, and showed that resin treatment produced a marked increase in rigidity which decreased with successive extensions to approach the value for an untreated fibre.

The modification of the fibre property of viscose rayon by acid formaldehyde, and other resins, was investigated by Gagliardi and Gruntfest[146] who related the decrease in fibre extension, increase in modulus and elastic recovery, with the increase in resin content, and with the increase in fabric crease recovery.

The same authors, reporting[202] on the modification of cellulose by reaction with formaldehyde, showed an increase in fibre stiffness (yarn strength) and elastic recovery with an increase in the wrinkle resistance of the fabric.

Inspection of their results suggested the following table, where the stiffness of yarn and fabric has been calculated as the ratio of breaking strength to breaking extension:-

Formaldehyde %	Yarn Stiffness	Fabric Stiffness
0.0	0.15	2.5
2.0	0.33	3.0
5.0	0.60	4.0
10.0	0.90	6.0

The trend of increasing stiffness with formaldehyde treatment shown in the figures for yarn stiffness is maintained in the fabric state and in fact there would appear to be a direct relationship between the two properties, and also between the amount of formaldehyde present and each property.

Unfortunately there were no results of bending stiffness available for comparison but the paper offers support for the technique of measuring changes in fabric property from changes in yarn property.

Details of fibre, yarn, and fabric properties relating to cyanoethylated cotton have been collected by Conrad [151]. Personal inspection of values relating to tensile stiffness of yarn and fabric showed that there was general agreement between them, the stiffness of both being decreased by cyanoethylation but the degrees being dependant again in both cases on the conditions of treatment. On the other hand although there was some degree of correlation between the tensile and the flexural stiffness of the untreated and scoured yarn and fabric, there was no apparent correlation with the treated fabric. This may be due to the fact that values at two different strains are being compared, that of the yarn being at break while that of the fabric is only of the order of 5 per cent.

Similar inspection of the results of Reinhardt et al[203] showed that they had given the breaking strength and elongation, and the stiffness of cotton fabrics before and after cyanoethylation, and after laundering. The stiffness measurements had been made on a Tinius Olsen Stiffness Tester[223]. Scrutiny suggested that there was some correlation between the stiffness of the fabrics that might be forecast from the strength elongation behaviour,and the ranking of stiffness by the bending behaviour but that this was not always the case. This observation has been made before and it would again appear that a possible reason for the lack of absolute correlation may lie in the difference in strains involved. A particularly notable exception was the case of the mercerised samples where the strength tests showed a marked increase in total extension at break compared with the control sample, and yet the bending stiffness given by the Tinius Olsen test was extremely high. The explanation in this case presumably lay in the change in the shape of the cotton fibre after mercerisation.

The effect on the stiffness of viscose rayon filaments in the wet state due to the introduction of vinyl polymers was investigated by Landells and Whewell[204]. The stiffness was obtained by the cantilever principle by measuring the deflection under a constant load and it was found that the stiffness was increased by the deposition of polymer, the quantity, rather than the nature of the polymer introduced being the main factor. The increase compared favourably with that brought about by treatment with urea formaldehyde resin, or with formaldehyde in the presence of an acid catalyst.

While some of the increase was due to an increase in the diameter of a filament, it was shown that about 8% of the polymer could be introduced without causing any change in the diameter, so that part of the explanation for increased stiffness lay in the change in molecular packing of the material.

Unfortunately no details of tensile properties were available for comparison as this would have been an interesting case to check the validity of the tensile bending forecast.

Steele[138] and Schiefer[205] have reported cases where there has been no change in the bending stiffness of a material due to resin treatment, and yet the crease recovery values have been affected, while in other cases there has been a change in stiffness as well as recovery. This may be dependant on the degree of polymerisation, a surface deposition tending to alter the hand and stiffness, as would the presence of hand-modifiers such as a softening agent.

Treatment with precondensates might not alter the initial stiffness and yet affect the degree of crease recovery. This point is similar in some ways to the previous case and the effect of softening agents with modification of frictional properties is being considered[181].

Woo et al[158] gave values for some mechanical properties of cellulosic fibres, yarns, and fabrics after treatment with formaldehyde. Inspection of their results for breaking load against treatment showed that there was reasonable correlation for the behaviour of the cotton fibre, yarn, and fabric, for the Fortisan filament, yarn, and fabric, and for viscose rayon filament, yarn, and fabric.

Comparing breaking strain correlation was found between cotton fibre and yarn but not fabric; Fortisan fibre, yarn, and fabric; viscose rayon fibre, yarn, and fabric. On the other hand comparison of the elastic modulus showed poor correlation for the cotton sample although the modulus of the (finally) treated sample was always below that of the untreated control sample, whereas there was apparently good correlation between the modulus of fibre, yarn and fabric in the case of the Fortisan and Viscose rayon samples.

