RESILIENCE OF SOME MAN-MADE FIBRES

T H E S I S

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Summary

The first part of this research is concerned with the standardisation of a test method to determine the resilience of fibres. The influence of both time and maximum pressure is studied and the loading and unloading cycle is standardised to measure resilience with three maximum pressures (0.01, 0.10 and 1.0 p.s.i.) in the minimum time. The effects of specimen preparation and specimen dimensions (areas and thicknesses) and also the effects of presser foot area and shapes (plane or hemispherical compressing surface) on measured resilience are investigated.

The second part of this work is devoted to investigating those intrinsic fibre properties which may affect resilience. Six fibre properties, namely, staple length, diameter (denier), crimp characteristics (i.e. percent crimp, uncrimping force, uncrimping energy), inter-fibre friction, tensile elastic recovery and initial modulus are studied. Crimp has the highest influence on resilience whereas fibre friction and diameter indicate comparatively less effect. The staple length shows no significant correlation with resilience and both elastic recovery and initial modulus are also not correlated with resilience. These investigations were carried out on Acrilan, Terylene, and Tricel fibre.

The possibility of expressing the thickness-pressure relationship by an equation is considered. The results fit an exponential equation of the form: $T = a P^b$, where 'T' is thickness of the specimen, 'P' is pressure and 'a' and 'b' are constants.

The effect of both humidity and temperature on the resilience of fibres is investigated. The resilience decreases as the relative humidity increases. On the other hand there is an increase in resilience with the increase in temperature. Comparison is made between Acrilan, Terylene and Tricel fibres.

The influence of surface properties (i.e. amount of finish) of Acrilan are studied in relation to the resilience of fibres.

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A B S T R A C T

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C O N T E N T S

Page

CHAPTER I

INTRODUCTION AND REVIEW OF LITERATURE

CONTENTS

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INTRODUCTION AND REVIEW OF LITERATURE

I. GENERAL INTRODUCTION

1.1 Introduction

The physical properties of man-made fibres are very important for their particular end-use, and although these properties largely depend on the chemical nature of the material, nevertheless, these can be modified to a considerable extent during manufacturing. Resilience is one of such properties and is used to determine the usefulness of a fibre mass for bulk purposes (i.e. as fibrefill) and in various other textile applications, e.g. retention of shape, drape, wrinkle resistance, hand, bulk, performance of pile in carpets etc.

A number of workers in the past have attempted to design an apparatus for the measurement of bulk-resilience and also to study the resilience of a fibre mass in relation to fibre properties. There is, however, no general agreement existing among these workers and their results rather seem to depend on the techniques and experimental conditions employed. It appears then, the important factors which are essential in a resilient fibre mass are not fully known or understood. The main aim of the work described in this thesis is to find out what are these factors. It is proposed to proceed along the following lines: (1) to standardise a test method for measuring resilience of fibres in bulk and to investigate the effect of varying experimental conditions, and (2) to determine precisely which intrinsic fibre properties are related to the resilience of fibre mass.

The methods of measurement of resilience can be divided into two main categories:

(1) Methods in which the material is deformed according to a fixed pre-determined compression ratio.

(2) Methods based on maximum pressure, that is, when the material is compressed to a fixed pressure.

The standardisation of the test for resilience of a fibre mass was concerned with the selection of an effective method of test.e. In addition it is necessary to evaluate the effect of specimen preparation, area and thickness of specimen and size and shape of pressure foot. In the course of the present work, a Shirley Thickness Gauge is used since it simulates the end-use conditions of fibre-fill, experiments are carried out on specimens of different areas, thicknesses, and also with the pressure feet of different sizes and shapes.

In an attempt to characterise the resilience in relation to the easily accessible fibre properties, it is necessary to investigate the fibre properties which affect the resilience. It is believed from the present knowledge that the following fibre properties may be important and they are studied in relation to the resilience of a fibre mass.

(1) Staple length and diameter of a fibre.

(2) Crimp characteristics of a fibre.

(3) Fibre friction.

(4) Elastic modulus and recovery from deformation.

The fibres may be hydrophilic and the moisture in a fibre not only depends on the humidity of the atmosphere but it also depends on the temperature. The mechanical properties of such fibres are affected by both relative humidity and temperature, and therefore, the resilience of fibre mass is studied in relation to these two parameters. Relative humidities of 45%, 65% and 85%, and temperatures of 20°C, 30°C and 40°C were chosen for the experiments, since these cover the most likely conditions which can be expected from the end-use considerations of the fibrefill.

It is a matter of common experience that the finish or any other lubricant on the fibre modifies the surface properties, depending upon the amount of finish, nature of the material, etc. This seems to play an important part as regards the behaviour of a fibre mass both in compression and recovery. Therefore, the effect of surface finish on Acrilan is studied from the resilience point of view.

It is noticed that most workers have used an Instron tester in conjunction with a compression unit for resilience measurement, so it is thought to make some resilience tests (cf. Appendix) with a similar type of equipment and see whether it is possible to get the same ranking of fibres as is obtained from a Shirley Thickness Gauge from the resilience point of view. Also testing fibres for their resilience on an Instron will greatly reduce the time involved in such experiments.

Resilience of fibres is a complex property, depending upon many factors. It is therefore appropriate to give its definition and conception, and also the factors which are involved in it. Further a brief survey of literature is given to provide a background for the discussion and understanding of the subject.

1.2 Definition and Conception of Resilience

Resilience has been defined in different ways by different workers, the most important of which are given in the following text.

Dillon[1] has examined various definitions and terms which have appeared in relation to resilience of single fibres, fibres in bulk and fabrics. He concluded that a reasonable expression for resilience is:

$$R = \frac{\text{energy of retraction}}{\text{energy of deformation}}$$

bearing in mind that the deformation may be tensile, compressional, shear, or a complex combination of various types of strains.

Mark[2] discussed resilience rather from a practical point of view and stated that if a given fibre is to be classified as resilient, such a bunch of irregular fibres should perform as follows:

(1) It must offer a certain moderate resistance to compression. If this resistance is too small the material is "limp"; if it is too large the fibre is "harsh" or "stiff".

(2) It has to spring back vigorously and rapidly upon relaxation, even if it has been kept under compression for a considerable time. If the recovery is only slow the fibre will be classified as unresilient.

Hamburger[3,4] defined resilience as the amount of strain energy present in a stressed system.

Smith[5] defined resilience as the ability to absorb work without suffering permanent deformation.

Winson[6] considered resilience to be inversely related to the area of the compression-decompression loop after the eighth cycle.

Robinson[7] defined three resiliences as follows:

(a) "Positive resiliency" - upward movement of fibre after release of compressive load.

(b) "Negative resiliency" - maximum compression of fibres below point of rest.

(c) "Total resiliency" - sum of positive and negative resiliences.

Rees[8] defined resilience of fibres in bulk as the amount of energy returned by the material between the given limits of pressure, since the compressional behaviour of fibre mass is highly dependent on the pressure to which it is subjected. For a perfectly elastic material the resilience would be 100 percent, while for a perfectly plastic material it would be zero.

Dillon and coworkers[9,10] have discussed the dynamic resilience as applied to rubber-like materials, which is defined as:

$$Rd = e^{-2\pi\omega b/s}$$

where ω is the natural radian frequency, b is a factor proportional to the "internal friction", and s is the "stiffness" of the material. The dynamic resilience, Rd, may be measured as the ratio of successive damped sinusoidal amplitudes in free vibrations, from the ratio of rebound height to height of fall in an impact test, or calculated from the resonance amplitude and frequency of a forced vibration test.

Much of the confusion is removed if it is recognised that the resilience has two aspects, namely (i) type, and (ii) extent. Each of these aspects has its own complex factors and although neither one can be measured entirely independently of the other, the two should be regarded as separate entities.

The type of resilience is separable into two factors, each of which is complex and measurable by various means. One of these factors is stiffness or stress per unit strain. The other factor is change of stiffness with elongation and with time. This effect is well described by the term "diminishing modulus", since the change is usually towards lower stiffness.

The extent of resilience is characterised by the ability of a body or a substance to recover from deformation and can be measured by either (i) the ratio of the work recovered to the work absorbed by the deformed material, or (ii) the ratio of strain recovered to the strain imposed. In considering this aspect, the time element and the environment must always be specified because both factors play an important role in the extent of recovery.

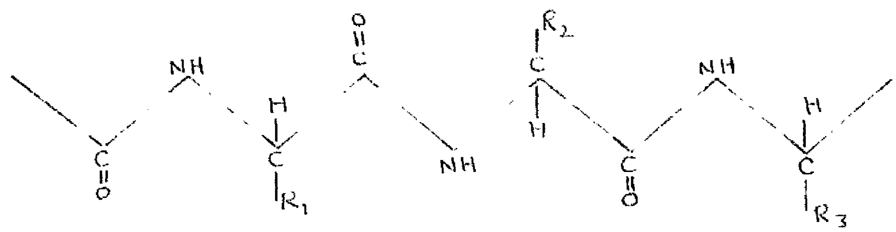
Hoffman[11] has discussed the concept of resilience and concludes that resiliency (Resiliency is used in referring to a substance such as glass, cotton, wool, etc. and resilience is used when referring to an entity, e.g. wool fibre, a mass of fibres, a fabric) may be defined as a stress-strain-time property of a material, characterising the degree of completeness of recovery from deformation and varying in kind with the modulus of elasticity and the rate of recovery. He proposed that the resiliency of different materials could best be compared by constructing a three dimensional model to represent the type of resiliency with modulus as ordinates and time factor as abscissae; the extent or degree of resiliency is measured by the vertical height above the plane with coordinates describing the type of resiliency.

It appears from the present broad knowledge of resilience of fibres that the following factors are particularly important as regards the resilience of fibres, and these are now discussed.

1.3 Factors in Resilience

1.31 The Chemical Nature of the Fibre:

It is well known that all natural protein fibres possess high resilience, e.g. all kinds of native wools are very resilient. The common structure of these materials is that they consist of a very long and flexible backbone chain molecules of the form:



in which there is a frequent repetition of the carboxylamide group - CONH - in such a way that only one substituted methylene - CHR - separates two - CONH - groups. The methylene groups of the chain carry various (up to 20) substituents, R_1, R_2, R_3 etc. which in turn contain groups of various chemical nature and polarity (OH, NH_2, COOH, SO_3H, NH, S-S etc.). The variety and the regular arrangements of the substituents along the chains provide for a considerable degree of interaction between them, ranging from weak van der Waals attraction to such strong bonds as hydrogen bridges, ionic forces and even covalent cross links[12].

There exist other fibres with - CONH - groups in the backbone chain, viz., nylon and native silk. Although they both exceed keratin fibres considerably in strength, they do not exhibit the high resilience of keratin fibres because, as pointed out by Mark[2], neither of them possesses the many different substituents of keratins.

The copolymers of vinyl chloride with other vinyl derivatives (vinyons) also possess a backbone chain of considerable internal flexibility, in this respect are not too dissimilar to protein chains, and therefore, these fibres may possess comparatively high resiliency. However, their substituents such as Cl, OH, acetate, are very different in chemical nature from the substituents which are distributed along a protein chain. Nevertheless, they apparently provide for a certain degree of mutual attraction which is partly due to weak polar bonds, partly to stronger ones, and partly to hydrogen bonds. The statistical distribution of substituents, however, prevents crystallisation and provides for the rubbery nature of these fibres.

Cellulose, on the other hand, is a material which does not easily give resilient fibres. This may be due to the comparative stiffness of the chains, which is probably due to the presence of large numbers of strongly acting hydroxyl groups. This probability seems to be true because acetate fibres are more resilient compared with viscose or cotton. The interaction between the chains in the case of acetate is smaller than viscose (cellulose) and moisture does not plasticise the acetylated cellulose as much as it does the unacetylated.

Thus, it is pretty clear that the fibre must possess: (a) a fairly strong ~~(not very strong)~~ interaction between the adjacent chains and (b) a long and flexible backbone chain, in order to be more resilient.

1.32 Molecular Structure:

All fibres, natural or synthetic, consist of arrays (molecular chains or segments) with different degrees of order. In order to understand its effect on resilience it is worthwhile to consider the following two extreme cases.

One extreme case is the disordered (amorphous, glassy) state in which the segments of the polymer chains are arranged completely at random and comply only with the conditions of dense packing, e.g. unstretched rubber, in most synthetic elastomers, vinyon, and commercial cellulose acetate. Materials which are completely or preponderantly in this state are either rubbery or glassy (viscous liquids). The other extreme is the crystalline (highly ordered) state, for example, highly oriented cellulose (Fortisan fibre), nylon, Saran, polyethylene etc. However, all these substances do contain a small amount of disordered state. Therefore, it is evident that the fibres are a mixture of both ordered and disordered state, the relative proportion of which is important for the mechanical properties particularly for resilience.

It seems, therefore, that not only the chemical nature of the material, but also the arrangement of the molecules in the substance determine its resilience and other mechanical properties[13-16]. In general, one can expect a very stiff and strong fibre from a highly crystalline material when all the crystals are oriented parallel to the fibre axis. On the other hand, when a large proportion of the material is in the disordered state (amorphous) then the fibres would be extensible and soft.

Mark[2] states that fibres, plastics and rubbers are not intrinsically different materials; they are only different combinations of three fundamental states in which organic high polymers can appear. These are the crystalline solid state with long-range molecular order and high modulus of elasticity, the rubbery state with short-range molecular order but long-range entanglement and low modulus of elasticity, and the liquid (molten) state with short-range molecular order and high viscosity. Frequently the temperature of the material determines its state, e.g. vulcanised rubber which is flexible and resilient at room temperature can be made hard and unyielding if the temperature is sufficiently reduced.

With textile fibres it is desirable that the liquid state should be restricted to localised regions within the fibre, that is, to the movement of segments of chain molecules and not to the movement of whole molecules relative to each other.

There exists a multitude of systems, starting with extreme fibre properties and ending with extreme rubber qualities and the balance must be set up in the proper way in order to combine strength with resilience. A filament having a highly crystalline skin and a rubbery core will be less desirable than one having a highly crystalline and oriented core and a rubbery (amorphous) skin.

It appears that one can expect a resilient fibre from a polymer of high Degree of Polymerisation (D.P.) which has flexible backbone chains and consists of substituents of various chemical nature. These chains must be brought into a highly ordered state, partly into a rubbery state, and this phase must be properly distributed across the cross-section of the filament.

1.33 Creep and Stress Relaxation:

It has been generally recognised that the creep and stress relaxation properties of fibres are related to resilience, since resilience is an expression of elastic reversibility. Secondary creep, of course, is a measure of irreversibility; and primary creep is a function of delayed elasticity. Leaderman[17] related creep functions to resilience of fibres, using the classical Maxwell concept. Eyring and coworkers[18-28], also, considered resilience in relation to creep and stress relaxation. They employed the following hyperbolic sine relationship:

$$\frac{dl_1}{dt} = K \sinh \alpha f = \frac{K(e^{\alpha f} - e^{-\alpha f})}{2} \quad \ldots\ldots (1)$$

which is derived from the activation rate theory of flow with the assumption of a symmetrical potential barrier. In this equation l_1 is the strain of a dashpot subjected to a force f_1, and α and K are constants for a given rate of deformation dl/dt of the fibre as a whole. They considered a simple "three-element model" (see Figure 1a), which consists of a Maxwell element (spring of stiffness k_1 and dashpot with "flow indices" α and β) in parallel with an open spring of stiffness k_2. The index β is defined as:

$$\beta = \frac{dl}{dt}/K$$

so that equation (1) becomes

$$\frac{dl_1}{dt} = \frac{1}{\beta}\frac{dl}{dt}\left(\frac{e^{\alpha f} - e^{-\alpha f}}{2}\right) \qquad \ldots. (2)$$

The above relationship (equation 2) was found to give excellent agreement between theory and experiment for the hysteresis loops obtained with several types of fibres, using proper values of the indices α and β. Also, it was found possible to predict accurately the creep and relaxation curves, from the same equation.

The assumption of a symmetrical potential barrier appears too simple for some fibres, notably wool, and a symmetry coefficient, μ, must be introduced to give:

$$\frac{dl_1}{dt} = \frac{1}{\beta}\frac{dl}{dt}\left(\frac{e^{2\mu\alpha f} - e^{-2(1-\mu)\alpha f}}{2}\right) \qquad \ldots. (3)$$

Initial slope of the extension curve (Figure 1b) is then given by the sum of the stiffness of the two springs of the model ($k_1 + k_2$) and the final slope by the stiffness k_2 of the open spring. Hence the resilience index is defined as

$$R'' = \frac{k_2}{k_1 + k_2}$$

which is the fraction of the resisting force which urges the stretched fibre back to its initial unstretched condition. Halsey and Eyring[24], however, have pointed out that the symmetry coefficient, μ, may be a more suitable parameter as a measure of resilience.

1.34 Modulus of Elasticity:

The type of resilience may be measured by determining the stiffness, which is defined as stress per unit strain. This definition applies equally well to Young's modulus when measured either in stretching or bending, to the torsional modulus or to the bulk modulus. The time effect, of course, is an important parameter in these experiments.

It is immediately evident that the fibre mass in compression undergoes bending and perhaps it might be more correct to measure stress-strain-time relationship in bending. In the case of elastic modulus, however, the usual practice has been to measure it in a tensile test and to assume that the same value holds good to a first approximation for the specimen in bending. Beste and Hoffman[29] found the ratio of bending to tensile modulus to be 86% $\pm$ 14% for a synthetic polyamide and 113% $\pm$ 12% for polyethylene terephthalate. These above limits are average deviations. Khayatt and Chamberlain[30] obtained values for the bending modulus of several animal hairs which ranged from 44% to 80% of the modulus as measured in tension. Therefore it seems reasonable to assume that the tensile modulus is a sufficiently good indication of bending stiffness which is an important parameter to characterise resilience. However, in order to establish the precise effect of modulus on resilience, it may be necessary to obtain Young's modulus in bending.

1.35 Elastic Recovery:

The extent of resilience is characterised by elastic recovery[11,29], which is defined as the ratio of the recoverable deformation to the total deformation.[31,32]

The recovery of fibres from deformation may be made in different ways - namely, in tension, in torsion, and in bending. In a tensile test, the sample is elongated and then allowed to retract. These tests can be carried out either:-
(i) with controlled rate of elongation, or (ii) with controlled rate of loading. Similarly, it is possible to measure torsional or bending recovery. Compression test on a mass of fibre involves the measurement of bending recovery. However, it is believed that tensile elastic recovery results compare very well indeed with those of bending recovery results[29].

Kaswell[33] has discussed the dependence of resilience of fibres on their elastic recovery, and concluded that there seems to exist a linear correlation between them.

1.36 Fibre Length:

It is evident that a certain minimum length of fibre is necessary in order to make use of it as a fibrefill or in other textile applications. Fibres only a few millimetres long would be useless even if each one is highly resilient because such a bunch of fibres would collapse upon compression. Also a very long fibre (6 inches or more) is undesirable since it would cause sufficiently high degree of entanglement and can considerably affect recovery properties of an irregular bunch of fibres. It is therefore necessary to find out what convenient length of fibre yields good results from the resilience point of view.

1.37 Diameter of Fibre:

The diameter of fibre is of great importance in characterising the resilience of a fibre-mass. The compression of the bunch of fibres leads, in general, to a bending of the individual fibres within the reversible limit and results in a storage of the compression energy in the bent fibres or filaments. The bending resistance of cylindrical rods is proportional to the fourth power of the radius, and a given mass of coarse fibres will therefore offer more resistance to compression and exhibit more tendency to return to the original state, than the same mass of finer fibres. A large diameter, however, conflicts with so many other properties such as softness, hand, lustre, etc.

1.38 Form of Fibre:

The form of the fibres (whether straight or crimped) is an important requirement for their textile and other applications, because it determines the capacity of fibres to cohere under light pressures, which in turn helps the processing on card and various other machines[44,45]. Further, crimp imparts bulk which is essential, particularly on products such as fibrefill and knitting yarns, etc.

Crimp is not a simple property to characterise. In broad sense, crimp may be defined as the waviness of a fibre. It may be measured in terms of either the number of crimps or waves per unit length, or in the percentage increase in the extent of the fibre on removal of crimp. Alexander et al[34] has discussed the definition and other parameters associated with crimp. However, these geometrical specifications (e.g., the number of waves per unit length and percentage crimp), disregard important properties such as crimp elasticity and performance under normal textile processing. Various kinds of apparatus have been designed to measure crimp by various workers[35-43].

In man-made fibres, the crimp is usually imposed:- (1) by mechanical means (e.g. in the stuffer box), and so it largely depends on the mechanical properties of the material, and (2) by introducing into the fibre, at the extrusion or drawing stage, a differential stress which is subsequently released by wet or heat treatment to produce a permanent crimp[46]. The chemical method of crimping fibres has also been developed[47].

In most synthetic fibres, crimp is permanently built into their structure; this means that the crimp is retained for long periods. In the case of regenerated fibres, however, crimp is not so permanent and a substantial amount of it may disappear during processing or manufacturing, etc. The elasticity of the crimped form may also vary considerably. In wools the crimp is highly elastic, as it is also in synthetic fibres, in which the applied axial deformations are properly set by suitable heat treatments.

It is also obvious that the crimp in a fibre is required to control the bulk of a fibre assembly. Whether or not crimp has any great effect on resilience is a question which needs investigation. Demiruren and Burns[48], however, concluded that crimp does play an important role in the compression behaviour of wool fibres.

1.39 Fibre Friction:

Interfibre friction influences the behaviour of fibre in a fibre assembly, yarn and fabric. For example, resistance to compression, recovery from compression, dimensional stability, etc., all depend on interfibre friction. It seems reasonable to assume that resilience of fibres may perhaps be affected by fibre-to-fibre friction to a considerable extent.

The frictional effect of the material can be measured in a number of ways. In most cases, the coefficient of friction over a single point-contact is measured to depict the friction. The coefficient of friction, μ, is defined as follows:-

$$\mu = \frac{F}{N}$$

where F = frictional force, N = normal load.

This relationship does not hold true, in case of fibres. However, it is assumed to apply in most cases to a first approximation. The most successful relation has been observed by Lincoln[49], and Howell and Mazur[50], which is as follows:-

$$F = a N^n$$

where a and n are constants.

Various workers have designed and developed different apparatus, employing different principles [51,52,53,54].

The frictional effect is changed if the surface is lubricated. For example, in case of acetate yarn with more than 1% of oil applied, the frictional force increases both as the oil content is increased and as the viscosity of the oil increases.

However, fibres from which all traces of lubricant have been removed show high values of friction. Moss[55] obtained $\mu = 0.25$ for raw cotton on steel, whereas scoured cotton on steel gave $\mu = 0.70$, and lubricated scoured cotton on steel gave values of $\mu = 0.14$ to 0.35. A similar effect was observed by King[56] on wool fibres.

The friction usually increases as the moisture regain of the fibre is increased. Changes of coefficient of friction with the variations in regain for nylon on nylon, wool on horn has been investigated by King[56].

Many theories of friction have been proposed in the past. The most recent and widely accepted one seems to be that of Bowden _et al_[57]. They have shown that an actual welding or union of the two surfaces at a point of real contact takes place, and the frictional force is due to the breaking of these junctions.

1.4 Effect of Humidity

Fibres absorb moisture from the surrounding atmosphere. The absorption changes the properties of fibres; it causes swelling which alters the dimensions of the fibre and this in turn will cause changes in the size, shape, stiffness of the material. The mechanical properties[58] and frictional properties[56] are altered too, so affecting the behaviour of fibres in bulk compression, in processing, and in various other uses. The electrical properties[59,60] are also changed, e.g. static charge is much less likely to occur in damp conditions[61].

Beste and Hoffman[29] have observed that the tensile elastic recovery of fibres depend upon humidity. It is, however, not fully known how far humidity affects resilience of fibre mass.

1.5 Effect of Temperature

The effect of temperature on most materials is rather simple, that is, the material expands gradually up to a certain temperature and then it melts into a liquid as the temperature is raised. In case of fibres, however, the behaviour is complex. At high temperatures fibres may contract instead of expanding, which may be reversible. Generally fibres do not indicate a sharp melting point, either they soften over a wide range of temperatures (in synthetic fibres) or decompose before melting, as is the case in most natural and regenerated cellulose fibres. At lower temperatures other important changes occur such as variation in percentage regain[62,63], and therefore mechanical properties[64,65,66], frictional effects[56], electrical properties[67,68] etc. are all temperature dependent. Changes in these properties due to variation in temperature seem to affect the resilience of fibres. Although a considerable amount of work has been carried out to investigate the effect of temperature on single fibre tensile behaviour, this is not so for fibre masses. Undoubtedly, it seems certain that the fibre interaction would be an important factor in such cases.

2. REVIEW OF LITERATURE

Over many years, a number of workers have been engaged in the evaluation of mechanical properties of fibres. Most of these researches were concerned with the study of inherent fibre properties. In fact very little has been published about the resilience of fibres in relation to their more easily accessible and simple properties such as elastic modulus, elastic recovery, creep, stress-relaxation, crimp, friction, etc. However, in order to provide background for the discussion and understanding of the subject, a brief survey of literature is given.

2.1 Measurement of Resilience and Compressional Behaviour of Fibre mass:

Attempts have been made to design and develop a reliable and reproducible test method which would give results that can characterise the resilience of textile materials.

Winson[6] measured the resilience of a volume of wool fibres by enclosing it in a thin spherical rubber membrane and submitting it to the mechanical action of the surrounding atmosphere whose pressure can be made to vary in a cyclic manner. He stated that the area of the loop (shape of compression-decompression curve) relating the pressure and volume of the mass of wool seems to serve as a measure of the resilience.

The compressometer - an instrument for evaluating the thickness, compressibility, and compressional resilience of textile and similar materials, was developed by Schiefer[69]. This apparatus consists of a 1 inch diameter, circular pressure foot, which can be lowered or raised by means of a rack and pinion acting through a helical spring. The pressure applied to the specimen by the foot is indicated on a dial micrometer and the corresponding thickness of the specimen on a second dial micrometer. Schiefer used a pressure range of 0.1 to 2.0 lbs. per square inch for the evaluation of compressibility and compressional resilience.

Saxl[70] devised an instrument to measure the load-compression characteristics of fibres. This apparatus consists of a three arm balance to support a beaker on the platform, a cylinder, and a plunger. An accessory vertical support carries a rack and pinion which controls the movement of a plunger. The descent of which into the beaker is measured by means of graduations on the vertical support. The plunger can be lowered into the beaker containing a weighed sample and its depression recorded. At the same time, the balance is brought to equilibrium and the weight necessary to do this is also recorded. The plot of these two observations gives a load-compression curve. The loading rate in this instrument obviously is not continuous and it is necessary to control the relaxation time carefully between the successive loadings. This can be done either by applying load in successive equal steps with a known relaxation period and bringing the balance into equilibrium by adjusting the plunger, or by adopting the alternative method of equal increments of plunger travel and a variable loading.

A dynamic test to measure resilience was developed by Robinson[7]. In this test a series of plant fibre masses were repeatedly compressed in a cylinder by means of a piston which could be raised and lowered rapidly by means of a motor-driven disc which acted in the manner of a cam against a lever connected to the piston through a chain.

Fox and Schwarz[71] devised an apparatus for the measurement of resilience and other compressional characteristics of fibres and fabrics. Their test consists of:- (1) calibrated plunger of precisely threaded steel shaft, (2) weighting lever, and (3) a low power telescope with a cross wire. There is a graduated dial of 250 divisions fitted at the top of the plunger and one division on this dial represents a plunger travel of 0.001 inch. Attached to the other end of this plunger is an interchangeable presser foot with an area of either 1 or 2 square inches. The weighting lever is provided with two knife edges, a table for the sample being tested and the counterbalancing weight. The table for the sample has two engraved circles cut on its surface possessing areas corresponding to the presser feet on the end of the plunger. A chainomatic system of loading is employed on the weighting lever. The counterbalancing weight can be used to balance the weight of the sample after it has been placed on the table for testing. The low power telescope with a cross-wire was used to establish a zero-reading for all observations.

The pressure on the sample may be applied by adding to the length of chain acting on the weighting lever arm. The lever should be kept in balance during any change in load by turning down on the plunger to compensate for the presser foot penetration into the sample. The difference in the plunger setting represents penetrations of the foot into the sample. These readings with their respective loading values give a load versus penetration plot. The cycle can be reversed when the maximum load has been reached so that the recovery of the sample can be measured at the successively decreasing loads. From the curves of load against penetration and recovery, the resilience can be computed.

Edelman[72] studied the filling power of feathers by three different methods, viz. (1) Inclined-plane compressometer, (2) Box-method, (3) Hydrostatic method.

The Inclined-plane compressometer (Scott I P 2 Model Serigraph) employed a maximum pressure of 0.22 pound per square inch on a sample of 0.04 pound enclosed in a cylinder. In case of the Box method and Hydrostatic method, the sizes of samples and the pressures used are 2 and 1 pound, and 0.0006 and 0.14 pound per square inch respectively. Of the three methods, Edelman concluded that the Box method is the best because it utilised a low pressure and much more is known about the filling power if measured at low pressures, since all the different grades of feathers approached asymptotically the same minimum filling power at high pressures. It follows that the most reliable evaluation of filling power should be obtained at the lowest test pressure and that little is to be gained by the use of higher values of compression.

Rees[73,8] developed a sensitive thickness gauge for textile materials. This instrument can be used to measure: (1) over-all specific volume, (2) compressibility, and (3) resilience of fibrous materials under a desired pressure. The gauge consists of a presser foot of 10 sq. inch area and employs a pressure range of 0.001 to 1.0 pounds per square inch. The apparatus possesses the advantages that the volume of the fibre mass may be measured directly under extremely low pressures and that errors due to friction between the fibres and the wall of the containing vessel are eliminated.

Skinkle[74] described the cylinder and plunger method for measuring the resilience of wool as follows: A 500 g sample of fibre is placed in a brass cylinder 7½ inches in diameter. A plunger is used to compress the sample and the compressed depth is measured by a vernier. The pressure is applied by an inverted jack, and the apparatus is connected to a platform scale to read the load. The resilience may be measured by the area of the hysteresis loop.

Finch[75] described an instrument to study the compressional characteristics of textile materials. It is composed of a compression mechanism and a control-recording unit. The compression chamber consists of a presser foot, the motion of which is controlled by a synchronous electric motor driving through a pair of reversing magnetic clutches. The rate at which the foot travels is controlled by change gears, which may be varied for a wide range of rates (0.01, 0.02, 0.05, 0.10, 0.20, 0.50, and 1.0 inch per minute) There is a dial gauge which reads to the nearest thousandth of an inch, the amount of penetration of the presser foot into the sample. The direction of travel of the foot is controlled by magnetic clutches. The load on the sample is measured by a sensitive resistance-wire strain gauge cantilever load cell.

Finch[75] employed a high-speed, sensitive, rectilinear, electronic recorder in conjunction with the strain gauges in an amplified and rectified A.C. Wheatstones bridge. Further, he obtained characteristic response curves under compression, for a variety of materials and illustrated the many ways in which the instrument may be used.

An apparatus to measure the compressional stress-relaxation behaviour of textile materials at a constant compression was developed by Finch[76]. In this instrument, he used a sensitive resistance-wire strain gauge cantilever weighbar and employed a deflection galvanometer in conjunction with the strain gauges in a D.C. Wheatstones bridge. Compression is applied instantaneously to the specimen and the semilog rate of stress relaxation is determined as a characteristic parameter of the behaviour of the material.

deMaCarty and Dusenbury[77] employed the Instron Tensile Tester[78] for their experiments. They developed an apparatus which is used in conjunction with the Instron tester and consists of a compressing piston with an attached weight that is suspended by appropriate linkages from the load cell. During the test, the cross-head is lifted to compress a specimen and the compressive load is measured by the amount of unloading that occurs during the test of the assembly suspended from the load cell. The specimen being tested is placed on a plate mounted on the cross-head. Fok and Finzel[79] suggested an improved piston cup assembly to be used for compression testing in conjunction with Instron tester.

Veith[80], Terasaki et al[81] used Instron tensile tester to measure the thickness of fibre mass under various pressures and evaluated different parameters to characterise the compressional behaviour of the material.

An instrument covering pressures of 0.25 to 12 lb. per square inch and measuring the thickness of pile fabrics during compression-recovery cycle is described by Anderson and Clegg[82,83]. It consists essentially of a loading shaft fitted with a circular presser foot, a dial gauge, and a shaft to prevent undue forces from being transmitted to the specimen. They also described a dynamic loading machine to assess the compressional characteristics of a carpet during wear.

Henno and Jouhet[84] developed an instrument for measuring the resilience of pile fabrics. This apparatus operates with an accuracy of 0.01 m.m. under a controlled pressure which can be varied from 1 to 100 g/cm^2 (or 0.014 to 1.41 p.s.i.).

Beste and Hoffman[29] attempted to measure the resilience of single fibres by determining tensile stress-strain curves at constant rate of extension. In order to obtain type of resilience from these curves they calculated the modulus of the linear part of the curve and the change of modulus with extension and with time, by calculating the average rate of change of compliance between 5% and 10% extension. This quantity they called the "compliance ratio" and computed it as $(10/f_{10} - 5/f_5)/_5$ where f_x is the stress at x% extension. In case the fibre breaks below 10% extension the compliance ratio was computed between 5% and the breaking extension. For breaking extensions less than 5% the compliance ratio was taken as zero since the stress-strain curve was nearly linear. The extent or degree of resilience was calculated, both as tensile elastic recovery and work recovery from constant extensions. Since the time factor is an important element in such experiment, and usually dealt with in an arbitrary way, so in this case Beste and Hoffman employed a constant rate of extension of 1% per minute, the specimen was held for 30 seconds at the maximum extension before it was allowed to retract. They calculated the extent of resilience both as (i) the ratio of the strain recovered to the strain imposed, and (ii) the ratio of the work recovered to the work absorbed by the deformed material.

2.2 Properties of Fibre Assembly

Several workers have attempted to characterise the behaviour of fibre assemblies (fibre mass, yarns and fabrics). A brief description of these researches is given.

Rees[8] studied the behaviour of fibrous materials used in bedding and upholstery, where the fibres are used in bulk. He described three important physical properties that determine their use as a bulk material as : (1) Filling capacity of the fibres, that volume occupied by a specified weight of the fibres; (2) Compressibility of the fibre mass; and (3) the ability of the mass to recover from compression.

Further, Rees[8] observed that the well opened fibres are very sensitive to changes of pressure, so that precautions must be taken in determining the initial pressure. He prepared his test specimen inside a Perspex glass cylinder. He then withdrew the cylinder and placed the prepared sample under the presser foot of the apparatus. By this method, he improved the accuracy of his tests because the effect of friction between the fibres and the wall of the container was eliminated.

Rees[8] found that the resilience of wool, silk and nylon is higher than that of the cellulose fibres.

Schofield[85] conducted a number of compressibility tests on wool and concluded that bulk fibre does not wholly elastically reverse the deformation. There is a decrease in volume after the wool is subjected to pressure.

Mutschler[86] measured the "compressed volume" and "relaxed volume" and calculated the bulk elasticity from the following formula:

$$E\% = \frac{K(V_e - V_d)\ 100}{V_e}$$ where V_e = relaxed volume, V_d = compressed volume and K = constant.

He compared wool, cotton and staple rayon and found that wool has the highest elastic volume. He made measurements at 20 points from the bale all the way to ring spinning. Maximum volume is reached at the card, it then decreases with each passage through drawing frames, fly frames, etc.

Fox and Schwarz[87] suggested that when testing bulk fibres, the conditions of the stock as to cleanliness or state of aggregation should be considered. Wool in the grease is quite different from scoured wool from the dryer or after further processing. Cotton from a new bale will exhibit different properties from cotton as delivered from a picker. Further, he stated that the quality of wool and staple length affect the compressional properties.

Burns and Johnston[88] observed differences in fibre springiness within and between grades. This they thought was a factor tending to interfere with the compressional method of yield estimation. They also found that the packing of the compression cylinder was a variable factor. They noticed that variations in the physical characters had some influence on the density of the raw wool.

It has been pointed out by Finch[76] that one of the most important considerations in a compression test is the preparation of the specimen for testing. If the fibre mass consists partially of matted and partially of loose fibre, the relaxation rate will be a reflection of both of these conditions. It is necessary, therefore, to have the fibrous mass as homogeneous throughout as possible. This, he stated, may be accomplished either by opening the material on a power-driven laboratory-card or by opening it with hand cards. Either method is satisfactory, the former being more conducive to obtaining a large sample from which the test specimens may be selected.

Beckwith and Barach[89] discussed the resilience of pile floor coverings and stated that some wools when walked on in carpet form flatten down readily and the portions of the pile lay in different directions, causing unattractive light-reflection patterns. This spoils the appearance of the fabric surface by giving it a "mangy" or "scraggly" appearance. Other wools do not crush as much; their surface is uniform and pleasing in appearance, with the pile laying in one direction. They suggested that the ability of the carpet pile fibres to resist the distorting effects of traffic could be evaluated by measuring their resilience, which can be considered as the ratio of work returned upon release of a compressional load to the total work done in compressing.

The reaction of fibres to high compressive forces has been the subject of study by Busse[90] and Kolb et al[91]. They noticed that the recoveries of fibres from bulk compression tests appear to depend, in part, upon the bulk properties of the fibres such as elasticity, plastic flow, and the strength and ultimate elongation for tensile, compression and shear stresses. It may also depend upon the surface properties of the fibres such as coefficient of friction and adhesion or tackiness, or tendency of the fibres to weld together when sliding past one another under pressure.

Further, they found that under pressure of 10,000 and 100,000 pounds per square inch fibres such Dacron, Saran, Nylon, Orlon, rayons and wool behaved very differently and it is clear that stressing beyond the elastic limit and breaking strength is the main reason for poor fibre recovery, surface adhesion and structural factor being secondary.

Weir[92] studied the general response of leather, cellulose, wool and silk fibroin to compression and found that it is virtually independent of moisture content, whereas, at high regains, moisture exerts a marked effect. The results are in good accord with the concept that the moisture exists in hydrogen bonded form at low, and as liquid water at high, moisture content.

Van Wyk[93] studied the compressibility of wool fibres and defined "resistance to compression" as:-

$$r = \frac{K\ Y\ m^3}{\rho^3}$$

Where K is a constant, Y = Young's modulus, m = mass of fibres, and ρ = density of wool. He stated that it is essential the wool be teased out as thoroughly as possible, so as to ensure random orientation of the fibres, for the presence of lumps has been found to raise the resistance to compression by as much as 32 per cent.

Further, Van Wyk found a significant correlation coefficient of 0.55 between the resistance to compression and number of crimps per unit length and a partial correlation of 0.43 between the resistance to compression and fibre diameter. He suggested that crimping may have a direct effect on the relationship of resistance to compression and found indirect evidence to suggest that the number of crimps per unit stretched length is a more relevant quantity than the normal staple length.

An evaluation of the bulk compression characteristics of widely different wool samples was performed by deMaCarty and Dusenbury[77]. They suggested that the compressive load (i.e. the load measured at certain fixed compressions of an initially strain free sample), rather than resilience provided a better measure of differences among wool samples. It means that quality differences in wools are related to differences in their resistance to compression rather than to differences in compressional resilience.

Further, they found an inverse relationship between the compressive load and the mean fibre diameter. It indicates that such measurements reflect a co-operative property of the entire fibre assembly rather than the properties of the individual fibres such as the bending or extensional moduli of elasticity.

When the compressing piston size is varied at a constant sample size for a Targhee 60's wool card sliver, deMaCarty and Dusenbury found that the effective volume of fibres being compressed is greater than the volume of fibres directly beneath the piston. It may probably be due to fibre-to-fibre entanglements. They concluded that a constant area should be added to the compressing piston areas in order to achieve a constant compressive stress. This area increment is independent of sample diameter, providing the sample diameter is sufficiently greater than that of the compressing piston, and this area increment decreases with increasing degree of compression.

Demiruren and Burns[48] tried to assess the basic fibre properties which affect the compressional bulk resilience of wool. They also studied the relationship of these fibre properties to maximum load or stiffness. Investigations were carried out in relation to 6 inherent fibre properties, viz. - tensile strength, fibre length, fibre thickness, contour, crimp - length to depth ratio, and crimp depth. They found that 31% of the variation in resilience can be accounted for by the variation in the six fibre properties measured, and in case of maximum load these fibre properties were responsible for 85% of the variations. In both cases, the most important property was tensile strength. It accounted for 18% of the variations in the resilience and 66% of the variations in the case of maximum load. They also showed that the shape or contour of the fibre and crimp were important measurable qualities affecting the bulk resilience. In the case of maximum load the two important factors besides tensile strength were fibre length and crimp. In both resilience and maximum load, fibre thickness or fineness was a less important factor. Further, they observed that both resilience and maximum load varies within wool types. Resilience is lowest in the fine wools and highest in the medium wools, with long wools intermediate. Maximum load is highest in fine wools, lowest in long wools and intermediate in the medium wools.

Demiruren and Burns concluded clearly that since only 31% of the variation in compressional bulk resilience of wool can be accounted for by the variations in the six fibre characteristics, therefore, most of the variations in resilience must be due to physical (molecular) structure and other factors.

Fok and Finzel[79] reported that a comparison of resilience when compressed to a fixed pressure and then made to recover does not agree with the result of subjective determination by handling and that it is appropriate to show the compression ratio and amount of work loss as criterion showing the difference among the various crispated fibres.

Vieth[80] obtained compressional characteristic values for 8 different kinds of fibres and concluded that it is difficult to compare compressional characteristics with one value (parameter) only and that maximum load, easiness of compression and compressional elasticity should be considered as compressional characteristic values.

Takikawa and Kawamura[94] carried out compression experiments on various fibres and suggested that it is necessary to consider compression energy, resilience, and fatigue ratio in order to characterise the compression behaviour of the fibres. Also they defined a new term - "Compressional Index" and claimed that it shows a good agreement with the evaluation by handling.

Winson[6] found that the resilience of a mass of fibres increases as the staple length decreases.

Saxl[95] found that in the case of dry rayon flock, a high denier fibre is harder to compress and recovers to a greater extent than a lower denier.

Kolb *et al*[91] reported that compressional recovery of Dacron is not dependent on denier.

Busse[90] and Kolb *et al*[91] noted that lubricating the surface of the fibre had little effect on recovery from compression to very high pressure.

2.3 Mathematical Expressions for Compression data

Considerable work has been reported to describe compressional behaviour of textile materials both from empirical and theoretical considerations. The most important of these studies are summarised briefly.

M. and J. Eggert[96] fitted the following equation to their compression curve of wool,

$$\left(\frac{v}{v_o}\right)^{ao}(P + Po) \quad = \quad Po$$

where v_o is the initial volume, while P_o is termed the "latent pressure" of wool at zero applied pressure. The quantity P_o is regarded as a measure of softness, and the index a_o as a measure of pliability.

The Eggert's equation suffers from some disadvantages. The two coefficient P_o and a_o are extremely sensitive to experimental errors, and depend on the observed value of v_o, a quantity which is hardly reproducible and does not appear to fit in with observations at high pressures, where the density of packing is more uniform.

Van Wyk[93] derived an equation to represent the compressibility of a mass of wool fibres and it is,

$$P = \frac{KYm^3}{\rho^3}\left(\frac{1}{v^3} - \frac{1}{v_o^3}\right)$$

where m is the mass, ρ is the density (1.30 gm/c.c.) of wool, Y is Young's modulus of elasticity and K is a constant, while P and v are pressure and volume respectively.

The above relationship between pressure and volume of mass of wool fibres is derived on the assumption that the compression of the mass consists solely of bending of fibres. Twisting, slippage, and extension of fibres are ignored, and consideration is given to the number of times the fibre would come in contact with other in compression. It is also assumed that the fibres are oriented at random, and the mass of fibres is uniformly packed and that frictional forces are negligible.

It is to be noted that Van Wyk's equation predicts that the compressive load is independent of both fibre diameter and fibre length. This equation can be reduced to a relationship in which the pressure varies with the inverse cube of volume. He obtained data on three Merino wool samples which appeared to satisfy this relationship.

Further, it is observed that both Eggert's and Van Wyk's equations are linear with respect to P and $\frac{1}{v^a}$ for a given mass of fibres. In case of Van Wyk's equation a = 3.

Matsushima and Matsuo[97] measured the pressure-deformation curves for blankets and carded fibre mass. These curves fit in the equation;

$$P = ae^{bx}$$

where P is pressure, x is deformation and 'a' and 'b' are constants.

Applying a model which consists of m(x) springs in series and n(x) serial springs in parallel to samples they derived the pressure-deformation equations.

Continuing the theme of the earlier publication, Matsuo[98] derived some more theoretical expressions to describe the compressional recovery of fibre mass (carded fibre mass and blankets). In these derivations, he considered the rheological character of bent fibres and the friction between them. The compressional resilience (R) is defined as:

$$R = \frac{\text{the work of 2nd compression to maximum pressure Pm}}{\text{the work of 1st compression to maximum pressure Pm}}$$

Further, Matsuo deduced the following equations from his pressure - deformation curve :

$$R = \left(\frac{n_1}{n_2}\right)^{\theta} \frac{g_1}{g_2}$$

where 'n_1' and 'n_2' are 'n' and 'g_1' and 'g_2' are 'g' in first and second compression respectively, and $\theta = 3$ (constant), 'g' is the coefficient of bending fibres rigidity. These results were analysed in terms of a model which consists of 'm' spring in series and the 'n' serial springs in parallel, where 'n' and 'm' depend on the deformation 'x'. The entanglements of fibres in the 1st compression causes the increase of 'n' from 'n_1' to 'n_2'.

Larose[99] performed compression tests on number of fabrics, viz., single and double pile fabrics, overcoatings, felts, and knitted fabrics.

He found that within the range of pressures used (0.1 to 1.0 p.s.i.), the results are well represented by the equation

$$T_o - T_p = a^1 \log P$$

where 'T_o' is the thickness at a pressure of 1.0 p.s.i., 'T_p' is the thickness at pressure 'P', and a^1 is a constant for any one particular fabric. This relationship was found to hold fairly well for pressures of 0.1 to 1.0 p.s.i. or more for all types of fabrics tested. It failed, however, to represent the behaviour of wool or cotton batting.

The equation suggested by Larose is purely empirical and does not appear to be suitable for very loose materials, since it failed to represent the compressibility of wool or cotton batting. Also it can only be applied to a limited range of pressures.

The equation:

$$P = K\ (T_o - T_p)^{\alpha}$$

where K, T_o, and α are constants and T_p is the thickness at pressure P, has been claimed by Hoffman and Beste[100] to fit their data quite well, α having a value of about 5/4 at low pressures and about 3 at high pressures. The value of α , however, depends on the value chosen for 'T_o' and the shape of the curve (pressure - thickness) does not change appreciably when 'T_o' is varied over a wide range of values.

Hoffman and Beste's equation is also empirical and of limited application, since the coefficient α at low pressures is different from that at high pressures.

Bogaty *et al*[101] proposed the following equation to express thickness - pressure relationship of fabrics.

$$(P + c)(T - a) = b$$

In this equation, 'a', 'b' and 'c' are constants. Bogaty *et al* chose 0.05 p.s.i. for the value of 'c' and the thickness under a pressure of 2.0 p.s.i. for the value of 'a'. The value of 'b' is a characteristic of the sample. These authors found that the results obtained at low pressures up to 0.1 p.s.i. were fairly well represented by such an equation, but at higher pressures the relationship does not hold so well.

The equation of Bogaty *et al* is again an empirical one, and it does not represent compressibility over a wide range of pressures unless the constants 'c' and 'a' are given different values for each sample. These values have to be determined by a process of trial and error in order to obtain an equation which satisfies a wide range of pressures. Therefore, the usefulness of the equation is reduced.

The most widely used correlation for graphical treatment of fibre mass compression data is the empirical compressibility equation

$$T = X P^Z$$

where T is the thickness of fibre mass sample, P is the applied pressure and X and Z are constants, depending upon the material and the test specimen.

Terasaki *et al*[81] expressed his results by the above compressibility equation for viscose rayon pads under various pressures.

CHAPTER II

EXPERIMENTAL

CONTENTS

CHAPTER II

EXPERIMENTAL

1. INTRODUCTION

The survey of various methods and instruments employed by different workers in their investigations, indicate that there have been as many test methods as the number of investigators, and each one has designed to fulfil one's own requirements. In general, however, these methods can be classified into two categories:

(i) Methods based on maximum pressure, that is, the specimen is compressed to a maximum pressure or load.

(ii) Methods based on fixed compression ratio. Here the specimen is compressed until a fixed predetermined compression ratio is attained.

Rees[8], Fok and Finzel[79] and Takikawa and Kawamura[94] used the first method while Demiruren and Burns[48], deMaCarty and Dusenbury[77] and Vieth[80] performed experiments based on second group.

The instrument (Shirley Thickness Gauge) used for this research is the same as used by Rees[8] for the measurement of overall specific volume of Kapok. This method belongs to the first group and has the following advantages over the methods falling within the second group.

The thickness of the specimen must be accurately known in order to maintain a constant compression ratio, and since the fibre mass is very sensitive to pressure changes in the low pressure-thickness region of the curve, it becomes very difficult to decide which point should be taken as original thickness. It can be easily visualised that in the methods based on a fixed compression ratio, the initial thickness always will have to be set at a fixed gauge length irrespective of the difference in the bulkiness of each specimen of fibres, and is compressed up to a fixed distance from there. This will, therefore, mean that some specimens would be tested under the condition of almost no load position, whereas in case of some bulky specimens the measurements would be made after it has already been compressed considerably. On the other hand, in the instrument based on maximum pressure, all fibre masses are compressed up to a constant maximum pressure from a no load position.

Further, Rees's[8] instrument simulates the practical end-use conditions under which a fibre mass is used as fibrefill in pillows in which the load is defined rather than the deformation. Also, it possesses the advantage that the thickness of the fibre mass may be measured directly under extremely low pressures.

2. MATERIALS

In the present study Acrilan, Terylene and Tricel fibres were used. Acrilan fibres were supplied by Chemstrand Ltd., Terylene was obtained from I.C.I., and Tricel from British Celanese Ltd. The fibres possessed different properties, as is indicated in the following Tables.