Finally inspection of the results for toughness, expressed as the area under the stress-strain curve, showed that there was good correlation between fibre, yarn and fabric property in all cases.

These examples are among the best found in literature to support a statement that single-fibre measurements allow a useful forecast of yarn and fabric properties, and that yarn properties forecast the performance of a fabric. Unfortunately Woo did not record the resistance to bending of each component, so that it is left to conjecture whether the measurements of tensile stiffness would have forecast bending stiffness as successfully. The Monsanto Wrinkle Recovery Angle was recorded but this has been commented on elsewhere.

CHAPTER 14. CONCLUSIONS REGARDING THE ELASTIC MODULI AND THE BENDING PROPERTIES OF TEXTILE MATERIALS.

At the beginning of this work a number of questions were suggested. During this work these have been answered and a number of items arising out of the investigations have been considered. Conclusions have been given where possible at the end of a chapter or section, but the present chapter is a summary reviewing the methods, terms, and expressions that may be used to measure or indicate the bending property of a textile material.

Tensile moduli

At low strains the value of the tensile modulus of a fibre is equivalent to the value of the bending modulus, and compressive modulus, of that fibre. This relationship has been shown to continue in compression until buckling occurs, when the value of the compressive modulus would drop. In bending the relationship between the tensile and bending moduli held up to the 5 per cent strain level and perhaps above. It has been shown that in any comparison it is imperative to keep test conditions constant, and to record changes in stress or strain accurately. The effect of test length on the value of the modulus has been shown to be much less than previously recorded.

The modulus of a yarn or fabric can be obtained and expressed on a fabric, yarn, or fibre basis, but the value has been shown to be dependant on the conditions of test, particularly the tension imposed on mounting the specimen. One method has been shown to be the taut method where the components of the fabric in the direction of test may be assumed to be undergoing tensile strain from the beginning of the test, but a case has been made for the use, or significance, of the slack modulus because of its possible indication of the handling properties of a yarn or fabric.

It has also been shown that, because of the similarity of tensile and bending moduli, the consecutive and cumulative tensile strain moduli at levels of strain up to break may indicate the probable bending behaviour of a material. This has been shown for fibres at several strain values between initial strain and breaking strain, but only for initial strain and breaking strain in the case of yarns and fabrics. The fact that excellent correlation was achieved between tensile average stiffness and bending properties is taken as offering some support for this statement.

It has been shown that in any comparison of moduli it is imperative that equal strain values are used, and that the value of the modulus may alter even within the region up to one per cent strain, a lower value of modulus being obtained as the strain approached this limit. Apart from the question of time this may be one reason why the values for the modulus obtained by dynamic methods are higher than the methods achieved by a semi-static test.

The strain moduli for yarn and fabric have been shown to approach the value of the fibre moduli in cases where the construction allows immediate strain to be transmitted to all the components of the material in the direction of test. Where this was not the case the value of the modulus was low and it was shown that the two extremes, a slack and a taut modulus, might measure different properties of the material.

Moduli may be expressed as a direct ratio of strength and extension, be measured in terms of specific stress of fabric, yarn, or fibre, or be expressed in terms of stress per fabric, yarn, or fibre area. Examples of each have been shown and while it is considered that no clear preference can be made for any one system, as each has advantages and disadvantages depending on what information is being sought and other tests that may be being carried out, expression as specific stress did allow ready comparison between fibre, yarn, and fabric and with other materials.

Bending moduli

Besides showing that the value of the bending modulus of a fibre was equal to the value of the tensile and compressive moduli, it has been shown that the effects of time, temperature, and humidity on the bending strain moduli were similar to the effects on the value of the tensile strain moduli. While this was important in that it supported the other experimental data, it is also considered important in considering manufacturing, finishing and service processes. The order of change of property within the day to day fluctuation of temperature and humidity may be large enough to explain why many differences of opinion arise regarding drape, handle, and resilience. The effects will vary with hydrophilic and hydrophobic fibres, and with thermoplastic and non-thermoplastic fibres. In some cases the changes will be reversible but with some thermoplastic materials, and in particular where the fibres have not been heat set, the change could be irreversible, a point affecting the behaviour of the material in dyeing, finishing, and laundering. The value of the bending modulus of a yarn or fabric has been shown to be affected by factors such as inter-fibre friction, yarn flattening, and fabric sett which affect the degree of freedom of fibre movement and the moments of inertia.