TABLE Ia

Acrilan

Code No.	Description		
	Length (inch)	Fineness (denier)	Type
A 1	2	3	Type 16, semi-dull, normal crimp
A 2	2	3	" "
A 3	2	8	" "
A 4	2	2	" "
A 5	2	5	" "
A 6	2	15	" "
A 7	$1^9/16$	2	" "
A 8	$1^9/16$	5	" "
A 9	$1^9/16$	15	" "
A 10	2	3	Type 16, semi-dull, no crimp
A 11	2	5	" "
A 12	2	8	" "
A 13	2½	5½	Experimental Type, chemically crimped

TABLE Ib

Terylene

Code No.	Description		
	Length (inch)	Fineness (denier)	Type
P 1	1½	1½	Cotton type, normal crimp
P 2	1½	3	" " "
P 3	1½	3	Filling type, normal crimp
P 4	2¼	3	" " "
P 5	2½	4	Flax type, normal crimp
P 6	2½	3	Wool type, normal crimp
P 7	3½	6	" " "
P 8	4½	10	" " "

TABLE Ic

Tricel

Code No.	Description		
	Length (inch)	Fineness (denier)	Type
T 1	2	3	Semi-matt, normal crimp
T 2	2	8	" " " "
T 3	2½	4½	" " " "
T 4	5	4½	" " " "

2.1 Method of Specimen Preparation

The resilience of a fibremass depends upon the manner in which the specimen is prepared. As is evident from the literature, while preparing test specimens for such studies it is essential to ensure that the fibremass is fully open and that the fibres are uniformly and randomly distributed. Also, in order to compare the characteristics of different fibres, the density of such specimens is maintained constant. The specimens for the measurement of resilience were prepared as follows:-

The fibres were opened on a Shirley Miniature power-driven card. The carding may have introduced a certain degree of preferred orientation.* Its effect, however, has been neglected here. A Shirley static eliminator was used to facilitate processing in certain cases, notably Terylene. From such laps, squared specimens of the required weight and dimensions were cut and tested. All specimens were prepared in this way, except when specimens of different thicknesses were made: in those cases, two or more layers of laps of similar nature were placed on top of each other. Results obtained from these specimens were reproducible and thus justified the method of preparation.

It should be remarked that in some cases the same specimens were required for testing again and in such instances, sufficient time (24 hrs. or more) was given in between the tests to ensure sufficient recovery from the previous compressions.

* See page 45(a)

Although the Shirley Miniature Card may be assumed to produce an open and uniform web of fibres, it is observed that the fibres tend to be aligned in the direction of rotation of the collecting drum. The effect of this slight orientation of fibres in a specimen is neglected because the fibrefill is often prepared on a large scale carding machine and this is likely to introduce the same type of fibre orientation as that produced by the Shirley Miniature Card, so that tests made on specimens prepared on the small machine should behave in a similar manner to most of the fibrefill prepared on an industrial machine, at least from the point of view of any influence that fibre orientation may have.

The method used to prepare the test specimens is as follows: Fibres were passed through the Shirley Miniature Card. The out coming web of fibres was collected on a rotating drum of the same length as the width of the fibre web from the miniature card. Some 25 to 30 layers of such fibre web were deposited one after another on the drum to form a uniform lap about 2 inches thick. This was then cut in a direction parallel to the axis of the drum and a lap of linear dimensions 10" x 35" approximately was obtained. From such laps the test specimens of required area were taken. Each specimen was weighed and its mass was adjusted to a constant value either by removing or adding one or more fibre web layers. From the results of resilience measurements on specimens of different thickness (p.74), it is not expected that the adjustment of specimen thickness in this way will alter the measured value of resilience.

3. APPARATUS

The Shirley Thickness Gauge (see Fig. 2) consists of a presser foot which rests on the specimen. This foot is secured to the lower end of the precision ground stainless steel stem which is constrained to move vertically in relation to the base and is suspended at its upper end by a flexible steel strip. The strip passes almost completely round the circumference of a cylinder and its end is secured under a clamping plate. The weight of the stem and the foot is counter-balanced by a weight fastened to a second strip which passes round the same cylinder in the opposite direction to the first. Movement of the foot upwards or downwards causes the cylinder to rotate through an angle proportional to the movement of the foot. The movement is magnified in the ratio of the pointer radius to that of the cylinder giving a scale in which each small division approximately 1/16 inch long, represents 5/1000 inch of foot movement.

The gauge covers a range in thickness of 2 inches and it is accurate to 1/1000 inch. Normally it is set to commence at zero thickness but by raising the measuring head until zero corresponds to a minimum thickness of one inch thickness up to 3 inch thick are accommodated.

A set of disc weights covering 0.01 pound to 10 pounds and a measuring presser foot of area 10 square inches enables measurements to be made at pressures which may be varied between 0.001 p.s.i. (pound per square inch) to 1.00 p.s.i.

Fig. 2. Shirley Thickness Gauge.

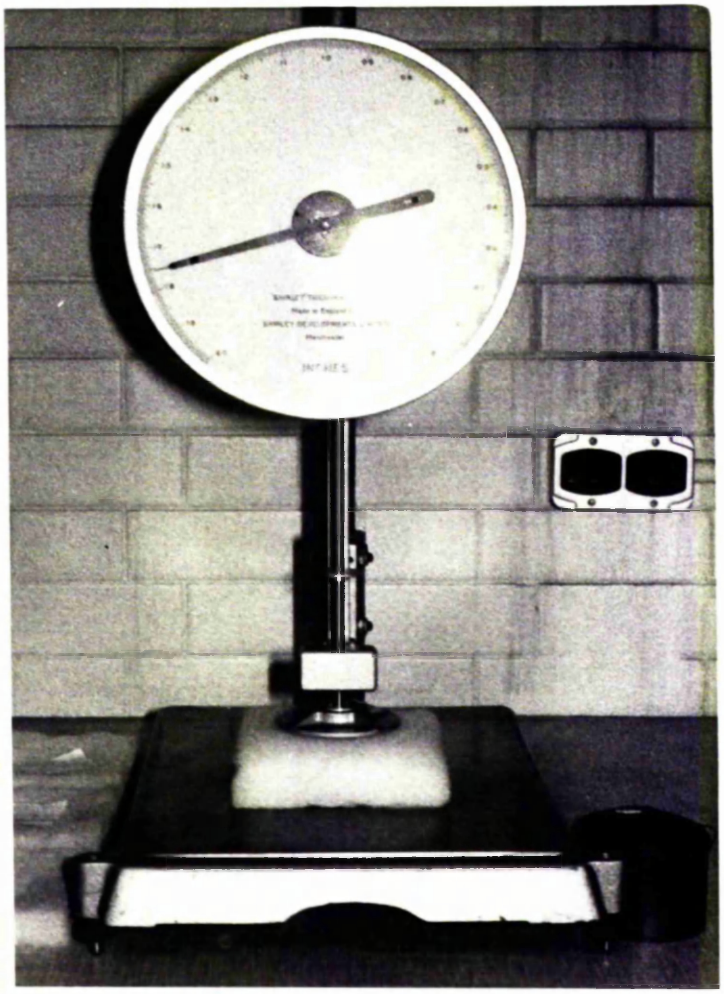


Fig.3. Movable Platform mounted on the thickness gauge.

3.1 Modifications

In the present work the apparatus described was modified to carry out investigations with the presser foot of varying sizes and shapes, and on specimens of different thicknesses and areas.

Two extra aluminium feet of areas 5 and 20 sq. in. were made to assess the influence of size, the standard foot being 10 sq. in. A third foot was constructed, its surface was hemispherical and the maximum diameter corresponded to that of the standard foot. This modification enabled to study the effect of shape of presser foot. Further, a movable platform (Teflon board) of 10 x 10 sq. in. area was attached to the base of the instrument and its measuring head was raised to the required height in order to investigate specimens of varying thicknesses and areas. Figure 3 shows the movable platform mounted on the thickness gauge and a specimen of 4 inch thickness being tested for resilience under a hemispherical foot.

3.2 Method of Test

First of all the base of the thickness gauge was set with the help of the levelling screws provided and then the height of the measuring head was adjusted according to the thickness of the specimen. The pointer was set to the zero mark on the dial by rotating the dial. Then, the specimen, prepared according to necessary specifications, was placed carefully underneath the presser foot of the apparatus. The foot was manually moved downwards until it was just in contact with the specimen, and then it was loaded with a maximum load (usually 10 pounds) in order to exert a maximum pressure which depended on the size of the presser foot. The fibres were compressed for a period of 10 seconds under the maximum pressure and then were allowed to recover for one minute under no load. This was done to obtain a definite starting point since the initial thickness of fibremass would depend upon the position of fibres in the specimen. This also provided a "mechanical conditioning" of the specimens.

In a resilience test, the fibremass was loaded and unloaded between 0.001 to 1.0 p.s.i. in a cyclic manner, great care was taken while adding (or removing) the weights by hand, in order to avoid sudden compression (or recovery) of a mass of fibres. This was done as shown in Table II.

Since the thickness of a mass of loose fibres decreases rapidly with increasing pressure in the region of low pressures, the weights were chosen so that a number of observations could be made in this region. The characteristic values for each type of fibre indicate greater differences at low pressures than at high pressures.

The pressure-thickness curves were drawn on graph paper indicating compression recovery behaviour of fibres for first, third and fifth cycles, that is, between 0.001 to 0.01, 0.001 to 0.10, and 0.001 to 1.00 p.s.i. respectively. Resilience was then calculated both as the ratio of energies and thicknesses at 0.001 p.s.i. The areas under the pressure-thickness curves were measured by means of a Polar Planimeter. Figure 4 illustrates a typical curve obtained from the thickness gauge during measurement of resilience. Three specimens were tested for resilience at each condition and the mean value was calculated.

TABLE II

Cycle 1	Pressure:	0.001	0.004	0.01	0.004	0.001	0.0	p.s.i.					
	Time:	10"	10"	10"	1'	2'	5'						
Cycle 2	Pressure:	0.001	0.004	0.01	0.025	0.01	0.001	0.0	p.s.i.				
	Time:	10"	10"	10"	10"	2'	5'	10'					
Cycle 3	Pressure:	0.001	0.004	0.01	0.025	0.10	0.05	0.01	0.001	0.0	p.s.i.		
	Time:	10"	10"	10"	10"	10"	1'	2'	5'	10'			
Cycle 4	Pressure:	0.001	0.004	0.01	0.10	0.40	0.10	0.01	0.001	0.0	p.s.i.		
	Time:	10"	10"	10"	10"	10"	2'	5'	10'	20'			
Cycle 5	Pressure:	0.001	0.004	0.01	0.10	0.40	1.0	0.40	0.10	0.01	0.001	0.0	p.s.i.
	Time:	10"	10"	10"	10"	10"	10"	1'	2'	5'	10'	20'	

4. EVALUATION OF TEST CONDITIONS

It is evident from the literature that there seems to be some confusion as regards the conditions under which the resilience of fibremasses should be determined. It has already been mentioned (cf. introduction) that it was essential to evaluate the proper conditions to study and to characterise the resilience of fibres in bulk. All experiments were performed in a room controlled at 20°C and at 65% r.h.

The effect of (i) area of specimen using a constant area presser foot (ii) thickness of the specimen (iii) size of presser foot (iv) shape of presser foot and (v) maximum pressure in any cycle, was investigated on Acrilan fibres of Type 16, normal quality (2", 3d).

Since the fibres are viscoelastic materials, the effect of the time cycle was first investigated in a resilience test. The main aim of it was to find whether the resilience measured with short loading and recovery times was the same as that measured with longer loading and recovery times, the ratio of recovery time to time under load being the same for the short and longer time tests.

4.1. Effect of Time Cycle

The resilience tests were made using a specimen of constant area (5.5 x 5.5 sq. in.) and weight (5g.) under the standard foot (10 sq. in.) in order to study the various time cycles. Four combinations of time cycles were employed, viz.:- compression for 12 seconds, 1 minute, 1 hour and 5 hours with recovery for times of 1 minute, 5 minutes, 5 hours and 24 hours respectively.

In service, fibrefill used in pillows will be subjected to a constant load for about 8 hours with 16 hours under no load. Loading and recovery cycles of such duration would be time consuming in the laboratory. Experiments were therefore made to see whether the measured resilience was the same for short duration cycles as for long duration cycles with the condition that in both types of test the ratio of recovery time to loading time was kept constant.

It should be noted at this stage that for this particular experiment the specimen was subjected to one complete cycle of pressure changes from a minimum to a maximum value (0.001 to 1.00 p.s.i.) and then decreased gradually in the reverse order to the initial value. The changes in pressure were made at an interval of 1 minute each. The compressed mass of fibres was held under a maximum load for a definite period of time and on reaching the initial pressure these fibres were allowed to recover according to definite recovery time.

4.2 <u>Effect of Maximum Pressure</u>

The next stage of this research was to investigate the influence of (a) pressure at which the resilience was measured and (b) the maximum pressure used in a compression-recovery cycle. In the first instance, the following cycle (Table IIa) of loading - unloading was used, each change in pressure being made at an interval of one minute.

TABLE IIIa

Cycle No.	Pressures in lbs/sq. inch
1.	0.001, 0.01, 0.001
2.	0.001, 0.025, 0.01, 0.001
3.	0.001, 0.05, 0.025, 0.01, 0.001
4.	0.001, 0.10, 0.05, 0.025, 0.01, 0.001
5.	0.001, 0.20, 0.10, 0.05, 0.025, 0.01, 0.001
6.	0.001, 0.40, 0.20, 0.10, 0.05, 0.025, 0.01, 0.001
7.	0.001, 0.60, 0.40, 0.20, 0.10, 0.05, 0.025, 0.01, 0.001
8.	0.001, 0.80, 0.60, 0.40, 0.20, 0.10, 0.05, 0.025, 0.01, 0.001
9.	0.001, 1.0, 0.80, 0.60, 0.40, 0.20, 0.10, 0.05, 0.025, 0.01, 0.001

Three specimens of 5.5 x 5.5 in. sq. area with their weights determined were prepared so as to keep the weight per unit area the same for each test. Thicknesses measured under various loads were plotted against $\log_{10}$ (pressure) (Fig. 9) and resiliences were calculated as a ratio of two thicknesses at 0.001, 0.01, 0.025, 0.05, 0.10, 0.20, 0.40, 0.60, 0.80 and 1.0 p.s.i. (Table V). Since the changes in pressures, particularly in the low load region, were very small, the resilience was plotted against the logarithm of the pressure.

A second set of experiments was performed to cover the low load region only. The load-recovery cycle was modified as follows:-

TABLE IIIb

Cycle No.	Pressures (p.s.i.)
1.	0.001, 0.004, 0.001
2.	0.001, 0.01, 0.004, 0.001
3.	0.001, 0.025, 0.01, 0.004, 0.001
4.	0.001, 0.05, 0.025, 0.01, 0.004, 0.001
5.	0.001, 0.10, 0.05, 0.025, 0.01, 0.004, 0.001
6.	0.001, 0.20, 0.10, 0.05, 0.025, 0.01, 0.004, 0.001
7.	0.001, 0.40, 0.20, 0.10, 0.05, 0.025, 0.01, 0.004, 0.001

As before, the resilience was calculated as the ratio of two thicknesses, but this time it was only computed at 0.001, 0.01 and 0.10 pressures.

4.3 Effect of Area and Thickness of Specimen

The influence of varying conditions of test specimen preparation was investigated. The experiments were performed under a constant area presser foot (10 sq. in.) and the standardised pressure-time cycle (Table II) was employed during compression-recovery of fibremass.

Experiments were made to study the effect of (a) the area of specimen and (b) the thickness of the specimen. In both cases the weights of the specimens were determined and the weights of all specimens adjusted to a constant value.

The effect of the area of specimen was investigated using four areas of specimens, the smallest area being equal to that of the presser foot size. The areas selected were 3.6 x 3.6, 4.5 x 4.5, 5.5 x 5.5 and 7.5 x 7.5 inches square and thus covered a fairly wide range.

The effect of the specimen thickness was investigated on 1, 2, 3 and 4 in. thick specimens of known weights. These experiments were carried out on a constant specimen area being 5.5 x 5.5 square in. and under a constant area presser foot. Since the Thickness gauge in its normal use can only accommodate specimens of not more than 2 in. thickness, therefore, a movable platform (Fig. 3) which can be moved vertically was used in conjunction with the gauge and the specimens were placed on this platform during resilience tests.

4.4 Effect of Size and Shape of Presser Foot

To investigate the effect of the size of the presser foot, experiments were performed with a circular foot of 2.52, 3.57, and 5.05 inch diameter so as to obtain a plane surface of 5, 10 (standard foot) and 20 sq. in. area respectively. In these experiments specimens of 5.5 x 5.5 square inch in area and approximately 4 in. thickness were tested. The weights of all the specimens were noted to maintain the density of the fibremass the same throughout.

So far all the tests were carried out using the presser foot of plane compressing surface. Under these conditions it is believed that most of the fibres in a mass are compressed under a constant pressure. It would, however, be interesting to perform experiments in which the fibremass is subjected to compression - recovery cycles employing a presser foot of non-plane compressing surface. For making such tests, a fourth presser foot having a hemispherical compressing surface and with the maximum diameter equal to that of standard foot (i.e. 10 sq. inch area), was made. Resilience tests were made on specimens of known weight and of 5.5 x 5.5 square inch area and approximately 4 inch in thickness, placed on the movable platform under the appropriate foot.

5. PROPERTIES AFFECTING RESILIENCE

After standardising the test conditions, the factors which are involved in the resilience of fibres were investigated. It was believed that the following fibre properties may affect the resilience of any given kind of fibre:

(1) Fibre length (2) Linear density (3) Crimp
(4) Friction (5) Elastic recovery (6) Modulus

5.1 Staple length

The staple length of all the fibres (Table VIII) was determined in the course of the present research. The average length determinations were carried out according to B.S. 3697; 1963, as outlined in British Standard Hand Book No.11[102]. This specification deals with the measurement of the length of an individual fibre. The length measured is the length of the straightened fibre when the crimp is removed. It employs manual straightening of the crimped fibre against a scale on a velvet pile cloth board.

The number of fibres tested for the length measurements was 100 in the present work and the mean of these values was calculated to obtain the average fibre length.

5.2 Linear Density

The measurements of linear density (mass per unit length expressed in denier) were made in accordance with B.S. 2016; 1961 specification[103]. According to this method, the individual fibre of known straight length is weighed accurately on a microbalance.

As described above, the staple length determinations were performed on 100 fibres from each sample, the same fibres (whose length is known) were weighed on a microbalance and the linear density (in denier) for each fibre was calculated as follows:-

$$900,000 \quad x \quad \frac{W}{L}$$

where 'W' is the weight in mgs. and 'L' is the length in cm. of a fibre.

The average was calculated from the values of these measurements (Table VIII).

5.3 Crimp

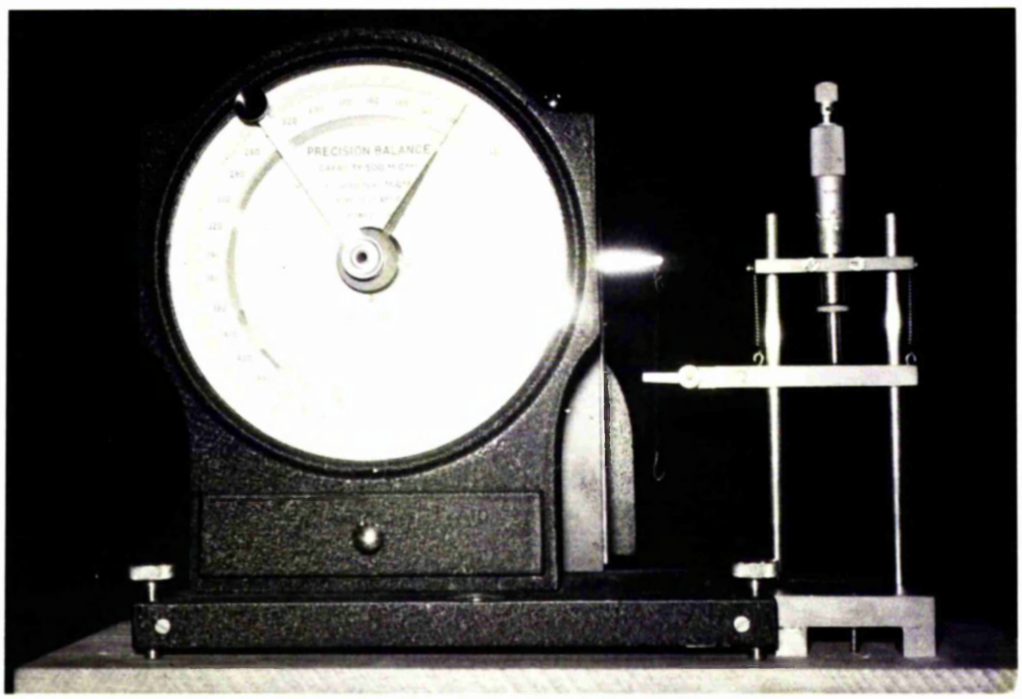
The form of fibre, i.e. the crimp, is one of the important parameters which has to be evaluated in the quantitative assessment of resilience of a fibremass. Crimp itself is a complex property and has been studied by a number of workers who used different techniques and apparatus. In the present work, the percentage crimp (defined as the ratio of increase in length on straightening expressed as a percentage of the original crimped length) was determined by a simple apparatus which was constructed in the Workshop. This method is, however, based on a test developed by Chemstrand Limited[104].

Apparatus

The apparatus for crimp measurement consists of a torsion balance, a micrometer head to measure the crimp extension of a fibre, a hook and a clamp to hold the fibres. The complete unit is shown in Fig. 5.

To measure the crimp, the fibre of a known length (1 in.) was held between the arm of the balance (by means of hook) and the clamp which is moved vertically up or down through the micrometer by hand. The movement of the lower grip determined the extension of a fibre and was measured accurately

Fig.5. Crimp Tester



by means of the micrometer. The torsion balance was required to apply a known specific stress to the fibre under which its crimp was to be determined. The length of the fibre between the grips was usually measured by a cathetometer. Initially, in this test, it was required to apply a very small pre-tension load to mount the fibre in position.

Procedure

The fibre was placed in position between the grips under a pre-tension load of 0.0055 g/d. The original length of the fibre between the grips was measured by means of a cathetometer and was 1 in. approximately for all fibres. At this stage, the micrometer reading was noted. The zero of the balance was adjusted and thus the pre-tension load was compensated for. A load equal to 0.025 g/d was applied to the fibre by moving the handle of the balance. The micrometer was rotated downwards until the pointer of the balance returned to zero. The micrometer reading was taken again. The difference between the first and second micrometer reading gave the fibre extension under 0.025 g/d load. The same procedure was repeated using a load of 0.050 g/d. The data were used to calculate the percent crimp.

Principle of Test Method

Girard[38] pointed out that when a crimped fibre is stretched, the curve (load - extension) obtained is composed of three sections. One is attributed to the crimp and is concave upwards. The straight portion of the curve was attributed to the elastic properties of the fibre, while the third section of the curve represented the yielding of the fibre (Fig. 6a). Girard also found that the load - elongation curve of fibre crimp (i.e. first section) could be described by an hyperbola (Fig. 6b) of the equation

$$Y = \frac{X}{AX + B}$$

This is the basic equation of the crimp curve in which

Y = fibre crimp extension

X = force to extend crimp 'Y' units

A and B = constants which are specific for the fibre sample tested.

These constants were determined from the data obtained with the apparatus (described above) in order to calculate percent crimp, and other crimp parameters.

<u>Calculations</u>

Let crimp extensions be Y_1 and Y_2 as measured under loads of X_1 = 0.025 g/d and X_2 = 0.050 g/d respectively. Under these conditions $X_2 = 2\ X_1$. Substitution of these values in the crimp equation:

$$Y = \frac{X}{AX + B} \qquad \text{.... (1)}$$

and by solving simultaneously 'A' and 'B' are obtained in terms of Y_1 and Y_2. The values are as follows:-

$$A = \frac{2\ Y_1 - Y_2}{Y_1 Y_2} \quad \text{inch}^{-1}$$

$$\text{and } B = \frac{0.050\,(Y_2 - Y_1)}{Y_1 Y_2} \text{ gms/denier - inch}$$

Since the hyperbola described by fibre crimp equation (1) approaches an asymptote at $Y = \frac{1}{A}$ according to Girard[38] and further, it was found that fibre crimp is essentially removed at 95% of this asymptote, therefore:-

$$\text{Crimp extension, } Y_c = \frac{0.95}{A}$$

Crimp of the fibre is the ratio of its crimp extension to its crimped length. This when multiplied by 100 is expressed as "percent crimp" and is given by :-

$$\text{Percent crimp} = \frac{95}{A}$$

since the original crimped length is one inch. This expression in terms of Y_1 and Y_2 becomes :-

$$\text{Percent crimp} = \frac{95\,Y_1\,Y_2}{2\,Y_1 - Y_2}$$

It can also be noted that the load required to extend a crimped fibre to its decrimped state is the uncrimping force and is given by the equation :-

$$\text{Uncrimping force } X_c = \frac{19B}{A}$$

This equation is derived in terms of A and B by substituting "Y_c" for "Y" and "X_c" for "X" in the crimp equation (1).

The uncrimping energy is the work required to extend a fibre from a crimped to an uncrimped state. This is given by :

$$E = \frac{2.05 \times B}{A^2} \text{ gm.inch/denier - inch of crimped fibre}$$

where E is uncrimping energy, A and B are constants and are specific for the fibre tested. These constants can be calculated as described previously.

The uncrimping energy expression is obtained by considering it as the area between the load-extension curve and the extension axis (Fig. 6c).

Experiments

The fibre crimp employing the apparatus and method described above was measured for all the fibres. From each lot, 10 fibres were tested. These were taken from the specimens prepared for the resilience tests, since the crimp in the fibres may not be the same before and after passage through the carding machine. The percent crimp, uncrimping force and energy was measured for each of 10 fibres from each test specimen (Table IX).

5.4 Friction

The coefficient of friction, defined as :-

$$\mu = \frac{F}{N}$$

where F = frictional force and N is the normal load was measured, in the present work, between two identical fibres making a single point contact and was held at right angles to each other. An instrument based on Howell's method[53] was built in the workshop for this purpose.

Friction measurements were carried out for all types of fibres. Ten fibres were tested for each sample and their mean values were calculated (Table X).

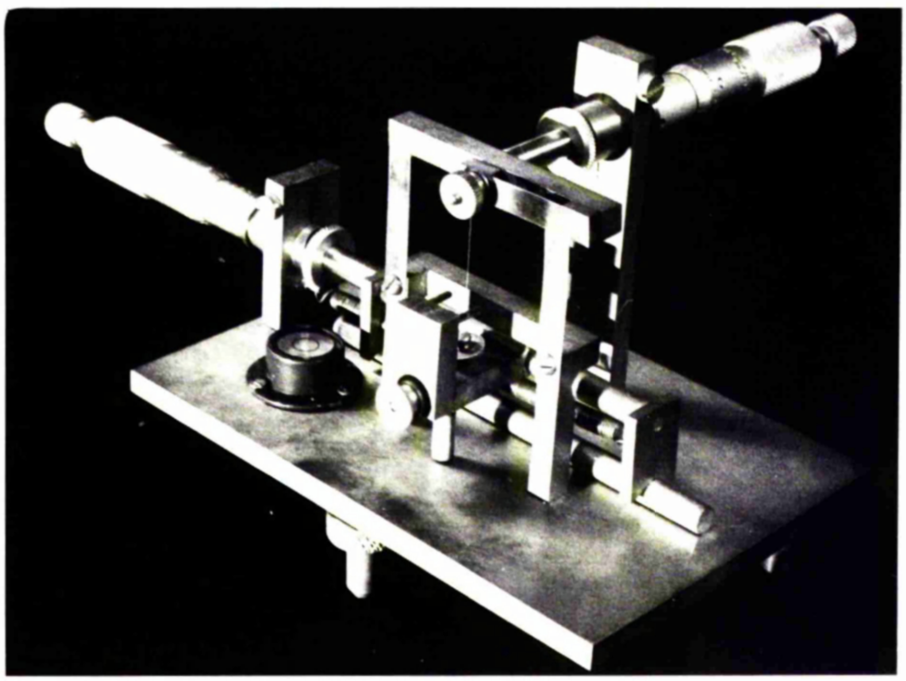
Apparatus

The apparatus for friction measurement is shown in Fig. 7. It consists of a carriage which can be moved forward and backward in the horizontal plane by means of a micrometer head. The direction of motion of this carriage is guided by a fixed rail and a coiled spring, one end of which is fixed to the side frame (near the micrometer head) and the other to the carriage. The carriage holds a fibre mounted in a frame. The other fibre is suspended from a fixed point under a constant load (1 gm). This fibre is also moved forward and backward in a horizontal plane by means of a second micrometer head, but in a direction at right angles to that of the carriage which holds the first fibre. Before the test, in its normal state, the fibres just touch each other and the micrometers are set to zero at this point. After the test, the movements of the carriage (i.e. the first fibre) and the suspended fibre correspond to the frictional force and normal load respectively.

Procedure

A fibre was suspended from a fixed point under a weight (1 gm.) After that a second identical fibre was mounted horizontally on a frame (i.e. on the carriage). Then the two fibres were brought near so as to be just in contact with each other by means of the two separate micrometers. Both the micrometer readings were noted. The vertically suspended fibre which was hanging freely under a constant weight was then deflected from its vertical position at an angle. When this position

Fig.7. Apparatus for measuring fibre-friction



was achieved, the frame was moved in a horizontal direction perpendicular to previous motion. Because of the frictional force, the freely suspended fibre would be carried along until slip takes place. Both the micrometer readings were noted again. The displacements of both the fibres from original position were obtained by taking the differences between first and second readings of the respective micrometers.

The displacement of the freely suspended vertical fibre is proportional to the normal load while the displacement of the frame is proportional to frictional force. The coefficient of friction was calculated from the ratio of these two displacement according to the definition.

5.5 Elastic Recovery

The elastic recovery of the materials from deformation may be measured by various methods. Generally, in any recovery test, it is intended either to determine the extent to which the material returns to its original shape and size or the proportion of the work of deformation which is returned. Each of these tests could be made in three ways, namely (1) in tension, (2) in torsion, or (3) in bending.

Experimental Method

In this work, the tensile elastic recovery of fibres was measured on an Instron tester employing a constant rate of extension and contraction. Figure 8 illustrates a typical trace. This method deals with the extension of the fibre by a selected amount OL which gives the stress-extension curve OA. The fibre is held at the extension for a given time during which stress relaxation AB occurs. The movable jaw of the Instron is then returned to its initial position and the fibre recovery BC is traced out. The strain value when zero stress is reached is taken to give the immediate recovery IC. The jaw is kept at zero for some time while further recovery CD takes place, where D is the beginning of the trace for the next loading cycle.

Fibre elastic recovery is then given by :-

$$\frac{ID}{IO} \times 100 \ (\%)$$

where the recovered extension ID consists of an initial recovery IC and a delayed recovery CD.

Experiments

The tensile elastic recovery of all the fibre samples was measured from extensions of 2% and 5%. These measurements were made on Instron tester at ratio of extension and contraction of 43% per minute. The Cross-Head speed was 0.5 in. per minute.

In a recovery test, each fibre was extended to 2% extension, held at this extension for 30 seconds and then returned to the initial gauge length. The time allowed for recovery was 2 minutes and 30 seconds. The fibre was extended again at the end of this period, but this time the extension was 5%. The entire sequence of load-recovery cycle was repeated so that the elastic recovery could be measured both from 2% and 5% extensions while carrying out only one single experiment.

For each case, 10 fibres of 3 cm. length were tested and mean elastic recoveries were calculated (Table X).

CHAPTER III

RESULTS AND DISCUSSION

CONTENTS

CHAPTER III

RESULTS AND DISCUSSION

This research covers two main aspects: (1) the evaluation of the test conditions for resilience measurement and (2) the investigation of those fibre properties that are necessary in a resilient mass of fibres. The results of all these experiments are given and discussed in this chapter.

1. EVALUATION OF TEST CONDITIONS

1.1 Effect of Time Cycle

When testing fibres for resilience, it is necessary to specify the time cycle (i.e. compression time and recovery time under various pressures) and also the minimum and maximum pressure in a cycle. Therefore, first of all the effect on resilience of the duration of compression and recovery was investigated and Table IV shows the results.

TABLE IV

Acrilan - 16 (2" - 3d)

Code No.	Area of specimen in. square	Mass of specimen g.	Compression time (T_C)	Recovery time (T_R)	(%) Resilience as ratio of thicknesses at 0.001 pressures (p.s.i.) I cycle (0.001-1.0)	II cycle (0.001-1.0)
A1	5.5 x 5.5	4.48	12 secs.	1 min.	74.0	65.5
"	"	4.45	1 min.	5 min.	73.0	65.0
"	"	4.10	1 hour	5 hrs.	73.0	66.0
"	"	4.17	5 hrs.	24 hrs.	74.0	66.0

Results in the Table IV indicate that the resilience of a fibre mass does not vary over the investigated range of compression and recovery periods. It appears due to the fact that the resilience is not affected considerably by the length of compression period if the fibres are allowed to recover sufficiently after they have been kept under pressure. In these investigations, the fibre mass is allowed to recover for a period that is five times as long as the period under compression and it is believed that these combinations of compression-recovery times (Table IV) do allow for the mass of fibres to recovery sufficiently. This suggests that any convenient combination of compression-recovery time can be chosen from the investigated range and that the resilience test may be carried out as a short period test. It is remarked here, however, that in order to simulate the exact end-use conditions of fibre mass (fibre-fill) the resilience test should be performed at longer periods, say, 8 hours compression and 16 hours recovery afterwards.

The selection of time cycle in such tests have generally been very arbitrary. Rees[8] carried out resilience determinations, allowing no extra time under either maximum or minimum load. The change in each load, in case of Rees measurements was made at an interval of 1 minute; however, Robinson[7] noticed that the compressions should not be more than two per minute in order to give sufficient time for good recovery which can characterise the fibre.

Takikawa and Kawamura[94] studied the effect of compression velocity on the resilience of rayon, Alon, and wool. The maximum pressure of 100g/sq. cm. (1.41 p.s.i.) and a 5 sq. cm. area of compression platform was used. In case of zero compression time (immediate recovery) they obtained a high value of resilience as the speed of compression cycle became faster whereas there was only a slight tendency for the resilience to increase when the compression was 5 minutes. For these experiments the recovery time allowed was 2 minutes and the rates of compression investigated were 0.5, 1.0, 2.0 and 5.0 cm./min. It is to be noted that the present experiments are made by an instrument which is based on controlled loading rather than controlled compression and a direct comparison is not possible. It can, however, be seen that the loads are changed after an interval of 1 minute each and the complete loading cycle corresponds to 0.5 cm./min. compression velocity, since the thickness of specimen being 2 inch approximately.

Further, Takikawa and Kawamura[94] investigated the influence of both compression and recovery periods. As expected they obtained a decrease in resilience as the compression time increased and an increase as the time allowed for recovery was more. To study the effect of compression time, compression time of 0, 2, 5, 10 and 20 minutes, speed of testing of 2 cm./min. and the recovery period of 2 minutes was used. All the measurements were carried out under a maximum load of 100 $g./cm^2$. Takikawa and Kawamura found that the difference in the characteristic values for resilience appeared more distinctly when the compression was continued for some known length of time rather than when made to recover at once. In case of recovery, they found that a sufficient recovery of fibres from compression had taken place when allowed to recover for 2 minutes and there was no appreciable change thereafter. These experiments were carried out under a maximum pressure of 100 g./sq. cm. and compressed for 5 minutes, the velocity of recovery being 2 cm./minute. In this case also it is not possible to draw a direct comparison between the results of the present research and those of Takikawa and Kawamura's[94] because no such attempt is made to study the precise effect of compression and recovery periods. Instead it was investigated whether or not it was possible to test resilience in a short time and at the same time the values so obtained held good to a considerable extent at longer periods. However, Takikawa and Kawamura's results can be taken here as information available as regards the influence of compression and recovery periods on the measurement of resilience of fibres in bulk.

1.2 Effect of Pressure

In a resilience test, the thickness was measured at various pressures ranging from 0.001 to 1.0 p.s.i. (Figure 9). From these results, the resilience was calculated as the ratio of thickness at 0.001, 0.01, 0.025, 0.05, 0.10, 0.20, 0.40, 0.60, 0.80 p.s.i. for all the cycles (i.e. from 1 to 9). These values are given in Table Va.

The pressures used in the above measurements seem to be too high to establish a marked difference among the various fibres from the resilience point of view. It was therefore thought to use a maximum load of 0.4 p.s.i. and carry out resilience tests in the usual way. Table Vb show these results.

TABLE V a

Acrilan - 16 (2" - 3d)

Compression-recovery cycle No.	(%) Resilience as ratio of thicknesses at pressure (p.s.i.) of :-								
	0.001	0.01	0.025	0.05	0.10	0.20	0.40	0.60	0.80
Cycle 1	96.8								
2	95.9	94.6							
3	94.8	87.7	89.2						
4	80.7	82.6	79.5	79.6					
5	78.2	80.3	73.7	69.5	78.7				
6	76.8	76.1	70.3	64.0	72.9	80.7			
7	75.7	73.0	66.8	61.7	66.9	74.7	88.0		
8	75.0	71.5	64.3	59.3	64.5	72.3	83.0	93.8	
9	74.1	70.8	63.0	57.5	61.9	69.9	78.0	89.8	95.5

TABLE V b

Acrilan - 16 (2" - 3d)

Compression-recoverty cycle No.	(%) Resilience as ratio of thicknesses at pressure (p.s.i.) of :-		
	0.001	0.01	0.10
1	97.7		
2	81.8		
3	78.4	82.2	
4	76.6	74.5	
5	75.3	70.6	
6	73.2	66.4	82.4
7	70.0	64.5	74.5

Figure 9 shows a typical pressure-thickness curve. It can be seen from these results that the fibres are compressed up to same extent as long as the amount of load on them remains the same, irrespective of the nature of loading, i.e. whether compressed in a cyclic loading or direct to that load. As expected the recovery from the compression depends upon the maximum pressure. Further, it can be seen that the pressure-thickness curve constitutes three distinct regions. The first one covers a range of pressure between 0.001 to 0.01 p.s.i. and characterises the behaviour of the fibres under low compression-recovery cycle. While the second and third portions cover a medium pressure range of 0.001 to 0.10 p.s.i. and a high pressure range of 0.001 to 1.0 p.s.i. respectively.

In the above investigations (Figure 9) the change in each pressure is made at an interval of 1 minute. This means that the fibres are compressed for 1 minute under a maximum pressure in each cycle and then the mass of fibres is left standing for recovery also for 1 minute under each load on the corresponding recovery curve.

From the results (Figure 9, and Tables IV and V) the pressure-time cycle given in Table II is to be used as standard. This enables one to obtain the resilience of fibres at low, medium and slightly high pressures in the minimum time. The choice of time is such that it allows a recovery for a period which is twice that of the corresponding compression period in each cycle.

A number of workers have measured the compressional behaviour of a fibremass. The pressures and maximum pressures used depend on each investigator's requirements and apparatus. Schiefer[69] suggested a pressure range of 0.1 to 2.0 p.s.i. for the evaluation of compressibility and compressional resilience of textile materials. Rees[8] employed a pressure range of 0.001 to 1.0 p.s.i. in his resilience test. Edelman[72] in his investigations of methods for determining the filling power of feathers, found that the most reliable evaluation was obtained at the lowest test pressures of 0.0006 p.s.i. and that little was gained by higher compressional values. Takikawa and Kawamura[94] measured the resilience of rayon, Alon, and wools under 50, 100 and 200 g./sq. cm. (i.e. 0.70, 1.41 and 2.82 p.s.i.) pressures. They found that the effect of maximum pressure was very small if the compression time was zero. The effect of maximum pressure, however, began to influence the results when the mass of fibres was compressed for a period of 2 minutes and over. In the present work the pressure range of 0.001 to 1.0 p.s.i. was used. This appeared to cover a reasonable range of pressures from the investigation of resilience of fibre-fill point of view.

1.3 Effect of Area and Thickness of the Specimen

The results showing the effect of area and thickness of the specimen on the measurement of resilience of fibre mass are given in Table VI a and b.

TABLE VI a

Acrilan - 16 (2" - 3d)

Code No.	Area of specimen (inch square)	Thickness of specimen at 0.001 p.s.i. (inch)	Mass of fibres g.	(%) Resilience as ratio of thicknesses at following pressures 0.001 to 0.01 p.s.i.	0.001 to 0.10 p.s.i.	0.001 to 1.0 p.s.i.
A1	3.6 x 3.6	1.49	2.07	80.7	73.3	66.0
A1	4.5 x 4.5	1.44	3.04	80.6	73.9	66.5
A1	5.5 x 5.5	1.42	4.29	81.0	73.9	66.8
A1	7.5 x 7.5	1.42	7.40	80.4	73.3	66.3

TABLE VI b

Acrilan - 16 (2" - 3d)

Code No.	Area of specimen (inch square)	Thickness of specimen at 0.001 p.s.i. (inch)	Mass of fibres g.	(%) Resilience as ratio of thicknesses at following pressures 0.001 to 0.01 p.s.i.	0.001 to 0.10 p.s.i.	0.001 to 1.0 p.s.i.
A1	5.5 x 5.5	1.15	3.82	80.8	73.0	66.0
A1	"	2.20	6.83	81.4	73.0	66.5
A1	"	3.30	10.27	81.5	73.2	66.0
A1	"	4.37	14.09	81.2	73.7	66.0

It is clear from the results in Tables VI a and b that the resilience of fibre mass is independent of both specimen area and thickness if tested under constant size presser foot between a pressure range of 0.001 to 1.0 p.s.i.

Each side of the smallest specimen is equal to the diameter of the presser foot and each side of the biggest specimen is approximately twice the diameter of the presser foot. This provides a range specimen areas from 13 to 56 square inches, bearing in mind that the presser foot (circular) area is 10 sq. inch. The thickness of the specimens is remarkably constant (Table VI a); this indicates the consistency of the specimen preparations. Further, it is to be noted that the resilience measured at low, medium and high pressures, i.e. between 0.001 to 0.01, 0.001 to 0.10 and 0.001 to 1.0 p.s.i. show the same trend. It is concluded therefore that from the investigated range any convenient area for the specimen in such studies could be employed. A specimen of 5.5 x 5.5 inch square area was always taken as a "standard specimen area."

When the effect of thickness of specimen was studied (Table VI b), the thickness varied from 1.1 to 4.4 inches and the area of each specimen taken was 5.5 x 5.5 inches square. To vary the thickness, thin layers of fibre are placed on top of each other. It is clear that increasing the thickness in this way does not affect the values of results. It can be seen also from Table VI b that the maximum pressure does not alter the basic trend in the results.

There is not much information available as regards the effect of specimen geometry on the resilience of fibre mass. It is, however, pointed out by various workers that the results depend on specimen preparation. Finch[76] stated that if the fibre mass consisted of partially matted and partially loose fibres, the relaxation rate would be a reflection of both these conditions. It was, therefore, necessary to have the fibrous mass as homogeneous as possible. This according to Finch was accomplished either by opening the material on a power-driven laboratory card or by opening it with hand cards. Rees[8] pointed out that the well opened fibres were very sensitive to changes of pressure, so that precautions must be taken in determining the initial volume of the fibre mass under the initial pressure. Rees prepared his test specimen inside a Perspex glass cylinder, which he withdrew and then placed the prepared specimen under the foot of the instrument. By this method, he avoided the friction between the fibres and the wall of the cylinder and thus eliminated its effect on the results. Van Wyk[93] suggested that the wool should be teased out as thoroughly as possible to ensure the random orientation of the individual fibre. He found that the presence of lumps raised the coefficient by as much as 32%. deMaCarty and Dusenbury[77] prepared samples by tamping down small amounts of fibres from a predetermined weight of wool into the area within a prescribed circumference marked on a board, until an even bulk density of the material was obtained throughout. In this way, cylindrical specimens 2 inches in height were prepared, each specimen consisting of four layers about ½ inch thick. deMaCarty and Dusenbury claimed a good reproducibility of the results from the specimens thus prepared and no special effects were produced as a result of compressing layered specimen.

In the present work fibres are opened thoroughly on a power-driven card (Shirley miniature card) and transformed into a uniform lap. From such laps, specimens of required dimensions (area and thickness) are obtained. As observed by deMaCarty and Dusenbury[77], layered specimens do not affect the results (Table VI b). Since the fibre mass is very sensitive to pressure changes and also it is necessary to fix the starting point, the fibres are compressed to 1.0 p.s.i. for 10 seconds and then recovered for 1 minute under zero load, in order to get a definite starting point always. It was pointed out by Van Wyk[93] that a random orientation of fibres should be used so as to avoid any orientation effect on the results. It is believed that the carded fibre mass is sufficiently randomly oriented for the present work although it is realised that specimens prepared on a carding machine must possess some degree of fibre orientation.

1.4 Effect of Size and Shape of Presser Foot

Results in Table VII a and b show the influence of presser foot size and nature (plane or hemispherical compressing surface) on the measurement of resilience of fibres in bulk.

TABLE VII a

Acrilan - 16 (2" - 3d)

Code No.	Size of presser foot (sq. inch)	Area of specimen (inch square)	Mass of fibres g.	(%) Resilience as ratio of thicknesses at following pressures. 0.001 to 0.01 p.s.i.	0.001 to 0.10 p.s.i.	0.001 to 1.0 p.s.i.
A1	5	5.5 x 5.5	3.82	81.0	73.0	66.2
"	10	"	3.44	81.2	73.7	66.0
"	20	"	3.66	80.8	73.1	66.0

TABLE VII b

Acrilan - 16 (2" - 3d)

Code No.	Area of specimen (inch square)	Mass of fibres g.	Shape of presser foot	Size of presser foot (sq.in.)	(%) Resilience as ratio of thicknesses at following pressures. 0.001 to 0.01 p.s.i.	0.001 to 0.10 p.si.	0.001 to 1.0 p.s.i.
A1	5.5 x 5.5	7.0	Hemispherical surface	10	75.0	68.0	60.0
A1	"	6.86	Plane surface	10	81.0	74.0	66.5

The results in Table VII a indicate the effect of the size of the presser foot in a resilience test. As described earlier, these involved measurement of the resilience of Acrilan (2" 3d) fibre specimens of known weight and size (5.5 x 5.5 inch square) under three separate presser feet. The areas of the feet are 5, 10 and 20 sq. in. It is evident from the results that the resilience is not affected by the size of the foot. Further, the results show that a similar effect is obtained when the resilience measurements are carried out at either 0.001 to 0.01, 0.001 to 0.10, 0.001 to 1.0 p.s.i. pressures. These results are consistent with those obtained using a constant size of presser foot with different sizes of specimen.

deMaCarty and Dusenbury[77] carried out an interesting investigation to study the effect of presser foot size on resilience, maximum load and secondary creep on the bulk sample prepared from Targhee 60's card sliver. They used three presser feet of 1, 3 and 5 inches in diameter. deMaCarty and Dusenbury found that the effective volume of fibres being squeezed was greater than the volume of fibres directly beneath the foot, probably due to fibre-to-fibre entanglements. It was suggested that a constant area should be added to the compressing foot areas in order to achieve a constant compressive stress. This area increment was independent of specimen diameter, provided that the sample diameter was sufficiently greater than that of the foot, and this area increment decreased with increasing degree of compression. The present research is not aimed at such a study about the presser foot size. deMaCarty and Dusenbury's[77] results, however, do not show any relationship as regards the resilience and presser foot size, whereas the present results indicate that the resilience is independent of the foot size. (Table VII a).

The choice of the size of presser foot, generally has been arbitrary. Schiefer[69] used a presser foot of one inch diameter in the measurement of compressional resilience. Saxl[70], Robinson[7], Fox and Schwarz[71], Finch[76], and Skinkle[74] used presser feet of different areas ranging from 1 inch to 7.5 inch diameter. For the present work, it is considered appropriate to use a presser foot of 10 square inch as the standard foot, because it allows a reasonable surface area which is neither too large nor very small. Also, it is clear that the size of foot does not vary the results.

When the shape of the presser foot is varied it can be seen (Table VII b) that the resilience of fibres determined under a plane surface foot is higher than that measured under a presser foot of hemispherical shape. This is an expected observation and it is thought useful to know how far the shape affects the results. It is believed due to the fact that the volume of fibres compressed with a plane surface is more as compared with the volume under the corresponding hemispherical foot. The fibres which remain in the centre are compressed to high compressions, whereas those lying near the edge are compressed much less. Consequently, both the force required to deform the fibre mass and its recovery behaviour upon release of pressure are affected.

2. RESILIENCE OF FIBRES

Using the standardised pressure-time cycle (Table II) under a standard presser foot (10 sq. inch area), the resilience of all the fibre samples (Acrilan, Terylene and Tricel) was determined. These results are given in Tables VIII a to e.

TABLE VIII a.

Acrilan

Code No.	Description of fibre	(%) Resilience as ratio of thicknesses at following pressures 0.001-0.01 p.s.i.	0.001-0.10 p.s.i.	0.001-1.0 p.s.i.
A1	Type - 16, 2" - 3d	80.5	73.0	63.8
A2	" 2" - 3d	86.0	74.2	69.0
A3	" 2" - 8d	88.0	79.6	70.4
A4	" 2" - 2d	78.0	72.0	61.5
A5	" 2" - 5d	86.3	78.9	70.6
A6	" 2" - 15d	89.5	80.9	73.6
A7	" $1^9/16$" - 2d	83.4	74.8	65.4
A8	" $1^9/16$" - 5d	84.5	73.0	66.3
A9	" $1^9/16$" - 15d	85.6	76.5	68.5

TABLE VIII b.

Acrilan

A10	" 16, uncrimped 2" - 3d	64.4	60.0	55.8
A11	" uncrimped 2" - 5d	69.0	61.0	57.0
A12	" uncrimped 2" - 8d	71.0	61.5	57.5

TABLE VIII c

Acrilan

Code No.	Description of fibre	(%) Resilience as ratio of thicknesses at following pressures. 0.001-0.01 p.s.i.	0.001-0.10 p.s.i.	0.001-1.0 p.s.i.
A13	Chemically crimped $2\frac{1}{2}$" - $5\frac{1}{2}$d	88.0	80.0	70.0

TABLE VIII d

Terylene

P1	Cotton type, $1\frac{1}{2}$" - $1\frac{1}{2}$d	78.5	71.3	68.4
P2	Cotton type, $1\frac{1}{2}$" - 3d	80.5	73.5	69.0
P3	Filling type, $1\frac{1}{2}$" - 3d	82.0	74.5	69.0
P4	Filling type, $2\frac{1}{2}$" - 3d	85.5	75.7	71.0
P5	Flax type, $2\frac{1}{2}$" - 4d	86.3	75.8	70.3
P6	Wool type, $2\frac{1}{2}$" - 3d	79.0	70.5	66.0
P7	Wool type, $3\frac{1}{2}$" - 6d	80.3	73.5	65.5
P8	Wool type, $4\frac{1}{2}$" - 10d	86.0	74.0	71.0

TABLE VIII e

Tricel

T1	Semi-matt, 2" - 3d	70.0	65.0	58.0
T2	" 2" - 8d	84.0	75.0	69.0
T3	" $2\frac{1}{2}$" - $4\frac{1}{2}$d	66.4	61.0	56.0
T4	" 5" - $4\frac{1}{2}$d	66.8	63.0	57.0

3. RESILIENCE AND INHERENT FIBRE PROPERTIES RELATIONSHIP

As mentioned in the introduction the main aim of this research is to establish precisely the relationship between the resilience of a fibre mass and the inherent fibre properties. The properties considered are, length, denier, crimp, inter-fibre friction, elastic recovery and modulus.