With fabrics made from monofilament yarns the bending modulus of the fabric was shown to be that of the yarns, while with some multifilament fabrics the modulus was that of the single filament. In other cases the difference between fabric modulus and component modulus could be due to effects already noted, or it may mean that the method of calculation requires correction. Several results have been showed based on different values for yarn and fabric diameter, but further work is required.

Compressive modulus

It has been shown that the value of this modulus is very similar to the value of the tensile and bending modulus, and that it is similarly affected by variations in experimental technique. No effect attributable to the length-diameter ratio was found provided the dimensions of the fibre were kept within the non-buckling region. No experiments were made regarding the effects of temperature and humidity other than those concerning the preparation and conditioning of the sample, but it would be expected that this modulus would show changes similar to those described for the tensile and bending values. Similarly no experiments were made on the longitudinal compression of multifilament yarns, and fabrics, but it would be expected that the buckling characteristics could be forecast from the dimensions of the sample, and a knowledge of either the tensile or bending modulus of the material.

Stiffness

Several connotations regarding stiffness have been discussed and the use of this term to describe a property of a material whether measured by tensile or bending test is regarded as justified because of the correlation between such results.

Bending stiffness can be considered in conjunction with bending length and flexural rigidity, but tensile stiffness has been shown to refer to the stress-strain relationship at initial strain or at final, or breaking, strain, the latter also being referred to as average stiffness. Which is the most useful must depend on circumstances in each case. Initial stiffness will be useful in any assessment where low strains are expected, as for instance in considering drape, or in certain aspects of handle, whereas final stiffness may give an indication of the probable characteristic of a material after a certain amount of service.

Changes in initial stiffness with temperature and humidity may be forecast from the present work, but changes in average stiffness would require inspection of the changes of breaking strength and extension under changing conditions.

Being a stress-strain property stiffness may be expressed, and applied, to fibre, yarn, or fabric form.

Flexural Rigidity

This property has been measured for fibre, yarn, and fabric, similar results being obtained from both beam and loop methods. It has an advantage over the use of bending moduli in that no measurements of moments of inertia are required and materials may quickly be ranked in order of stiffness according to the numerical value obtained, the value increasing with increasing stiffness.

The value for a fibre has been shown to increase in proportion to the tex and diameter of the fibre, while the value for a yarn may increase in proportion to the number of component fibres, but there may be a greater increase in effective value because of inhibition of freedom of movement leading the yarn to behave as though it were composed of thicker fibres. In the present case the effect of twist was considered slight, but twist cannot be discounted, while the effect of friction must also be considered.

These comments also apply to a fabric where the theoretical value of rigidity will be affected in addition by such factors as crimp, interlacing, and cover factor. It would be expected that the rigidity would reflect the changes in modulus caused by temperature and humidity.

Bending Length c; Flexural Rigidity G and Bending Modulus, q.

These properties of a fabric have been measured as being representative of what might almost be called the traditional methods of describing the stiffness of a fabric.

Agreement was found between bending length and flexural rigidity from cantilever measurement, and flexural rigidity from beam and loop measurement. It has been shown that there was good correlation between the ranking of fabric stiffness by the initial taut modulus, the final strain modulus, and the rigidity. It was also suggested that the initial slack modulus might prove of assistance as one measurement of fabric handle and that some correlation existed between such a modulus and the bending modulus q.

It is known that the values of these terms alter with temperature and humidity and because of the correlation with tensile and bending moduli it would now be expected that it will be found that the actual change can be forecast from a knowledge of the change in modulus with temperature and humidity for the specific material.

Other Properties

Because of the similarity in tensile and bending properties it would be expected that some correlation might exist between a tensile modulus and any property involving stress-strain characteristics provided both could be measured within the same condition of time, and strain, and of course at the same temperature and humidity. Brief examples relating to knot and loop strength and flexural fatique have been given, and it is considered that such correlation may be found provided that the construction involved does not impose restrictions which are not recorded by a tensile test. Similarly only brief reference to tensile elastic recovery, bending recovery, crease recovery, and resilience has been made but again the author would expect that a comparison of a tensile property will enable a reasonably accurate forecast of bending probability to be made.

Finally it is considered that in the measurement of bending resistance the main need with regard to test methods is for increased sensitivity in design so that the small stresses and strains implied in the testing of fine fibres may be accurately recorded. In this respect tensile methods already possess advantages over bending techniques while they would also permit compressive testing with minor modifications. It has been shown that tensile tests may be used with coarse fibres, and yarns and fabrics.

In direct bending measurement both beam and loop methods may be used for fibre, yarn, and fabric. The advantages and disadvantages of each have been considered and it may be concluded that possibly the beam method is preferred. The reason for the apparent neglect of these methods may well lie in the ease and general applicability of the cantilever bending test.

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