3.1 Staple Length and Denier of a Fibre

TableVIIIa to e, show the values of resilience for Acrilan, Terylene and Tricel fibre samples together with the average length and denier of each fibre.

Since the samples of Acrilan fibres available for this work possess very little variation in the length (i.e. 2 to 1^{9}/16 inch), the discussion is concerned more to Terylene and Tricel fibres regarding the effect of length on resilience. In general it appears from the Table VIII a to e that the average fibre length does not appreciably vary the resilience of fibres in bulk. In the case of Terylene fibres (Table VIII d) when considering the samples, code Nos. P2, P3, and P6, however, there seems to be a very slight tendency for the resilience to decrease with the increase in length. It is to be noted that these three fibre samples possess very nearly the same percent crimp, inter-fibre friction, elastic recovery and modulus (Tables IX and X). The sample code No. P4, although of the same denier, is not considered in the above discussion because it has a high percentage of crimp, so tend to indicate high resilience. Tricel fibres also indicate the same tendency if fibre samples code Nos. T1, T3 and T4 are considered (Table VIII e). These fibres possess nearly the same properties as regards denier, crimp, friction, elastic recovery and modulus.

Very little has been published in the literature about the effect of length on the measurement of resilience. Fox and Schwarz[87] stated that the quality and staple length affect the compressional properties. Winson[6] found that the resilience of mass of wool fibres increased as the length decreases. The experimental result as discussed above in case of Terylene and Tricel fibres appear to show some agreement with the results of Winson.

Demiruren and Burns[48] carried out more interesting and detailed study about the measurement of resilience in relation to fibre properties. Over a wide range of wools tested (29 wools), the resilience values obtained showed a very weak dependence on mean staple length, whereas the maximum load values appeared to be considerably more sensitive to changes in fibre dimensions. They obtained a positive correlation between resilience and staple length ($r = 0.380$, significant at 5% level). It should be remarked here that deMaCarty and Dusenbury[77] concluded from Demiruren and Burns[48] results that compressive load served better to characterise the compressional behaviour of fibre samples rather than resilience. Further, deMaCarty and Dusenbury showed that there is an inverse relationship between maximum load and fibre length. The present results, however, indicate no such relationship and it seems reasonable to conclude that there is no significant correlation between fibre length and resilience over the range investigated.

When considering the effect of fibre denier (diameter) the results from Tables VIII a to e are plotted in Figures 10 to 13. It appears that the resilience is greater in the case of the thicker fibre, in other words the resilience increases as the fibre denier increases. This is probably due to the fact that the fibres bend in a compression test and the bending modulus varies directly with the square of fibre diameter. Further, it is observed that the increase in resilience is more pronounced when it is measured between 0.001 to 0.01 p.s.i., rather than at higher pressures. These effects can be seen more distinctly in the case of uncrimped Acrilan fibres (Figure 13).

Van Wyk[93] carried out experiments on different Merino wool samples and found no correlation between resistance to compression and fibre diameter. This was an apparent confirmation of his equation derived to represent a relationship between the pressure (compressive load) and the volume of the mass of fibres being compressed. For this derivation, he assumed that the compression consisted only of bending the fibres; twisting, slippage, and extension of fibres were ignored. The mass of fibres was treated as randomly oriented rods and consideration was given to the number of times each fibre would come in contact with another during compression. Further, after eliminating the possible effect of crimp, Van Wyk found a positive partial correlation (0.43) between compressive load and fibre diameter. Experimental results indicate that there seem to be a positive correlation between fibre denier and resilience and also appear to support the view held by Van Wyk, who mentioned that an influence of fibre diameter may be masked by crimping. The effect of crimp in a fibre during compression is discussed later in detail.

Further, it is interesting to note the following researches. The results of Demiruren and Burns[48] showed an inverse relationship between the compressive load and fibre diameter. In the case of resilience, however, they obtained positive correlation between resilience and diameter ($r = 0.322$, significant at 5% level when $r = 0.367$ or more). Rees[8] found no significant correlation of compressional resilience with fibre diameter among his five different cottons. He found, however, that at higher pressures the finer the cotton the greater was its specific volume, that is, at the same compressions the compressive loads varied inversely with fibre diameter. Saxl[95] found that with dry rayon flock, a higher denier fibre was harder to compress and recovered to a greater extent than a lower denier. Kolb <u>et al</u>[91] reported that compressional recovery of Dacron was not dependent on denier, but in this case the maximum pressure used was very high (100,000 p.s.i.).

It is now clear that the available information about the effect of fibre dimension on resilience is somewhat contradictory and there does not seem to be general agreement. There are probably two reasons for this: (1) In such experiments the elastic modulus was not controlled which is at least partially responsible for the behaviour of fibres in compression, and (2) the compressional resilience is a property of the fibre assembly and factors such as inter-fibre friction, crimp, are to be considered as well.

3.2 Fibre Crimp Characteristics

The crimp measurement experiments were carried out and the values of percent crimp in a fibre, uncrimping force and uncrimping energy was given in Table IX a to d. The values of percent crimp are plotted against resilience in Figures 14 to 16 for Acrilan, Terylene and Tricel fibre samples.

TABLE IX a

Acrilan

Code No.	Crimp (%)	Uncrimping force (g/d)	Uncrimping energy (g.- inch/den. - inch)
A1	8.0	0.10	0.0017
A2	14.0	0.20	0.0036
A3	14.3	0.20	0.0039
A4	6.2	0.10	0.0004
A5	11.4	0.20	0.0019
A6	25.6	0.20	0.0048
A7	8.6	0.10	0.0012
A8	9.2	0.10	0.0015
A9	11.8	0.10	0.0021

TABLE IX b

Acrilan

Code No.	Crimp (%)	Uncrimping force (g/d)	Uncrimping energy (g. - inch/den. - inch)
A13	15.4	0.10	0.0002

TABLE IX c

Terylene

Code No.	Crimp (%)	Uncrimping force (g/d)	Uncrimping energy (g. - inch/den. - inch)
P1	8.4	0.10	0.0032
P2	8.5	0.10	0.0033
P3	10.2	0.10	0.0037
P4	14.8	0.20	0.0045
P5	15.4	0.20	0.0049
P6	9.0	0.10	0.0030
P7	8.0	0.10	0.0030
P8	12.6	0.10	0.0032

TABLE IX d

Tricel

Code No.	Crimp (%)	Uncrimping force (g/d)	Uncrimping energy (g. - inch/den. inch)
T1	6.0	0.10	0.00022
T2	13.0	0.20	0.0025
T3	4.4	0.10	0.00018
T4	5.0	0.10	0.00020

It is clear from the results (Tables IX a to d) that the fibre possessing a high percent crimp, also has a high resilience. Further, the results (Figures 14 - 16) indicate that the resilience increases as the percent crimp increases up to a certain value only, beyond which it has very little effect. In the case of Acrilan fibre samples, the optimum limit of crimp is seen quite distinctly as 15% approximately (Figure 14). Similar results to those of Acrilan fibres are obtained for Terylene and Tricel fibre samples. The crimp in Terylene and Tricel fibres, however, do not cover the higher percentage (i.e. beyond 15%), but it appears that there is a tendency for the resilience versus crimp curve (Figures 15 and 16) to flatten at about 15% value of crimp indicating the same relationship as obtained in the case of Acrilan fibres.

Further, it can be seen (Tables IX a to d) that the fibre which requires greater force to remove crimp and also possesses high uncrimping energy, shows high resilience. This effect is seen very clearly in the case of Terylene and Tricel fibres (Tables IX c and d).

The present results clearly show that the crimp is a very important property from the bulk-resilience point of view. It seems likely that the crimped fibre is straightened on compression, i.e. the crimp is removed, while on release of pressure the fibre recovers because of the potential energy (uncrimping energy) stored in it when compressed. It should, however, be kept in mind that the compressional behaviour of a fibre mass also may depend on the inter-fibre friction and modulus of the fibre.

The resilience increases up to a certain value of crimp percentage (Figures 14 - 16) only, the reason for it seems to be that beyond a particular value of crimp (15% in the present experiments), the crimp becomes so much that there is hardly any room for the fibres to move in relation to each other during compression (or recovery) due to high entanglement of fibres.

The resilience versus percent crimp curves indicate the same trend whether measured at low, medium or high pressures, i.e. between 0.001 to 0.01, 0.001 to 0.10 and 0.001 to 1.0 p.s.i. pressures (Figs. 14 to 16).

It is also evident that the resilience of the straight fibres (uncrimped) is much lower than that of the crimped fibres. This can be seen if the values of resilience for the Acrilan fibres, code Nos. A1, A2, A5 and A3, in Table VIII a are compared with the corresponding fibres in Table VIII b.

Demiruren and Burns[48] carried out an important investigation in an attempt to find the effect of crimp parameters and other fibre properties on the resilience of a fibre mass. They found a simple correlation of 0.27 for crimp depth to length ratio and 0.20 for crimp depth, with resilience. Both these correlations, however, were insignificant since correlation coefficient of 0.367 or above were significant at 0.05 level. Further, they found that only 31% of variations in the compressional bulk resilience of wool fibres could be accounted for by the variation in the six inherent fibre properties (viz: tensile strength, length, diameter, contour, crimp depth to length ratio and crimp depth). The tensile strength had highest coefficient of determination (16%) whereas crimp depth to length ratio accounted for only 4% and crimp depth added very little to the cumulative relationship. This means that Demiruren and Burns's results show a very weak dependence of resilience on crimp. The present results, however, indicate a high dependence of resilience on crimp in a fibre, for all the fibres of Acrilan, Terylene and Tricel.

The only other work which the author has found as regards the influence of crimp on resilience of fibres in bulk is that of Van Wyk[93]. He pointed out that crimping may have a direct effect on the relationship of resistance to compression. Also, he found indirect evidence to suggest that the number of crimps per unit stretched length was a more relevant quantity than the normal staple length. Van Wyk found a significant correlation coefficient of 0.55 between the resistance to compression and number of crimps per unit length.

Further, it was attempted to see if the nature of the crimping process (e.g. mechanically or chemically crimped) has any effect on resilience of fibre mass. The results in Table VIII c and Table IX b show that the chemically crimped fibres possess as high a resilience as is obtained with the corresponding normally crimped fibres (Table VIII a and Table IX a). This is probably due to the almost same high percentage of crimp in both types of fibres. It can, however, be noticed that the chemically crimped fibres need a smaller force to remove crimp and also have a lower uncrimping energy as compared with normally crimped fibres.

3.3 Inter-fibre Friction

The results showing the effect of fibre - to - fibre friction on the bulk - resilience of Acrilan, Terylene and Tricel fibre samples are given in Tables X a to e and are plotted in Figures 17 to 20. The TablesX a to e also include the tensile elastic recovery and initial modulus determined for each fibre sample.

TABLE X a

Acrilan

Code No.	Elastic recovery from 2% extension (%)	Elastic recovery from 5% extension (%)	Initial Modulus (g/d)	Coefficient of friction
A1	90.7	71.0	24	0.28
A2	90.0	72.8	32	0.24
A3	93.4	78.1	36	0.26
A4	84.7	62.0	30	0.30
A5	88.0	67.8	36	0.27
A6	92.0	68.5	40	0.24
A7	91.5	70.0	32	0.28
A8	93.4	70.8	36	0.25
A9	95.0	72.1	38	0.24

TABLE X b

Acrilan

Code No.	Elastic recovery from 2% extension (%)	Elastic recovery from 5% extension (%)	Initial modulus (g/d)	Coefficient of friction
A10	91.0	68.7	32	0.32
A11	94.8	70.3	36	0.29
A12	94.9	72.2	38	0.25

TABLE X c

Acrilan

A13	90.5	72.0	35	0.25

TABLE X d

Terylene

P1	92.0	75.0	30	0.19
P2	95.3	82.6	32	0.18
P3	86.3	79.9	30	0.20
P4	90.5	83.9	34	0.20
P5	95.0	85.2	32	0.20
P6	89.0	81.6	33	0.21
P7	95.0	84.1	34	0.20
P8	88.0	81.2	32	0.19

TABLE X e

Tricel

Code No.	Elastic recovery from 2% extension (%)	Elastic recovery from 5% extension (%)	Initial modulus (g/d)	Coefficient of friction
T1	89.2	57.0	24	0.35
T2	95.0	72.0	28	0.25
T3	91.3	57.4	22	0.32
T4	94.0	58.1	24	0.30

The experimental results (Figures 17 to 20) indicate that the resilience decreases with increase in the coefficient of friction of the fibre and there seems to be a linear relationship between these two parameters. This effect can be seen more precisely with straight fibres (uncrimped) in Figure 20 since the crimp plays a more dominant part in the resilience results. In these uncrimped fibres the coefficient of friction varies between 0.25 to 0.32 and the corresponding resilience ranges from 64 to 71 per cent for the resilience tests measured at 0.001 to 0.01 p.s.i. pressures. It is an expected observation because during compression the fibres slip relative to each other and when the friction between the fibres is more naturally the compression - recovery behaviour of fibre mass is affected. These results, however, show the magnitude of frictional effects in the case of resilience of fibres in bulk. Further, it will be noticed from the results (Figures 17 - 20) that same trend is obtained for all the fibres of Acrilan, Terylene and Tricel regarding resilience and coefficient of friction between fibres. Usually a surface finish of some kind is applied on the fibres during manufacturing. This changes its frictional behaviour depending on the nature of the surface finish and the material. A more detailed study in order to find out whether or not it is possible to enhance the resilience by reducing further the coefficient friction of the fibres is given in the Later Chapter V.

Further, it is noticed from the results that the resilience measured at low, medium and high pressures (i.e. 0.001 to 0.01, 0.001 to 0.10 and 0.001 to 1.0 p.s.i.) seem to indicate similar trends. This suggests that within the range of pressures investigated, the pressure and maximum pressure in a cycle does not change the trend as regards the influence of fibre friction on resilience, in other words, the slope of resilience versus coefficient of friction of the fibre curves remain nearly constant (Figures 17 - 19). However, in the case of uncrimped fibres (Figure 20) it appears that the variation in resilience with fibre friction is more pronounced if the resilience is measured at low pressures (0.001 to 0.01 p.s.i.)

There are no data published regarding the effect of fibre friction on the compressional behaviour of the fibre mass. However, Matsuo[98] and Van Wyk[93] pointed out the possible importance of inter-fibre friction in such studies.

3.4 Elastic Recovery and Modulus

Figures 21 - 24 show the results of tensile elastic recovery measured from 2% extension and resilience of fibres in bulk for all the samples of Acrilan, Terylene and Tricel fibres.

The correlation between resilience and elastic recovery for the Acrilan samples (Figure 21) is weak and if the point for sample A4 is ignored (this sample has the lowest percent crimp), there is no correlation. For the Terylene fibre samples (Figure 22), there is no correlation. For the Tricel fibre samples (Figure 23), there is no correlation (sample 2 which has the highest resilience also has by far the highest percent crimp for this group). For the uncrimped Acrilan samples (Figure 24) sample A10 has a lower resilience and lower elastic recovery than samples A11 or A12, but only under the lowest maximum pressure used. It is concluded that elastic recovery from 2% extension as measured here is not correlated with resilience.

It should be remarked at this stage that the recovery of a fibre is measured after removing the normal crimp in order to avoid its (crimp) effect and to assess the precise effect of single fibre recovery from extension, when these fibres are compressed as a mass. Also in these instances, it is assumed that the recovery of a fibre measured from extension and that obtained in bending are the same, because the bending recovery would be more appropriate to consider in such cases since most fibres are believed to undergo bending during compression. The same argument applies to elastic modulus (initial modulus) of a fibre.

When considering the effect of pressure, it is seen (Figures 21 - 24) that the same trend (i.e. same slope of resilience vs. elastic recovery plot) regarding resilience and recovery of a fibre is obtained, whether the resilience measurements are carried out at low, medium or high pressure (i.e. between 0.001 to 0.01, 0.001 to 0.10 and 0.001 to 1.0 p.s.i.). In the case of uncrimped fibres (Figure 24), however, it appears that in order to establish a marked difference among the fibre resilience, it is better to measure it at low pressure range (0.001 to 0.01 p.s.i.)

The effect of elastic modulus (initial modulus) of a fibre on its bulk-resilience can be seen in Tables X a to e. These Tables show the initial modulus of all the fibre samples of Acrilan, Terylene and Tricel fibres together with their elastic recovery both from 2% and 5% extensions. It might be expected that the high modulus fibre would form a more resilient mass. In the case of Terylene fibres (Tables X d) there does not seem to be any relationship between resilience and modulus whereas Acrilan and Tricel fibres (Tables X a and e) tend to show a relationship. The uncrimped fibres again do not indicate any such relationship between resilience and modulus (Table X b).

The elastic recovery measurements from 5% extensions are not taken into consideration while discussing the possible effect of a fibre elastic recovery on its bulk-resilience since it is very unlikely that the fibres during compression between 0.001 to 1.0 p.s.i. pressures can be extended beyond 2%.

It has been pointed out by Kaswell[33] that there seems to exist a linear relationship between resilience of fibremass and elastic recovery of single fibre. This suggestion, however, is empirical and is rather based on the analysis of Rees[8] and Meredith[31] results on resilience and elastic recovery.

Beste and Hoffman[29] proposed that the resilience has two aspects, viz. (1) Type and (2) Extent. The former is characterised by the stiffness (Young's modulus) and 'compliance ratio' and the latter being given by ability of the fibre to recover from deformation. They found wool possessing a relatively low modulus but high compliance ratio and silk has a high stiffness and compliance ratio, whereas Nylon shows low stiffness and low compliance ratio. Further, they found a linear correlation between the fibre elastic recovery and crease recovery of fabrics made from these fibres. The experimental results cannot be compared with those of Beste and Hoffman. However, it is clear that both elastic recovery and modulus of the fibre are required to determine the bulk resilience of such fibre mass.

4. MATHEMATICAL TREATMENT OF THICKNESS-PRESSURE RELATIONSHIP

As described in the introduction, considerable work has been reported to express the compressional behaviour of textile structures and fibre mass. In the present investigation the possibility of expressing the pressure-thickness relation by an equation is considered.

The analysis of $\log_{10}$ (Thickness) versus $\log_{10}$ (Pressure) (Figure 25) curves between 0.001 to 1.0 p.s.i. pressures for each fibre sample compression-recovery data of Acrilan, Terylene and Tricel, indicate that the results can be fitted to the most commonly used empirical exponential equation given below :

$$T = a P^{b}$$

where 'T' is the thickness of fibre mass in inches, 'P' is the pressure in p.s.i., 'a' and 'b' are constants which are specific for each sample.

Figure 25 shows a typical $\log_{10}$ (Thickness) versus $\log_{10}$ (Pressure) plot between 0.001 to 1.0 p.s.i. pressures. From such plots the slopes of pressure-thickness curves are calculated. The values are given in Figures 26 to 28 in relation to the corresponding values of resilience.

A close examination of pressure-thickness curve (Figure 25) indicates that the exponential relationship ($T = a P^{b}$) appears to hold good only when the thickness measurements are made between 0.004 to 1.0 p.s.i. pressures.

It is more true in the case of the compression part of the curve which tends to deviate from a straight line at 0.004 p.s.i. pressure. Therefore the rate of change of thickness with pressure

$$\frac{d \log_{10} (\text{Thickness})}{d \log_{10} (\text{Pressure})}$$ as given in Figures 26 to 28

is the slope of the straight portion of the plot.

It can be seen clearly from the rate of change of thickness with pressure curves (Figures 26 - 28) that the higher the rate of compression with pressure the lower is the recovery from that compression, in other words the less is the resistance to compression the poorer is the recovery. This is a very natural result but the manner in which each fibre sample of various materials behave under compression test is different. These results therefore show how the thickness of samples of Acrilan, Terylene and Tricel vary under different pressures during compression. Comparing Acrilan and Terylene (Figures 26 and 27) it is seen that the rate of change of thickness with pressure in the case of Terylene is slightly more. However, the values of resilience for Terylene and Acrilan seem to be much the same. In the case of Tricel, the rate of change of thickness with pressure (Figure 28) is much smaller compared with both Acrilan and Terylene. Consequently this makes the Tricel fibre mass less resilient than both Acrilan and Terylene.

Terasaki _et al_[81] measured the compressed height under various compression loads with the cylindrical fibre assembly of viscose rayon using an Instron. They obtained the following relationship

$$\log H = a' + b' \log Z$$

where H is compressed height, and Z is the compression load, a' and b' are constants.

The experimental results appear to be in agreement with those of Terasaki _et al_[81].

Various other equations have been proposed. Matsushima and Matsuo[97] obtained pressure-deformation curves for carded fibre mass and blankets. These curves fit in the equation:

$$P = a'' e^{b''x}$$

where P is pressure, x is deformation, a'' and b'' are constants.

Van Wyk[93] and Eggerts[96] also derived equations to represent compressibility of a mass of wool fibres.

It is quite clear that it is hard to find any one equation which can represent adequately the relationship between pressure and thickness and compressibility of fibre mass. The reason may be that it is necessary to consider various other factors (e.g. inter-fibre friction, crimp, elastic modulus etc.). These factors play an important role when fibre mass is compressed.

For samples of Acrilan, the correlation between resilience and compliance (as represented by $\frac{d \log_{10} (\text{Thickness})}{d \log_{10} (\text{Pressure})}$) is high and the same observation applies to the samples of Terylene. The same line cannot be drawn through the data for both Acrilan and Terylene and the data for three of the Tricel samples fall in a distinctly separate group, so that there appears to be no general relationship between resilience and compliance. However, the three Tricel samples which lie so far from the remainder have the highest coefficients of friction. Now friction would be expected to decrease both resilience and compliance and so may account for the isolation of this group. The observation that for a given resilience, the compliance of the Terylene samples is greater than for the Acrilan samples supports this hypothesis for the coefficient of friction of the Terylene samples, as a group is less than for the Acrilan samples as a group. In other words, these data support the conclusion that friction is one of the important factors in the resilience of fibres in bulk.

5. COMPARISON OF RESULTS WITH THOSE OF OTHER WORKERS

The resilience data on fibre masses are scarce and difficult to compare, because the values obtained by each investigator apply only for a particular kind of fibre mass and under specific test conditions. However, an attempt is made to examine the data of Takikawa and Kawamura[94] and Rees[8] in comparison with the experimental values for resilience of Acrilan, Terylene and Tricel fibre samples.

Rees[8] measured the resilience as the ratio of energy returned by the specimen during recovery to the energy required to compress the specimen and expressed it as a percentage. In a resilience test, he subjected the specimen to only one complete cycle of pressure changes, that is, the pressure was gradually increased from a minimum to a maximum value (0.001 to 1.0 p.s.i.) and then decreased gradually to the initial value in the same order. The change in each pressure was made at an interval of 1 minute. Rees employed ten intermediate pressures to reach the maximum pressure of 1.0 p.s.i. from 0.001 p.s.i. pressure. He obtained the following values of resilience for various fibres (Table XI).

TABLE XI

Description of the Fibres

Name	Source	Resilience (%)
Cotton, Bengals	After processing through Shirley analyser.	39.1
Wool, 70's	Sliver	55.8
Kapok, Prime Java	Bale	44.0
Silk, degummed China	1st draft	52.2
Nylon waste	Sliver	53.0
Cellulose acetate staple	Bale	44.4
Hollow viscose staple	Bale	30.7

Rees[8] calculated resilience as a ratio of energies, and for comparison a corresponding ratio has been calculated from our compression-recovery data. These values are given in Tables XII a to c.

In spite of the fact that both these results and the present experimental results are obtained on different kinds of fibres and measured under different conditions, it is considered worth-while to try to draw a rough comparison. The above results (Table XI) show that wool has the highest resilience (55.8%) and viscose staple fibre the lowest (30.7%). Nylon waste and silk have resilience values approaching that for wool. The cellulose acetate staple and kapok specimen have resilience greater than viscose and lower resilience than wool (44.4%).

It can be seen from Table XII a to c that the average value of resilience measured between 0.001 to 0.01 p.s.i. pressure for Acrilan is 41.7%, for Terylene 41.0% and for Tricel 34.2%.

Comparing the results of Rees[8] with the present experimental results, it seems that the resilience values obtained by him are higher than ours. These two separate sets of values for resilience should, however, be regarded as different entities because these values are obtained under specific conditions and on particular materials and are true in those cases only.

The other work on the measurement of resilience of fibre mass is that of Takikawa and Kawamura[94]. They determined resilience of various fibres using an Instron tester and employed the following conditions:

Compression velocity	=	2 cm/min.
Maximum pressure	=	100 g/cm.sq.(1.41 p.s.i.)
Compression time	=	5 minute
Recovery time	=	2 minute
Area of pressure foot	=	5 cm. square.

TABLE XII a

Acrilan

Code No.	Description of the fibre			Resilience (%) between 0.001 to 0.01 p.s.i.
A1	Type - 16,	normal crimp,	2" 3d	40.0
A2	"	"	2" 3d	44.0
A3	"	"	2" 8d	44.5
A4	"	"	2" 2d	38.0
A5	"	"	2" 5d	42.0
A6	"	"	2" 15d	46.0
A7	"	"	1 9/16" 2d	38.5
A8	"	"	1 9/16" 5d	41.0
A9	"	"	1 9/16" 15d	41.5
A10	"	uncrimped	2" 3d	31.0
A11	"	"	2" 5d	33.0
A12	"	"	2" 8d	36.0
A13	Acrilan (Experimental) chemically crimped		2.5" 5.5d	44.0

TABLE XIIb

Terylene

Code No.	Description of the fibre			(%) Resilience as ratio of energies between 0.001 to 0.01 p.s.i.
P1	Cotton type,	1.5"	1.5d	36.0
P2	"	1.5"	3d	38.0
P3	Filling Type,	1.5"	3d	41.5
P4	"	2 1/4"	3d	43.0
P5	Flax Type,	2½"	4d	43.5
P6	Wool Type,	2½"	3d	38.0
P7	"	3½"	6d	41.5
P8	"	4½"	10d	47.0

TABLE XIIc

Tricel

Code No.	Description of the fibre			(%) Resilience as ratio of engergies between 0.001 to 0.01 p.s.i.
T1	Tricel, semi-matt,	2"	3d	34.0
T2	"	2"	8d	42.5
T3	"	2.5"	4.5d	30.0
T4	"	5"	4.5d	31.0

The results of Takikawa and Kawamura's[94] experiments are given in Table XIII. They also calculated resilience according to the definition of Rees[8].

TABLE XIII

Kind of fibre	Resilience (%)
Cotton, Bed clothes wadding	47.5
Rayon I, 3d	33.0
High Tenacity Rayon, 1.5d	49.7
Alon I, 3d	52.9
Alon II, Bed clothes wadding	57.3
Acetate, 3d	61.4
Wool II, Aust 60's, treated with 30% water	70.1
Polyester fibre, 3d	73.5
Acryl fibre I, 3d A CO	57.7
" II, 3d B CO	58.9
" III, 3d, C CO	56.9
" IV, 3d C CO	68.9
" V, Bed clothes, Wadding, D CO	63.8

Examination of Table XIII indicates that Takikawa and Kawamura's[94] results appear to be higher as compared with our experimental results (Table XII a to c) on Acrilan, Terylene and Tricel fibres.

CHAPTER IV.

EFFECT OF HUMIDITY AND TEMPERATURE

CONTENTS

CHAPTER IV

EFFECT OF HUMIDITY AND TEMPERATURE

1. INTRODUCTION

Fibres absorb moisture from their surroundings which in turn changes their physical properties. The amount of moisture in a fibre not only depends on the chemical nature and molecular texture of the material but also on the humidity of the atmosphere to which it is subjected. The quantity of moisture in a fibre is measured either as percent moisture regain or precent moisture content. The surrounding atmosphere is specified in terms of percent relative humidity and temperature.

A considerable amount of work has been carried out as regards the influence of humidity and temperature on various physical properties of textile materials. Urquhart et al[105,106] measured regain (%) at different relative humidities for cellulosic fibres; Hutton and Gartside[107] and Hill[108] determined regain for Terylene, Acrilan and other man-made fibres. Speakman[109] obtained regain for wool at different relative humidities.

The percent regain of the fibre at constant humidity also depends upon the temperature to some extent. For cotton, Urquhart and Williams[62] found that the regain decreases as the temperature increases excepting at very high temperatures and humidities. Wiegerink[63] determined regain for a variety of fibres between 35°C to 150°C temperature and 0 - 100 (%) relative humidity and also found that regain decreases as the temperature is increased.

When stress is applied to a fibre its regain is changed. In the case of cellulose, Treloar[110,111] found that the regain is increased if the filament is subjected to a tension. On the other hand it has been shown by Mathews[112] that lateral compression, such as would come from applying tension to a twisted yarn, would lower the regain.

The mechanical properties of the fibres are affected by humidity and temperature. Meredith[58] obtained stress-extension curves for various fibres at different relative humidities. Beste and Hoffman[29] measured elastic recovery of fibres at relative humidities of 60% and 90%. They found that at small strains the elastic recovery was less at higher humidities but at longer strains it was greater for most fibres. The effect of temperature on the initial modulus of wet fibre at temperatures between 20°C and 100°C was investigated by Guthrie[66]. He found that the modulus of viscose rayon dropped to a low value as the temperature was raised. Similar results were obtained for Nylon, Terylene and Tricel fibres. King[56] measured the friction for nylon on nylon, wool on horn with different percent regains and found that the coefficient of friction increases as the regain increases.

It would be noticed, however, that very little has been known about the behaviour of fibre mass under different atmospheric conditions. Therefore the present research is undertaken with a view to study the effect of humidity and temperature on the compressional resilience of fibre mass. The important point here is that when a person's head lies on a pillow, the temperature of the fibres near the head will reach approximately body temperature (35°C) and the relative humidity may locally be quite high.

2. EXPERIMENTAL

2.1 Materials

The following fibres were used to measure the bulk-resilience. Care was taken to choose fibres which possessed similar specification in order to draw a reasonable comparison among them.

TABLE XIV

Code No.	Description of the fibre	Staple length (inches)	Linear density (denier)
1	Acrilan, Type - 16, semi-dull normal crimp	2	3
2	Terylene, Filling Type, normal crimp	2 1/4	3
3	Tricel, semi-matt, normal crimp	2	3

2.2 Experiments

To simulate the end-use conditions of fibrefill in pillows, quilts, mattresses, etc., experiments were performed at 45%, 65%, and 85% relative humidities and 20°C, 30°C and 40°C temperatures because these were the most likely conditions which could be created by the human body. For each temperature, resilience tests were made at all the three relative humidities.

For the measurement of resilience, the specimen preparation, testing techniques and test condition experiments were made according to the methods described in detail previously (cf. Chapter II). For each type of fibre, three specimens of 5.5 x 5.5 inches square, with their weights determined so as to keep fibre mass per unit area constant throughout, were prepared and then tested for resilience in the usual manner.

2.3 Gallenkamp Conditioning Oven

The humidities and temperatures were maintained and controlled inside a Gallenkamp conditioning oven. The oven consists of an insulated copper humidity chamber with a separate control compartment. Access to the chamber is provided by a door which has a window and two holes. To these holes are fastened two long rubber gloves which give sealed access for manipulating the specimen before and during a test. A motor driven fan is provided to maintain the proper circulation of air within the chamber.

The oven is designed to maintain a humidity between 0 - 100% r.h. and a maximum temperature up to 100°C. The minimum temperature inside the chamber would depend on the ambient temperature. The appropriate saturated salt solutions [113] are used in order to allow the equilibrium inside the oven to be attained in a minimum time in the case when the ambient humidity is higher than that of the inside one.

The oven is also provided with standard wet and dry bulk thermometers to regulate the temperature and humidity of the chamber. An extra pair of wet and dry bulb thermometers mounted on a stand are kept near the test sample in order to ensure a check on the observations. Percentage relative humidity is obtained from the standard tables.

2.4 Control of Humidity and Temperature

To maintain the required relative humidity and temperature a Gallenkamp oven was used. This oven controlled humidity between 45 $\pm$ 1% to 85 $\pm$ 1% relative humidity and temperature from $20^{\circ} \pm 1^{\circ}C$ to $40^{\circ} \pm 1^{\circ}C$. When the outside humidity of the atmosphere was more than that intended inside the chamber, then in such cases appropriate salt solutions[113] were used to maintain the proper condition.

Since the existing door of the oven was replaced by another door which has a window and two glove parts in order to test a specimen while maintaining any desired conditions, this caused an extra condensation of water particularly at high temperature and humidity. For this reason sufficient precautions were taken to wipe off the moisture from the gloves while handling the specimen inside the chamber during resilience tests.

3. RESULTS AND DISCUSSION

3.1 Effect of Humidity at Constant Temperature

The resilience tests were carried out at 20° ± 1°C temperature with the increasing humidity at 45%, 65% and 85% r.h. This procedure was repeated at 30°C and 40°C temperatures. All specimens were kept inside the oven over a period of 24 hours for each humidity before making the resilience measurement. This was done to ensure that the fibre mass had attained equilibrium as regards its regain.

For each humidity and temperature three tests (specimen) were made from each fibre sample and their mean values determined. The same three specimens were tested at all temperature and humidity combinations. After each test, therefore, the specimens were re-prepared by hand and a sufficient time (24 hrs.) was allowed in between each test in order to make sure that all the fibres in a specimen had sufficiently recovered from previous compression.

The resilience was calculated as ratio of thicknesses at 0.001 to 0.01, 0.001 to 0.10 and 0.001 to 1.0 p.s.i. pressures. The results are given in Table XV a to c. From these Tables, resilience measured at 0.001 to 0.01 p.s.i. (i.e. low pressures) was plotted against humidity and is shown in Figures 29 to 31.

TABLE XV a

Description of fibre	Mass of specimen g.	Temp. °C	85% r.h. (%) Resilience at following pressures			65% r.h. (%) Resilience at following pressures			45% r.h. (%) Resilience at following pressures		
			0.001 to 0.01 psi	0.001 to 0.10 psi	0.001 to 1.0 psi	0.001 to 0.01 psi	0.001 to 0.10 psi	0.001 to 1.0 psi	0.001 to 0.01 psi	0.001 to 0.10 psi	0.001 to 1.0 psi
Acrilan, Type-16 2" 3d	5.05	20	81.0	68.5	57.5	86.5	76.0	69.5	88.5	78.0	70.5
" "	"	30	83.5	68.0	59.0	87.3	76.0	70.0	88.5	78.5	72.5
" "	"	40	87.0	71.0	61.5	88.5	77.0	71.0	89.0	78.0	73.0

<u>TABLE XV b.</u>

Description of fibre	Mass of specimen g.	Temp. °C	85% r.h. (%)Resilience at following pressures			65% r.h. (%)Resilience at following pressures			45% r.h. (%)Resilience at following pressures		
			0.001 to 0.01 psi	0.001 to 0.10 psi	0.001 to 1.0 psi	0.001 to 0.01 psi	0.001 to 0.10 psi	0.001 to 1.0 psi	0.001 to 0.01 psi	0.001 to 0.10 psi	0.001 to 1.0 psi
Terylene, Filling Type, $2\frac{1}{4}$" 3d	5.0	20	83.0	76.0	70.0	86.0	77.0	72.0	89.0	79.0	75.7
"	"	30	84.0	76.5	71.0	87.0	79.0	73.0	89.0	80.5	75.8
"	"	40	86.0	78.0	71.0	88.0	80.5	73.0	89.5	80.8	75.0

TABLE XV c

Description of fibre	Mass of specimen g.	Temp. °C	85% r.h. (%) Resilience at following pressures			65% r.h. (%) Resilience at following pressures			45% r.h. (%) Resilience at following pressures		
			0.001 to 0.01 psi	0.001 to 0.10 psi	0.001 to 1.0 psi	0.001 to 0.01 psi	0.001 to 0.10 psi	0.001 to 1.0 psi	0.001 to 0.01 psi	0.001 to 0.10 psi	0.001 to 1.0 psi
Tricel, 2" 3d	5.05	20	65.0	62.0	56.0	70.0	63.5	56.0	74.0	65.0	59.0
"	"	30	69.0	64.0	56.0	73.0	64.5	56.5	75.0	65.0	60.0
"	"	40	73.0	66.0	56.0	75.0	65.5	58.0	76.0	65.5	60.5

Figures 29 to 31 indicate that the resilience of fibres in bulk in the case of Acrilan, Terylene and Tricel fibre samples, decreases as the percent relative humidity increases. This is probably due to the fact that the elastic modulus (initial modulus) of most man-made fibres is reduced with the moisture and the fibre becomes weaker which in turn seems to affect the resilience. Meredith[58] determined stress-extension curves of various fibres at different relative humidities and found that all the man-made fibres become more extensible at high humidities, the modulus becoming smaller and the breaking extension greater, and the fibres become weaker. However, it has been pointed out by Morton and Hearle[114] that the fibres which absorb little water, their properties would not be expected to vary much with humidity. Further, it is believed that the elastic recovery of the fibre contributes towards increasing the resilience of fibres in bulk. It follows that if the elastic recovery is increased it is quite likely that the resilience may also increase and vice-versa. Beste and Hoffman[29] have shown that the tensile elastic recovery from small strains of most fibres decreased as the relative humidity is raised. This suggests that the resilience of fibres may be reduced with an increase of relative humidity, due to the possible decrease in elastic recovery of a fibre from samll extensions.

Further, it seems reasonable to think that the decrease in resilience with relative humidity (Figures 29 to 31) can be due to inter-fibre friction. The water acts as a lubricant and after a definite percent regain in a fibre, the coefficient of friction increases with increase of regain. King[56] has obtained an increase in coefficient of friction in case of nylon as the moisture regain is increased. Therefore, it is also possible in this case that by increasing relative humidity the coefficient of friction is increased which may be partially responsible for the reduction in resilience at high humidities.

In the case of present results, therefore, it seems likely that the resilience of a fibre mass may be reduced with increase in relative humidity (Figures 29 to 31) due to variation in both elastic properties and inter-fibre friction with humidity. It is, however, not possible to conclude exactly which of the two main properties (elastic or friction) affect more in the case of variation in bulk resilience with humidity, but it appears certain that both these properties are involved in such studies.

It can also be noted from Table XV a to c that the resilience has been measured under low, medium and high pressures, i.e. between 0.001 to 0.01, 0.001 to 0.10 and 0.001 to 1.0 p.s.i. pressures. This was done to study the effect of maximum pressure as regards the variation in resilience of fibres in bulk with relative humidity. The resilience measured at low, medium and high pressure show the same trend with humidity, in other words the resilience determined at low, medium and high pressures decreases as the humidity is increased.

Further the Table XV a to c indicates that the resilience of Acrilan, under low pressures (0.001 to 0.01) is as high as that of Terylene at all the three relative humidities (85%, 65% and 45%), whereas the resilience of Acrilan drops as compared to that of Terylene at 45%, 65% and 85% r.h. in the case of both medium and high pressure measurements. It can also be noted that the rate of change of resilience with relative humidity in the case of Acrilan is more than Terylene as the maximum pressure in a cycle increases.

3.2 Effect of Temperature at Constant Humidity

The results showing the influence of temperature on the bulk resilience of fibres (Acrilan, Terylene and Tricel) are also presented in Table XV a to c. From these results the resilience determined at low pressures (0.001 to 0.01 p.s.i.) are plotted in Figures 32 to 34 with increasing temperature at various humidities (85%, 65% and 45% r.h.) for Acrilan, Terylene and Tricel fibres.

It can be seen from these results that there seems to be an increase in resilience with the increase in temperature at a constant humidity for all the fibres (Acrilan, Terylene and Tricel). The similar behaviour is obtained at all the three humidities (45%, 65% and 85% r.h.) for Acrilan, Terylene and Tricel (Figures 32 to 34). It is probably due to the following reasons:

Within the range of temperature investigated (20°C to 40°C) it seems more likely that the moisture regain of a fibre is reduced as the temperature is increased at a constant humidity.

This reduction in regain in turn perhaps increases the resilience due to decrease in inter-fibre friction. Urquhart and Williams[105] have shown that the moisture regain decreases as the temperature is increased at constant humidity for viscose and other fibres. King[56] has shown an increase in coefficient of friction in the case of nylon as the moisture regain is increased. From these observations it seems reasonable to conclude that the increase in temperature reduces the moisture regain; this in turn reduces the inter-fibre friction. Consequently with the increase in temperature (over the investigated range i.e. 20°C to 40°C) the resilience of fibre mass is enhanced. It should be remarked, however, that the effect of temperature generally has been studied in two distinct regions, that is, at high temperatures and at low temperatures. At high temperature, the most materials become soft, more extensible and also the recoverty behaviour is reduced, whereas at low temperatures, some other important changes in various physical properties take place, such as obtained by Urquhart and Williams[105] and King[56].

The results in Table XV a to c show the resilience of fibres (Acrilan, Terylene and Tricel) at low, medium and high pressures, i.e. between 0.001 to 0.01, 0.001 to 0.10 and 0.001 to 1.0 p.si. respectively. It is seen from these results that the variation in resilience with temperature at all three humidities (45%, 65% and 85% r.h.) indicate the same trend irrespective of the maximum pressure in a cycle, that is, the resilience increases with the increase in temperature over the investigated range. Further, a close examination of the results show that the increase in resilience with temperature is more pronounced at high relative humidity as compared to low relative humidity.

3.3 Comparison of Variation in Resilience with both Humidity and Temperature for Acrilan, Terylene and Tricel fibre samples:

When the relative humidity is increased, it can be seen from Figures 29 to 31 that the resilience decreases, the rate of change of resilience with relative humidity is higher for Tricel than both Acrilan and Terylene, and Acrilan shows a greater rate of change as compared to Terylene. It means that the resilience drops at a much faster rate with an increase in relative humidity in the case of Tricel, followed by Acrilan and Terylene respectively. This appears due to the fact that Tricel possesses a high percent regain, whereas Terylene has a low regain and Acrilan occupies an intermediate position at any constant humidity. Consequently, in the case of Tricel the variation in regain with relative humidity would be more as compared with both Acrilan and Terylene. This in turn seems to affectthe rate of change of resilience with relative humidity accordingly for all fibre samples.

Further, the results (Figures 32 tc 34) showing the effect of temperature indicate that resilience increases with the increase in temperature at a constant humidity for Acrilan, Terylene and

Tricel fibre samples. From these results it is clear that the rate of change of resilience with temperature is much faster in the case of Tricel, Acrilan and Terylene lie behind second and third respectively. As has been argued before while considering the influence of relative humidity, it also appears due to different percent regain in Tricel, Acrilan and Terylene and its variation with temperature in these fibres, which may possibly account for this difference in the rates of change of resilience with temperature.

CHAPTER V

SURFACE FINISH ON THE FIBRE

CONTENTS

CHAPTER V

SURFACE FINISH ON THE FIBRE

1. INTRODUCTION

It is a matter of common practice to apply various finishes whenever it is desired to modify the surface properties of the fibres. Usually the effect of such finishes is to vary the inter-fibre friction. The choice of the finish, however, depends on the particular process of manufacturing or end-use conditions of the material. For example, surface finish is applied to the fibre in order to eliminate static electrification, in separating fibres during carding and in various other applications in the field of textiles.

The effect of lubrication (surface finish) on the textile materials during different manufacturing processes and for various purposes have been reported in the literature[115]. Van Wyk[93] and Matsuo[98] have pointed out the importance of inter-fibre friction while considering the behaviour and performance of fibre assemblies. It is, however, not yet clear or properly understood how much the fibre friction contributes towards the resilience of fibre mass. The aim of this research, therefore, is to apply a surface finish to a fibre in various proportions to vary fibre friction in order to investigate precisely how much it is possible to improve the resilience of fibres in bulk by varying the inter-fibre friction.

2. EXPERIMENTAL

2.1 Materials

Acrilan, 2 inch 3 denier, semi-dull, normal crimp, Type-16, fibre was used for these experiments. "C.F.15" surface finish - a chemical finish developed by Chemstrand Ltd.[116] was applied to vary the surface properties of the material.

2.2 Application of Finish

Since only Acrilan fibre with normal finish level was available, it was necessary to remove the existing finish. This was done by extracting the finish from the fibre using methanol as solvent in a Soxhlet apparatus.

After extracting the existing surface finish, the clustered mass of fibres was opened thoroughly by hand so as to ensure the uniform application of the finish. The "C.F.15" finish was applied from four different baths. The concentrations of these baths were 5%, 10%, 20% and 40%. The extracted fibres were then dipped in each of these baths maintained at 30°C for a period of 5 minutes in order to obtain the fibre samples possessing different amounts of percent finish. During this period the fibres were stirred constantly. Finally the fibres were taken out of the baths, squeezed gently by hand to remove the soaked solution of the "C.F.15" finish, opened and dried in an oven at 40°C for 24 hours. In this way four fibre samples were obtained which possessed different percent finish level. In addition, a fifth fibre sample was taken which had no finish at all, that is, after removing the existing finish.

2.3 Determination of Percent Finish

In order to assess the exact effect of the surface modification due to the surface finish, it is necessary to measure the amount of finish applied to the fibre. The method is described below[116].

Procedure:

On an analytical balance, weigh 5 - 7 g. of fibre sample (w_1) and a 300 ml. Soxhlet receiving flask (w_2). Carefully place the sample in the extractor and be sure that the top of the fibre sample is below the upper bend of the siphon. Now add the methanol in the extractor care being taken so that the solvent does not siphon over. Afterwards connect the extractor and receiving flask to the condenser and add further methanol through the condenser until the solvent siphons over. Then add about 25 ml. more methanol.

Next, with the hot plate set at full heat, extract the fibre sample with methanol for about 3 hours after it starts to boil. End the extraction with the solvent level in the extractor as high as possible without having the methanol siphon over. Turn off the hot plate and allow it to cool. Remove the receiving flask and take it to dryness on a steam bath. Finally remove the flask from the steam bath, wipe the outside of it dry and place the flask in the oven set at 105°C for 1 hour. Then cool the flask in a desiccator and again on an analytical balance weigh it (w_3).

Calculations:

The percent finish level is calculated as follows:-

$$(\%) \text{ Finish level} = \frac{w_3 - w_2}{w_1} \times 100$$

where w_3 = weight of flask and finish

w_2 = weight of flask

w_1 = weight of fibre sample.

2.4 Experiments

Five samples of Acrilan fibre (2" 3d, normal crimp) with the following specifications were prepared (according to the method described above) to study the resilience of fibre-mass in relation to the surface properties thus modified.

Fibre samples with zero finish level, i.e. just after removing the existing finish, and also with surface finish applied from 5%, 10%, 20% and 40% solution of the finish (C.F.15 finish), were prepared.

The coefficient of friction of a fibre and percent finish level was determined to characterise each of the prepared samples with different amount of finish. The friction measurements were made by an instrument, the details of which have already been given elsewhere in the thesis. The percent finish level was determined according to the method given above in the earlier section. Three readings were taken for each sample and the mean value of percent finish level was calculated.

To measure the resilience, three specimens of 5.5 x 5.5 inches square area, with their weights determined so as to keep the density of fibres in the specimen constant were prepared and tested in the usual manner. The details of these tests have also been given in Chapter II.

3. RESULTS AND DISCUSSION

The resilience of each fibre sample with different amount of finish was obtained. Also, the coefficient of friction of a fibre and percent finish level of each sample was determined. The results are given in Table XVI and then discussed.

3.1 Effect of Inter-fibre Friction

It is evident from Table XVI that there is a gradual decrease in the coefficient of friction of a fibre as the amount of percent finish applied is increased. However, this trend is continued only up to a certain value of finish level and beyond which the friction increases with the increase of finish applied to a fibre. This is probably due to the fact that the frictional force decreases with the application of any lubrication only when it is applied in a definite proportion. Further increase of either the viscosity of the lubricant or the amount of lubricant is likely to increase the friction. Lyne[117] found that in the case of acetate yarn with more than 1% of oil applied, the frictional force increases both as the oil content is increased, and as the viscosity of the oil increases. The coefficient of friction of Acrilan-16 fibre is

TABLE XVI

Code No.	Description of fibre	Amount of finish %	Coefficient of friction	(%) Resilience as ratio of thicknesses at following pressures:- 0.001-0.01 p.s.i.	0.001-0.10 p.s.i.	0.001-1.0 p.s.i.
1	Acrilan, 2" 3d	0.0	0.40	78.0	70.0	60.5
2	"	0.505	0.33	81.0	72.0	64.0
3	"	1.025	0.24	83.0	73.0	65.8
4	"	1.320	0.20	84.0	73.7	67.0
5	"	1.500	0.22	83.5	73.8	66.5

reduced from 0.4 with no surface finish on it, to 0.2 and it is believed that it is not possible to decrease the value of coefficient of friction farther down than 0.2, because this seems to be its limit in the present case.

Figure 35 shows the effect of fibre friction (as modified by the application of surface finish in various proportions) on the resilience of fibre mass of Acrilan-16 (2" 3d) sample. It is clear from these results that the resilience increases as the coefficient of friction decreases and there seem to be a linear relationship between them. Further, it is seen that same trend is obtained as regards resilience and coefficient of friction of a fibre, irrespective of the maximum pressure in a cycle during resilience measurement. However, there seems to be a slight tendency for the resilience versus coefficient of friction curve to bend at high values of friction, when the resilience is measured at high pressures, i.e. between 0.001 to 1.0 p.s.i. pressure.

3.2 Effect of Finish Level

The effect of percent finish level (i.e. the amount of finish applied to the fibre) on the resilience of Acrilan-16 fibre sample is shown in Figure 36. The resilience increases as the finish level increases but only up to a certain value of finish level, beyond it the resilience decreases. The reason for this effect seems to be due to the variation in fibre friction, since the point where the resilience starts to decrease with the increase of finish level is the same where the increase in fibre friction with percent finish is noticed (Table XVI).

It is reasonable to conclude from the above discussion that if it is possible to decrease substantially (below 0.2) the coefficient of friction of Acrilan-16 fibre, then such a mass may possess a high resilience. It should, however, be remarked that such a fibre mass may create some extra problems while opening it on a machine like a power-driven card. Since the fibres are usually clustered and need opening before they can be used for filling and other similar purposes.

CHAPTER VI

SUMMARY AND CONCLUSIONS

CHAPTER VI

SUMMARY AND CONCLUSIONS

This research was undertaken with two main aims: (1) to evaluate the proper test conditions for determining the resilience of fibres in bulk, (2) to investigate which intrinsic fibre properties are involved in a resilient fibre mass. Acrilan, Terylene and Tricel fibres of different specifications (e.g. fibre length, diameter, crimp, etc.) were used.

A Shirley Thickness Gauge was employed for the measurement of resilience and was considered more suitable for the present work because it simulates the end-use conditions of a fibrefill in pillows, mattresses, etc. in which the load is defined rather than the deformation. Also, it possesses the advantage that the thickness of the fibre mass may be measured directly under extremely low pressures.

In an attempt to standardise the resilience test, first of all the influence of time cycle was investigated. Four combinations of time cycle were used, namely, compression for 12 seconds, 1 minute, 1 hour and 5 hours with recovery for times of 1 minute, 5 minutes, 5 hours and 24 hours respectively. The main consideration in choosing these time cycle combinations was to see whether the resilience measured with short loading and recovery times was the same as that measured with longer loading and recovery times. It was found that the resilience of a fibre mass did not vary over the investigated range of compression-recovery times and that the resilience test could be carried out as a short time test.

The next stage of this work was to study the effect of (1) pressure at which the resilience was measured, and (2) the maximum pressure used in a compression-recovery cycle. Various combinations of pressure were tried. It was then decided to use a cyclic loading between 0.001 to 1.0 p.s.i. pressures; five load-recovery cycles were employed in this range to reach the maximum pressure of one pound per square inch. The time allowed for recovery under each load was twice than that of the corresponding compression time. This enabled the resilience to be measured at low, medium and high pressure (i.e. between 0.001 to 0.01, 0.001 to 0.10 and 0.001 to 1.0 p.s.i.) in the minimum time.

Experiments were performed to investigate the effect on the resilience of (1) area and thickness of specimen using a constant area presser foot and (2) size and shape of the presser foot.

The areas of the specimen selected were 3.6 x 3.6, 4.5 x 4.5, 5.5 x 5.5 and 7.5 x 7.5 inches square, the smallest area having a linear dimension equal to the diameter of the presser foot and thus covered a fairly wide range. The effect of the specimen thickness was investigated on 1, 2, 3 and 4 inch thick specimens of constant area (5.5 x 5.5 in. sq.). The weights of the specimens were determined so as to maintain the density of fibres in a specimen the same. It was observed that the resilience of a fibre mass was independent of both specimen area and thickness if tested under a constant size presser foot between a pressure limit of 0.001 to 1.0 p.s.i.

When the effect of the size and shape of presser foot was investigated, experiments were carried out with three circular feet of 2.52, 3.57, and 5.05 inch diameter, i.e., plane compressing surface of 5, 10 and 20 sq. inch area respectively and with a fourth foot of hemispherical compressing surface, the maximum diameter of which was equal to that of the standard foot (10 sq. in. area). For these experiments, specimens of 5.5 x 5.5 inches square in area and approximately 4 inches thick of known weights were tested. The results showed that the resilience was not affected by the size of presser foot. As regards the shape of the foot, it was noticed that the resilience determined under a plane surface presser foot was higher than that measured under a foot of hemispherical shape.

After standardising the test conditions, the factors which are involved in the resilience of fibres were investigated. In the first instance, the resilience of all the fibre samples (Acrilan, Terylene and Tricel) was determined. Then the following fibre properties were studied in relation to their resilience,

(1) Fibre length (2) Linear density
(3) Crimp characteristics (4) Inter fibre friction
(5) Tensile elastic recovery (6) Tensile modulus.

The staple length of Acrilan fibres ranged from 1 9/16 to 2 inch, for Terylene and Tricel fibres it varied from 1½ to 4½ inches and 2 to 5 inches respectively. The results indicated that there was no significant correlation between fibre length and resilience.

When considering the effect of fibre diameter on resilience, linear density (denier) of Acrilan (2 to 15 denier), Terylene (1½ to 10 denier) and Tricel (2 to 4½ denier) were determined. It was found that the resilience was greater in the case of the thicker fibre, in other words the resilience increases as the fibre diameter increases. This is probably due to the bending of fibres in compression, since the bending modulus varies directly with the square of fibre diameter.

Crimp measurement experiments were carried out and the values of percent crimp in a fibre, uncrimping force and uncrimping energy were calculated for each fibre sample. For Acrilan fibres percent crimp ranged between 6.2 to 25.6, whereas for Terylene and Tricel it varied from 8.0 to 15.4 and 6.0 to 13.0 respectively. The results indicated that the resilience increases as the percent crimp increases up to a certain value only, beyond which it has no appreciable effect. In the case of Acrilan fibres, no further increase in resilience was observed beyond 15% crimp. Terylene and Tricel fibres also showed similar tendencies. Further, it was noticed that the fibre which required greater force to remove crimp and also possessed high uncrimping energy, showed high resilience.

In an attempt to see if the nature of the crimping process (e.g. mechanically or chemically crimped) had any influence on resilience, it was found that the chemically crimped fibres possessed as high a resilience as was obtained with the corresponding mechanically crimped fibres.

In order to investigate the effect of inter-fibre friction on resilience, coefficient of friction between two identical fibres making a single point contact was determined for each fibre sample. The results showed that the resilience decreases with the increase in the coefficient of friction of the fibre and there appears to be a linear relationship between these two quantities.

The tensile elastic recovery was measured both from 2% and 5% extensions on an Instron tester employing a constant rate of extension and contraction. From these traces the initial modulus of a fibre was also computed. It was concluded that there was no correlation between elastic recovery and resilience. Also the initial modulus results did not indicate any correlation with resilience.

The possibility of expressing the thickness - pressure relationship by an equation was considered. The analysis of $\log_{10}$ (thickness) versus $\log_{10}$ (pressure) between 0.001 to 1.0 p.s.i. pressures for each fibre sample, indicated that the results could be best fitted to the most widely used empirical exponential equation:

$$T = a P^b$$

where 'T' is the thickness of fibre mass in inches, 'P' is the pressure in p.s.i. and 'a' and 'b' are constants.

Since the fibres are hygroscopic materials their mechanical properties are affected by both humidity and temperatures. Therefore the behaviour of a fibre mass under different atmospheric conditions was studied from the resilience point of view. Experiments were carried out with Acrilan, Terylene and Tricel fibres at relative humidities of 45%, 65% and 85% and temperatures of 20°C, 30°C and 40°C because these covered the most likely conditions which could be expected from the end-use considerations of the fibrefill in pillows, etc. It was found that the resilience of fibres in bulk decreases with increase in relative humidity at a constant temperature. The rate of change of resilience with relative humidity was higher for Tricel than both Acrilan and Terylene, and Acrilan showed a greater rate of change as compared with Terylene. When the influence of temperature was considered, it was observed that there appeared to be an increase in resilience with increase in temperature at a constant humidity. In this case the rate of change of resilience with temperature was faster for Tricel, Acrilan and Terylene remained behind second and third respectively.

The effect of surface finish on Acrilan fibre was studied in relation to the resilience. The 'C.F.15' surface finish - a chemical finish developed by Chemstrand Limited was applied in different proportion (with zero percent finish and also with finish applied from 5%, 10%, 20% and 40% solution of the finish) to vary the surface properties of the fibre. It was found that the resilience increases as the amount of finish applied to the fibre increases but only up to a certain value of finish percent, beyond which the resilience decreases. This was probably due to the variation in fibre friction which was found to decrease with the increase in the amount of finish on the fibre only to a definite value and the further increase of percent finish on the fibre caused an increase in the fibre friction.

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A P P E N D I X

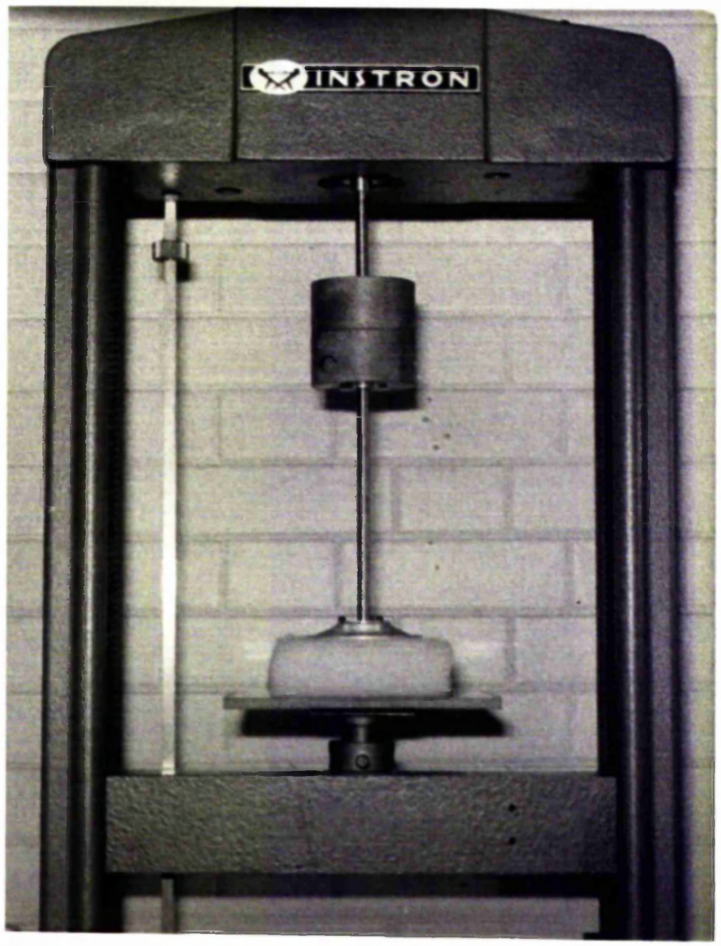
A Comparison of Resilience obtained by using a Shirley Thickness Gauge and an Instron:

In the present research, a Shirley Thickness Gauge was mainly employed because it simulates the end-use conditions of a fibrefill in pillows, mattresses etc. in which the load is defined rather than the deformation. Also, it possesses the advantage that the thickness of the fibre mass may be measured directly under extremely low pressures. However, resilience measurements were also made with an Instron tensile tester in order to make a comparison between the two methods.

Equipment

For measuring resilience on an Instron a compression unit shown in Figure 37 was constructed. The unit consists of a Square base of 10 inches side mounted on the cross-head of Instron and a presser foot of 10 square inches area which is connected by means of a rod to the load cell B. Initially, the presser foot was loaded to the maximum presser (0.1 p.s.i.) and the cross-head was moved first upwards and then downwards in order to obtain a compression-recovery trace for resilience measurements. The specimen was placed on the base of the compression unit directly underneath the presser foot.

Fig.37. Compression unit on Instron Tester



Experiments

Resilience measurements were performed on the same specimens of Acrilan and Terylene fibres as were used for similar studies using the Shirley thickness gauge. Two compression-recovery cycles from zero to 0.01 p.s.i. and from zero to 0.1 p.s.i. were made and resilience was calculated as a ratio of thickness at 0.001 p.s.i. pressure for both the cycles (i.e. between 0.001 to 0.01 and 0.001 to 0.1.p.s.i.). The fibre mass was kept under compression for a period of 1 minute and then allowed to recover for 2 minutes. A mechanical conditioning cycle of 30 seconds compression and 1 minute recovery under a maximum pressure of 0.1 p.s.i. was used. The Instron settings used were as follows:

Gauge length	= 2 inches
Cross-head speed	= 0.5 inch/minute
Chart speed	= 1.0 inches/minute
Full scale load	= 1 pound

Results and Discussion

The results of the experiments together with the values of resilience obtained from the Shirley thickness gauge are given in the Tables XVII a. and b. For each sample three tests were made and the mean values calculated. The low pressure results from these Tables XVII a. and b. are plotted in Figure 38. The loading-unloading cycles for both the methods are shown in Figure 39.

TABLE XVII a.

<u>Acrilan</u>

Code No.	Kind of Fibre	Shirley Thickness Gauge (%) Resilience at following pressures:- 0.001 to 0.01 p.s.i.	Shirley Thickness Gauge (%) Resilience at following pressures:- 0.001 to 0.10 p.s.i.	Instron Tester (%) Resilience at following pressures:- 0.001 to 0.01 p.s.i.	Instron Tester (%) Resilience at following pressures:- 0.001 to 0.1 p.s.i.
A_1	Type-16, 2"-3d	80.5	73.0	86.0	79.0
A_2	" , 2"-3d	86.0	74.2	88.0	80.0
A_3	" , 2"-8d	88.0	79.6	90.0	82.0
A_4	" , 2"-2d	78.0	72.0	84.0	78.0
A_5	" , 2"-5d	86.3	78.9	88.0	81.0
A_6	" , 2"-15d	89.5	80.9	92.5	82.0
A_7	" , $1\frac{9}{16}$"-2d	83.4	74.8	86.0	79.0
A_8	" , $1\frac{9}{16}$"-5d	84.5	73.0	86.5	79.8
A_9	" , $1\frac{9}{16}$"-15d	85.6	76.5	88.0	80.0

TABLE XVII b.

Terylene

Code No.	Kind of Fibre	Shirley Thickness Gauge (%) Resilience at following pressures:- 0.001 to 0.01 p.s.i.	Shirley Thickness Gauge (%) Resilience at following pressures:- 0.001 to 0.1 p.s.i.	Instron Tester (%) Resilience at following pressures:- 0.001 to 0.01 p.s.i.	Instron Tester (%) Resilience at following pressures:- 0.001 to 0.1 p.s.i.
P_1	Cotton Type, $1\frac{1}{2}$"-$1\frac{1}{2}$d	78.5	71.3	84.0	76.0
P_2	" " , $1\frac{1}{2}$"-3d	80.5	73.5	85.8	77.0
P_3	Filling " , $1\frac{1}{2}$"-3d	82.0	74.5	86.0	78.5
P_4	" " , $2\frac{1}{4}$"-3d	85.5	75.7	90.0	80.5
P_5	Flax " , $2\frac{1}{2}$"-4d	86.3	75.8	90.8	80.5
P_6	Wool " , $2\frac{1}{2}$"-3d	79.0	70.5	84.0	75.0
P_7	" " , $3\frac{1}{2}$"-6d	80.3	73.5	85.0	78.0
P_8	" " , $4\frac{1}{2}$"-10d	86.0	74.0	90.6	80.0

It is evident from the results in Tables XVII a. and b. that the values for the resilience of a fibre mass (Acrilan and Terylene) measured on an Instron tester are slightly higher than those obtained from the Shirley thickness gauge. Further it is clear from the Figure 38 that the resilience of Terylene fibre samples as measured by means of Instron is 5% higher as compared to the corresponding values for resilience obtained from Thickness gauge. In the case of Acrilan fibre samples the values for resilience measured with Instron are nearly 3% more than the corresponding values of resilience determined by Thickness gauge. In this instance, it should however, be noted (Figure 38) that the samples code nos. A_1 and A_4 rather behave little different than rest of the Acrilan fibre samples and indicate a difference in the values for resilience of about 5%. Comparing the values of resilience for Acrilan fibre samples with those of Terylene fibre samples, it is clear (Figure 38) that Terylene has slightly low resilience. The difference between the values of resilience for Terylene (5%) measured by using an Instron and Shirley thickness gauge is more than that for Acrilan (3%). This is probably due to the fact that Terylene fibre as a group has a low coefficient of fibre friction (0.20) than Acrilan as a group (0.26). The high values for resilience in the case of Acrilan as compared to Terylene, however, are obtained because the Acrilan fibres possess greater amount of crimp which undoubtedly play a more dominant part in such cases.

The compression-recovery time cycles are shown in Figure 39. In a resilience test, the time required to reach the maximum load in the case of Thickness gauge (30 secs. for low pressures and 50 secs. for high pressures) is one third of the time required for Instron (96 seconds for low pressures and 180 seconds for high pressures), whereas when considering recovery the same relationship between these two time periods is not true because the fibres are made to recover in twice longer period in the case of Thickness gauge (180 seconds and 480 seconds at low and high pressures respectively) as compared to time required to unload the fibre mass on the Instron. Further, it is to be noted that the fibre mass is kept compressed for 60 seconds at maximum load while using Instron. The recovery time allowed at zero load is 300 seconds (low pressure) and 600 seconds (high pressures) when using Thickness gauge and 120 seconds each for both low and high pressure cycle in the case of Instron tester. The difference between the rates of loading and recovery and also the compression and recovery times both at zero and maximum pressure in a resilience cycle may probably account for the slight difference in the values of resilience as determined by these two instruments.

Further a close examination of Figure 39 indicates that the recovery time (for Shirley thickness gauge 180 seconds and 480 seconds at low and high pressures respectively, and for Instron 120 seconds each for both low and high pressure cycle) perhaps dominates the overall recovery from compression which in turn affects the resilience. Therefore, in an attempt to find out the precise reason for the difference between the values of resilience determined both by using a Shirley thickness gauge and an Instron, resilience measurements for three Acrilan fibre samples code nos. A_1, A_2 and A_3 were carried out by Thickness gauge and in these experiments the fibre mass was recovered in one single step from the maximum pressure (0.01 p.s.i. for low pressure cycle and 0.10 p.s.i. for high pressure cycle) to 0.001 p.s.i. pressure. These values are shown in Table XVIII.

TABLE XVIII

Code No.	*Shirley Thickness Gauge (%) Resilience at following pressures:-*		*Instron Tester (%) Resilience at following pressures:-*	
	0.001 to 0.01 p.s.i.	*0.001 to 0.10 p.s.i.*	*0.001 to 0.01 p.s.i.*	*0.001 to 0.10 p.s.i.*
A_1	87.5	80.5	86.0	79.0
A_2	88.5	82.0	88.0	80.0
A_3	92.0	83.5	90.0	82.0

As expected the values for resilience (Table XVIII) obtained by means of Shirley thickness gauge are higher than those determined by using an Instron. Therefore, it is clear that the difference between the values for resilience as measured by both these instruments is more due to the rate and nature of recovery.

Further it is seen from the results (Tables XVII a. and b.) that the fibre samples (Acrilan and Terylene) can be ranked in the same order from the resilience point of view by these methods and that the range of resilience values for the samples (78 to 89.5% for Acrilan and 78.5 to 86.3% for Terylene) is greater when measured by means of the Thickness gauge as compared with the values of resilience (84 to 92.5% for Acrilan and 84 to 90.8% for Terylene) determined with the Instron.

It is concluded that resilience measurements can be made with either instrument (i.e. Shirley Thickness Gauge or Instron Tester). The Instron, however, possesses the advantages that it is quicker and is also more convenient to use.

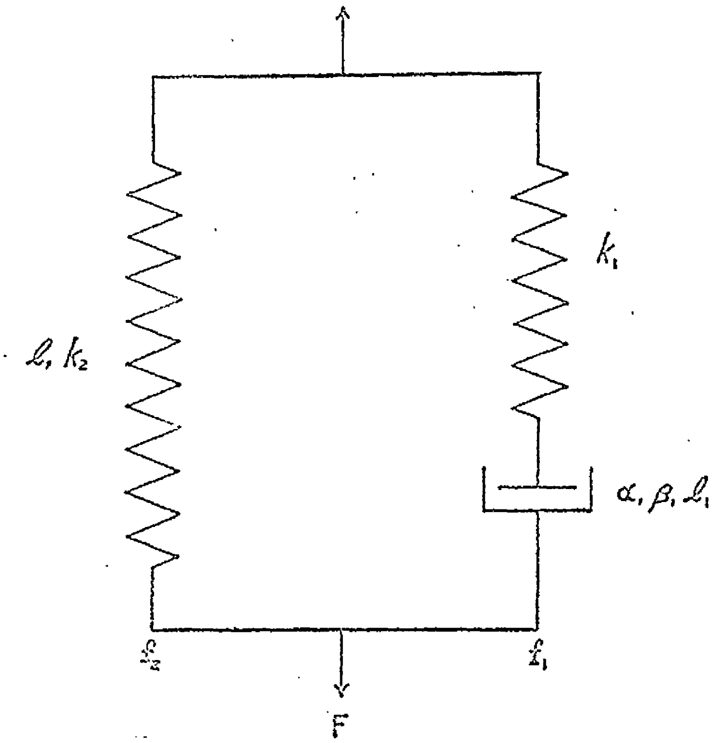


Fig. 1a

The "three-element" model of Eyring and coworkers.

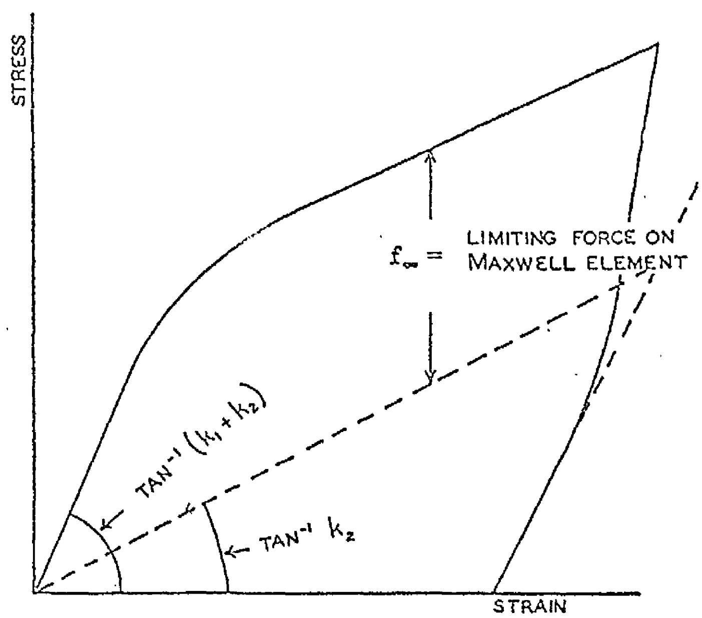


Fig. 1b

Principal features of a stress-strain cycle.

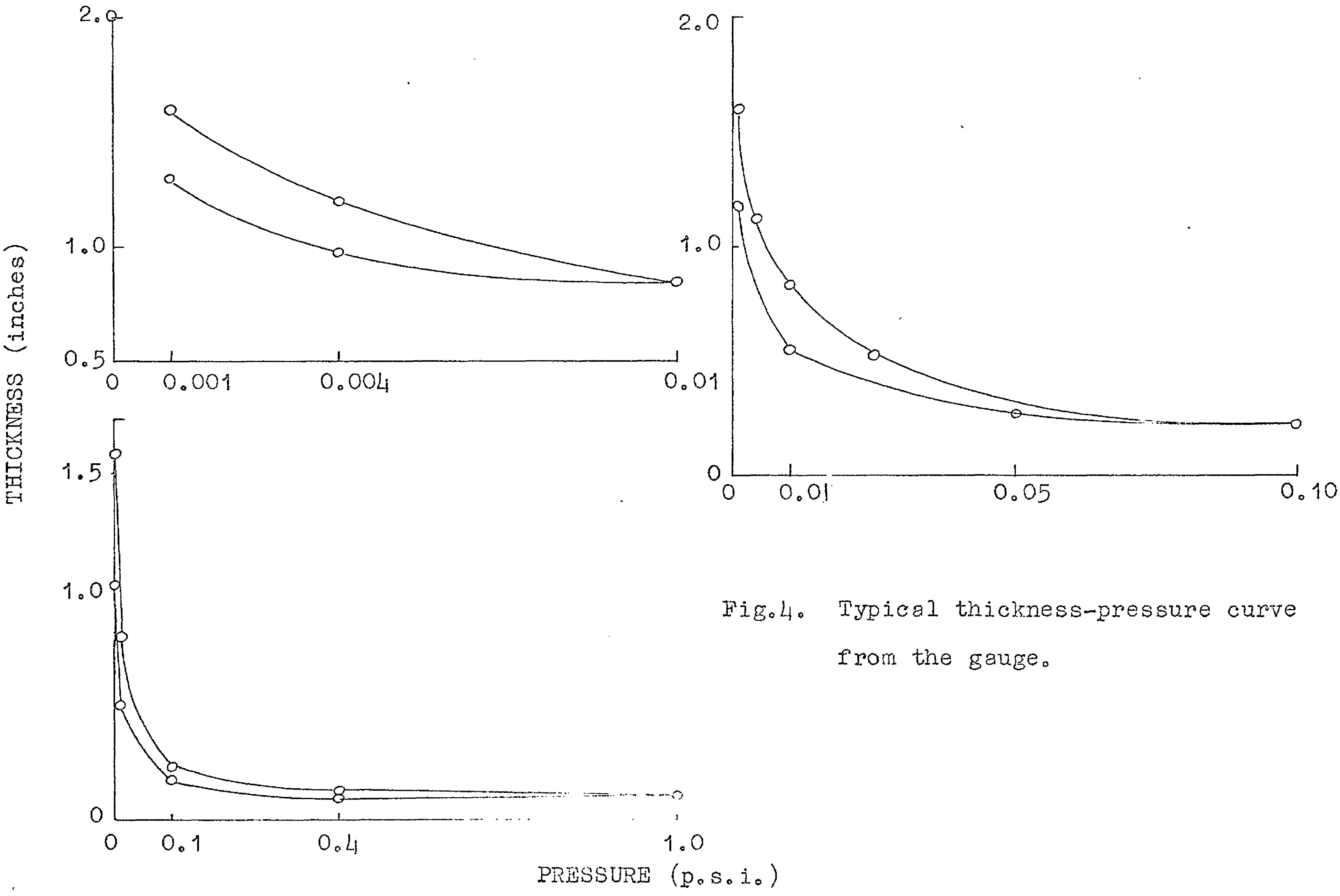


Fig.4. Typical thickness-pressure curve from the gauge.

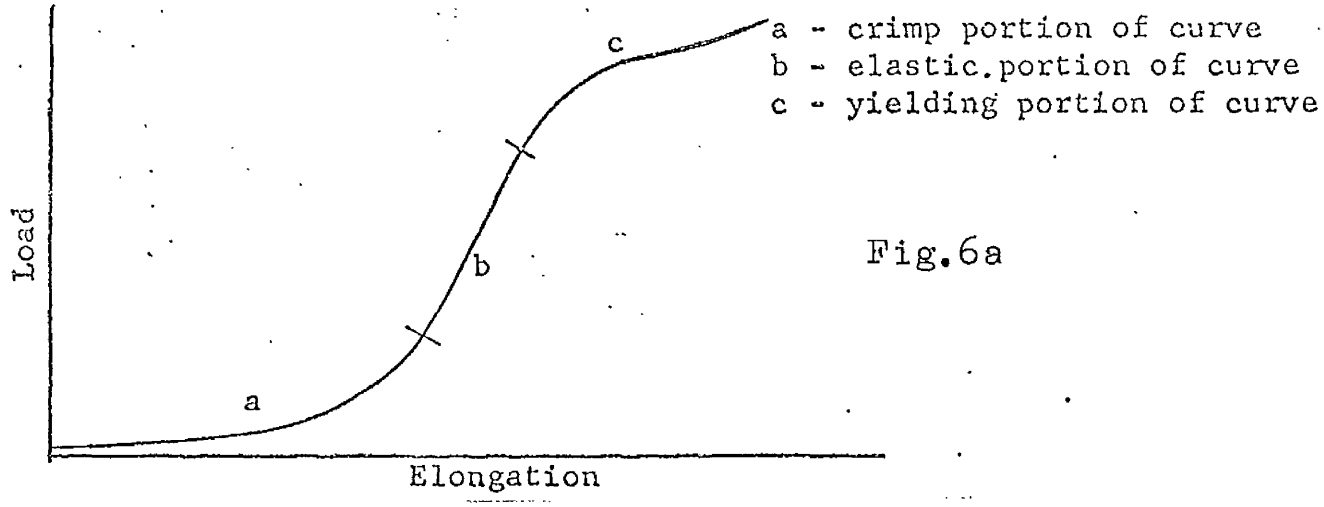


Fig.6a

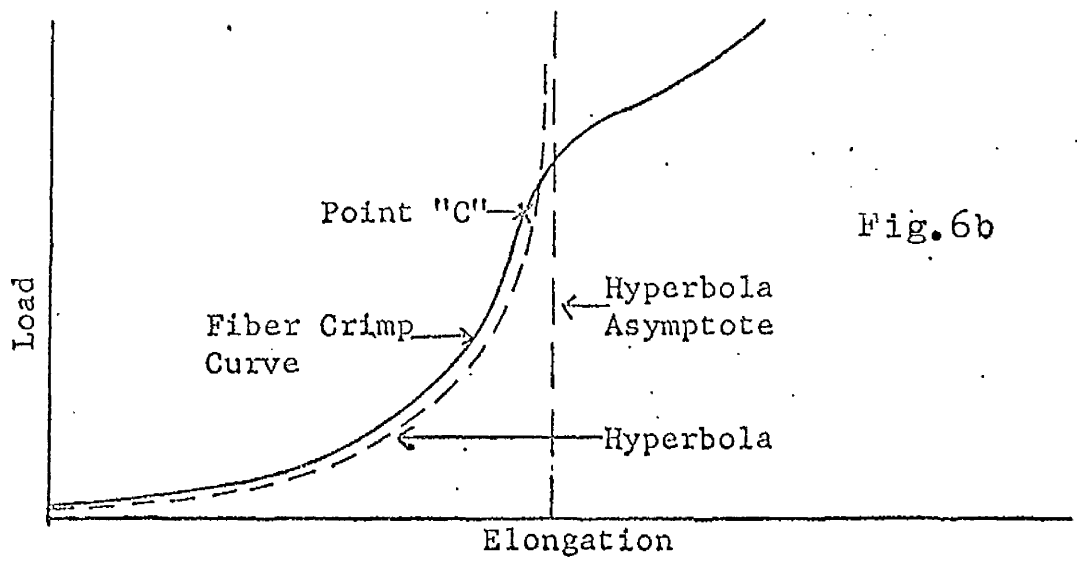


Fig.6b

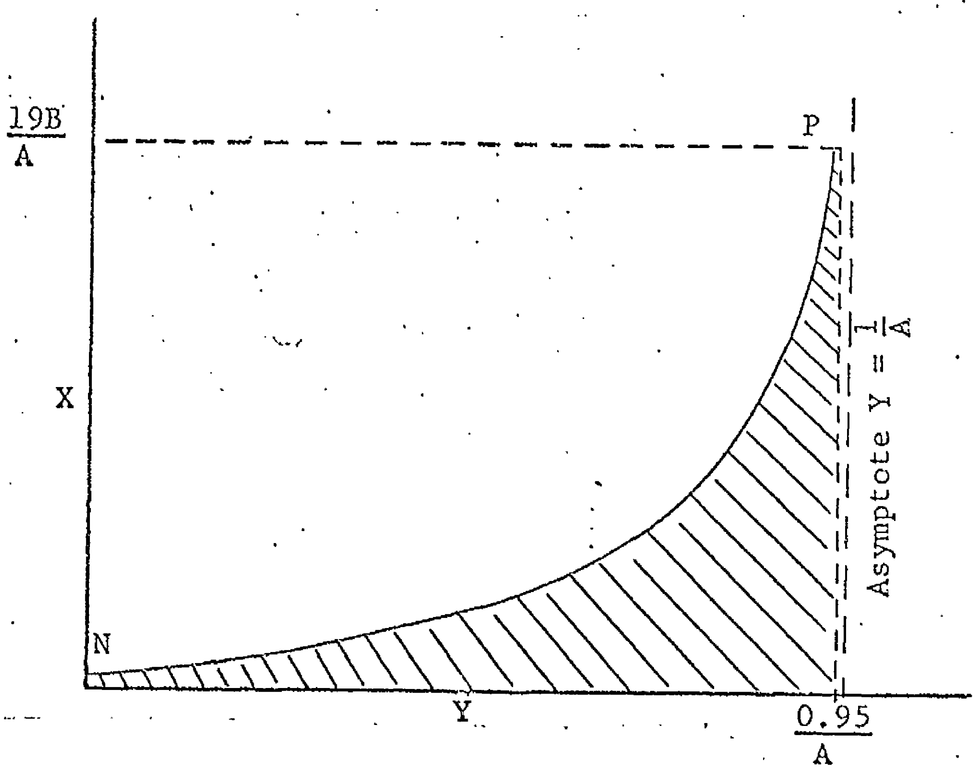
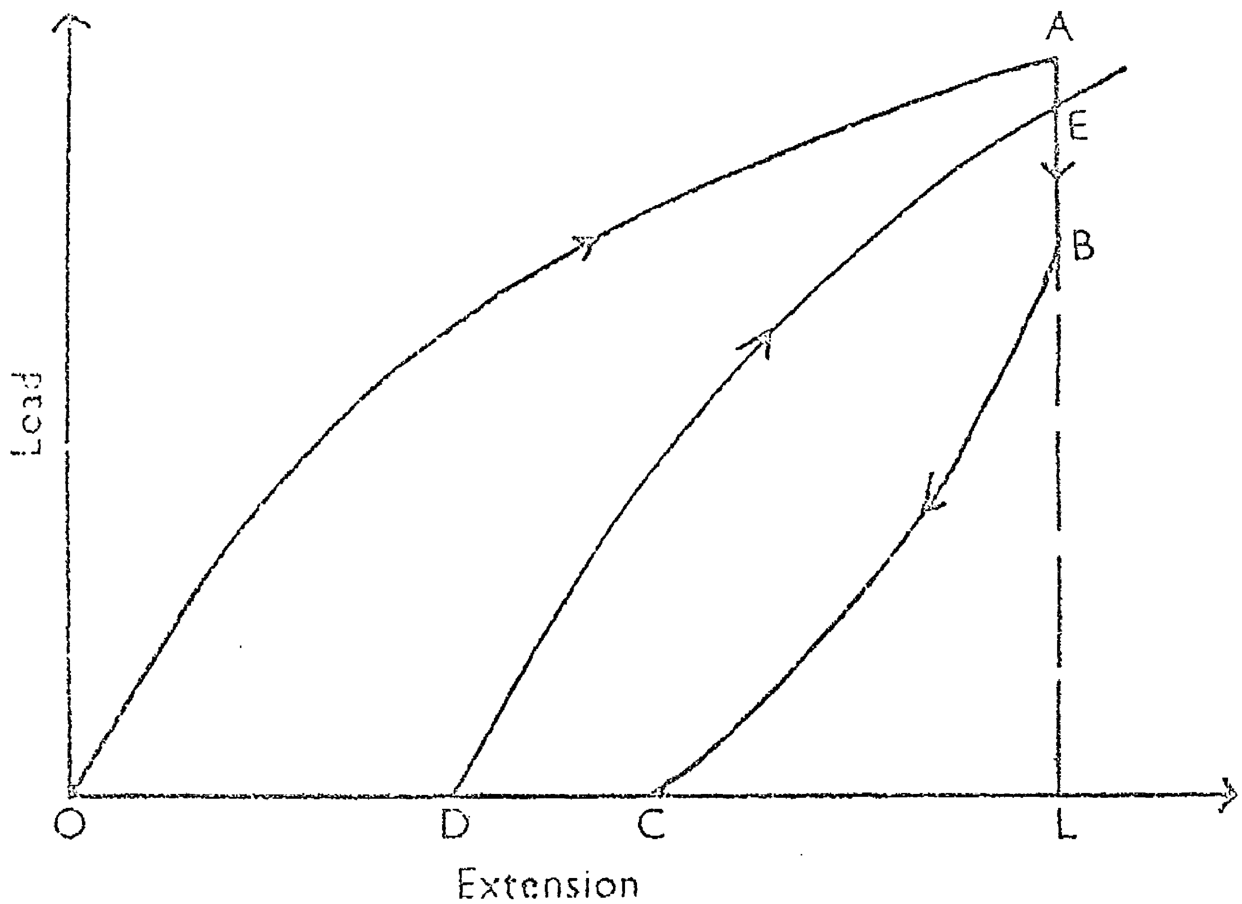
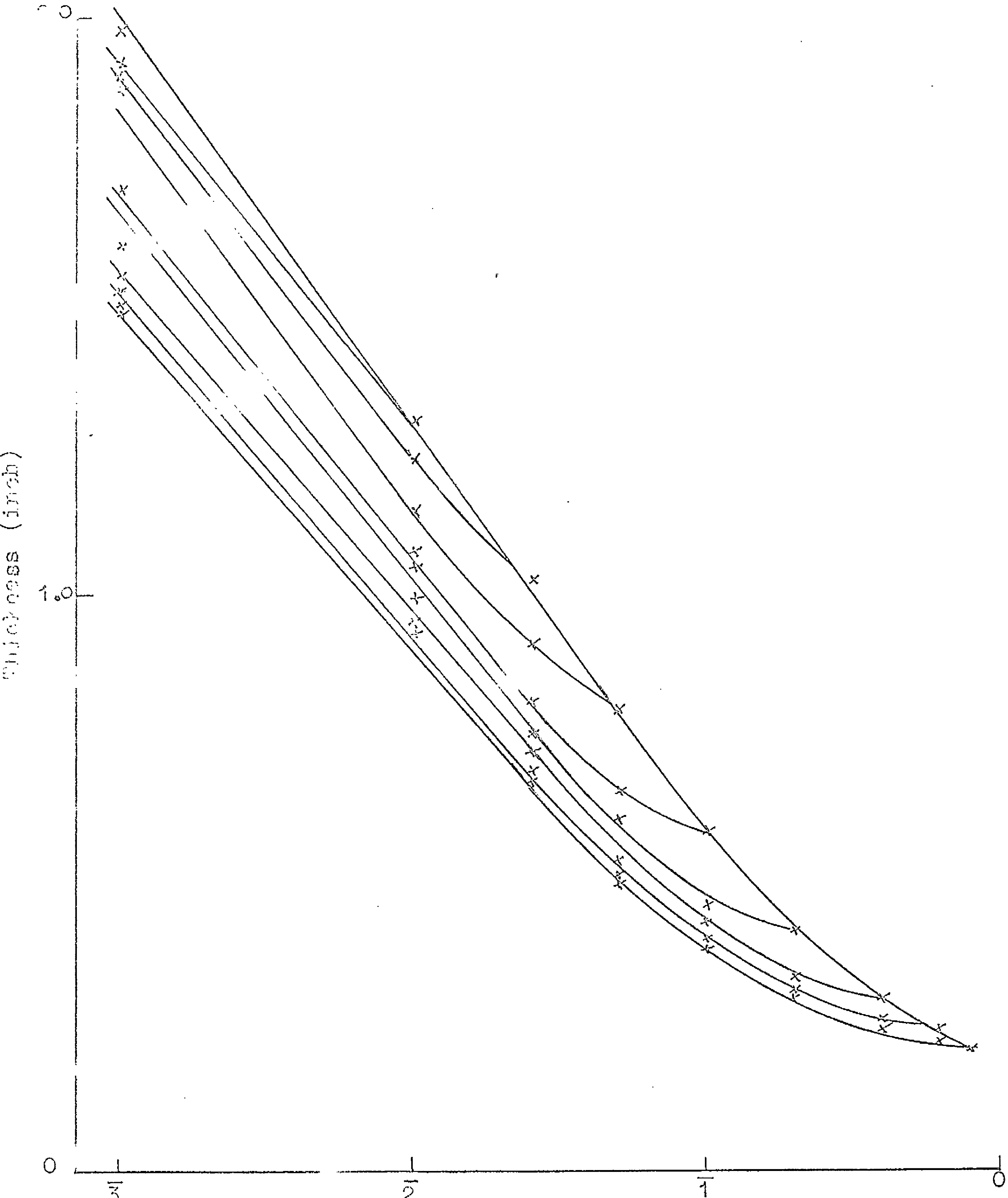


Fig.6c

Fig. 8. Typical load-extension trace for elastic recovery measurements.

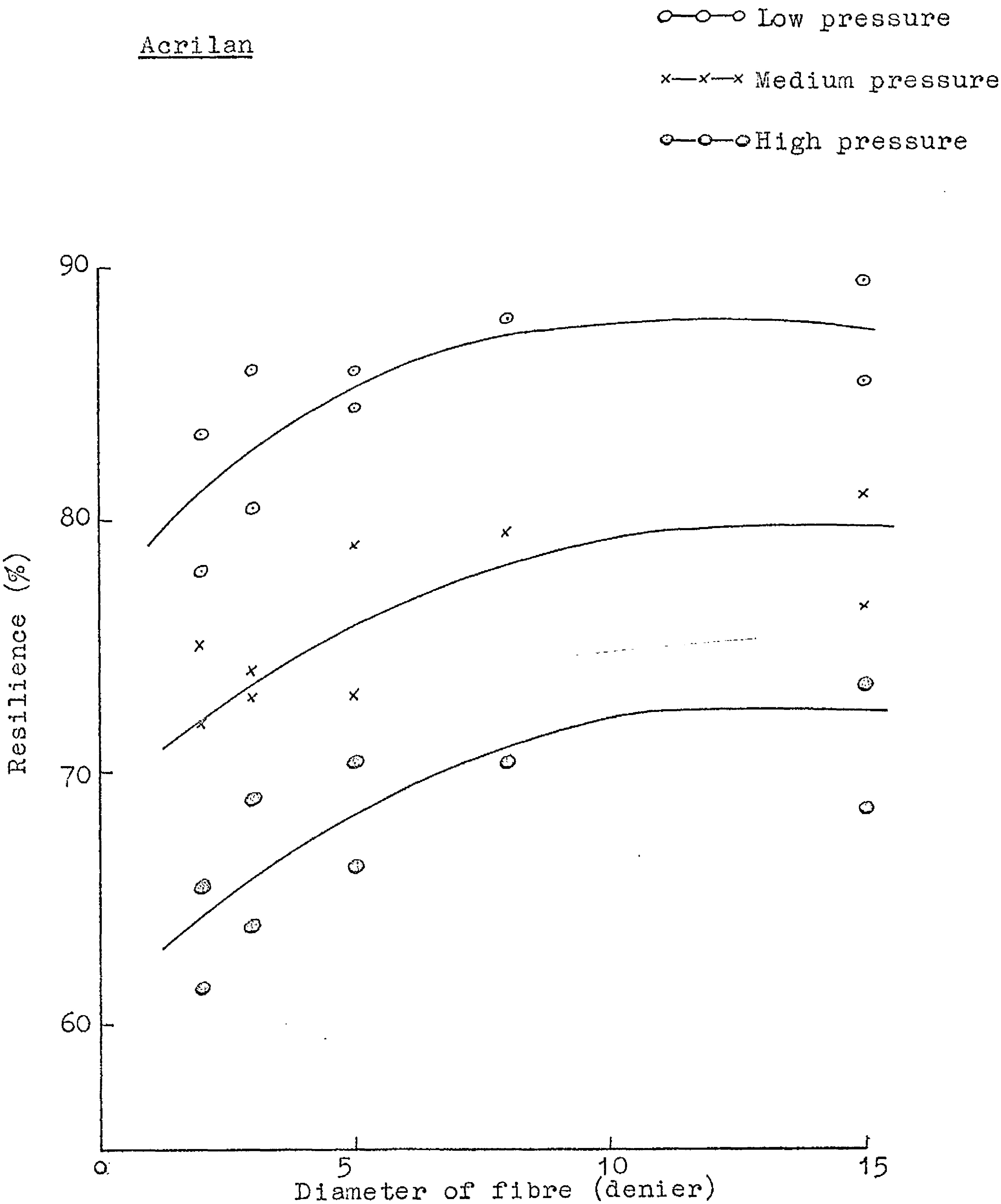


Acril an Fig. 9. Thickness vs. $\log_{10}$(pressure)



Log_{10}(pressure in p.s.i.)

Fig. 10. Resilience vs. fibre diameter



Acrilan

Fig.11. Resilience vs. Fibre diameter

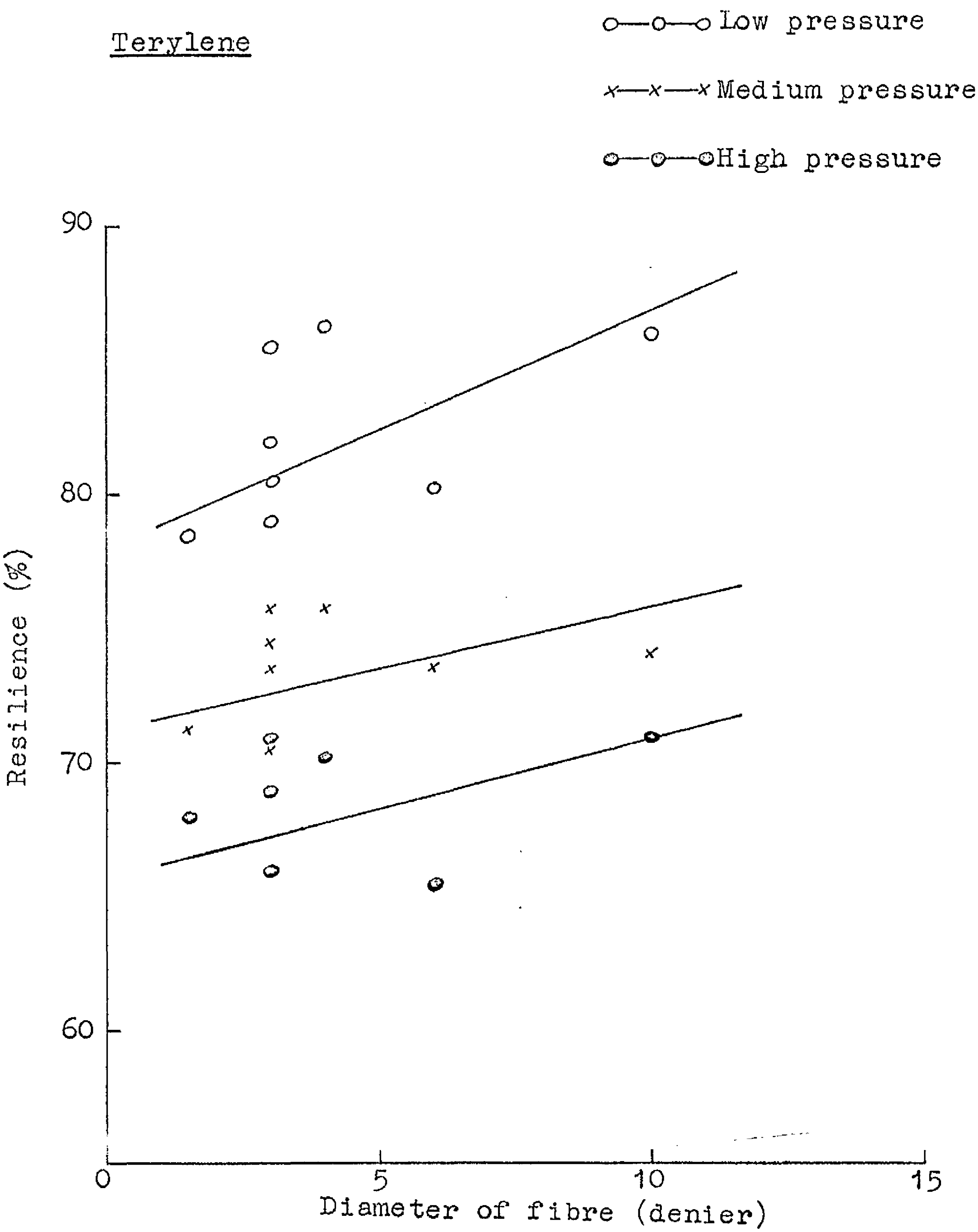


Fig. 12. Resilience vs. fibre diameter

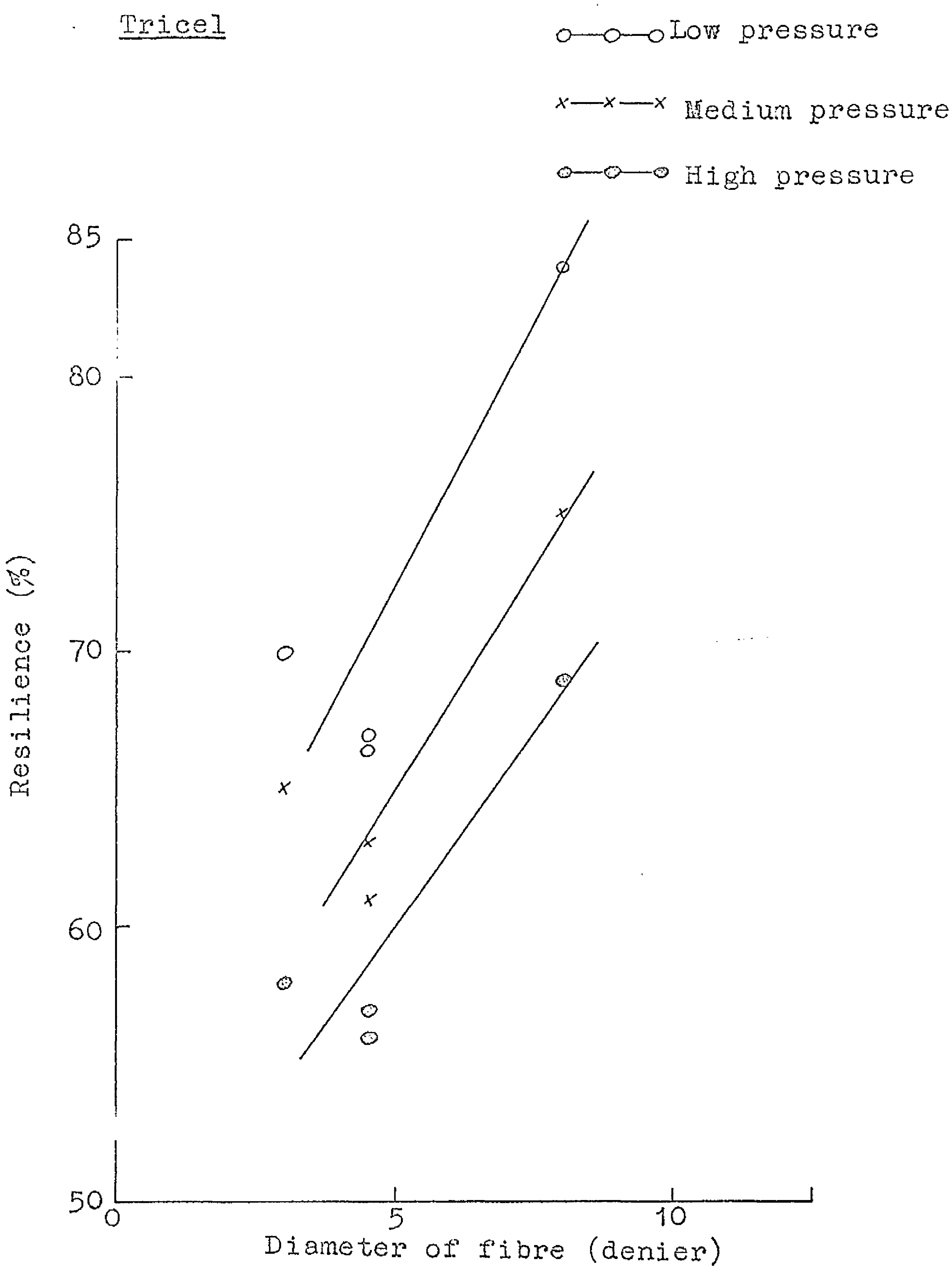


Fig. 13. Resilience vs. fibre diameter

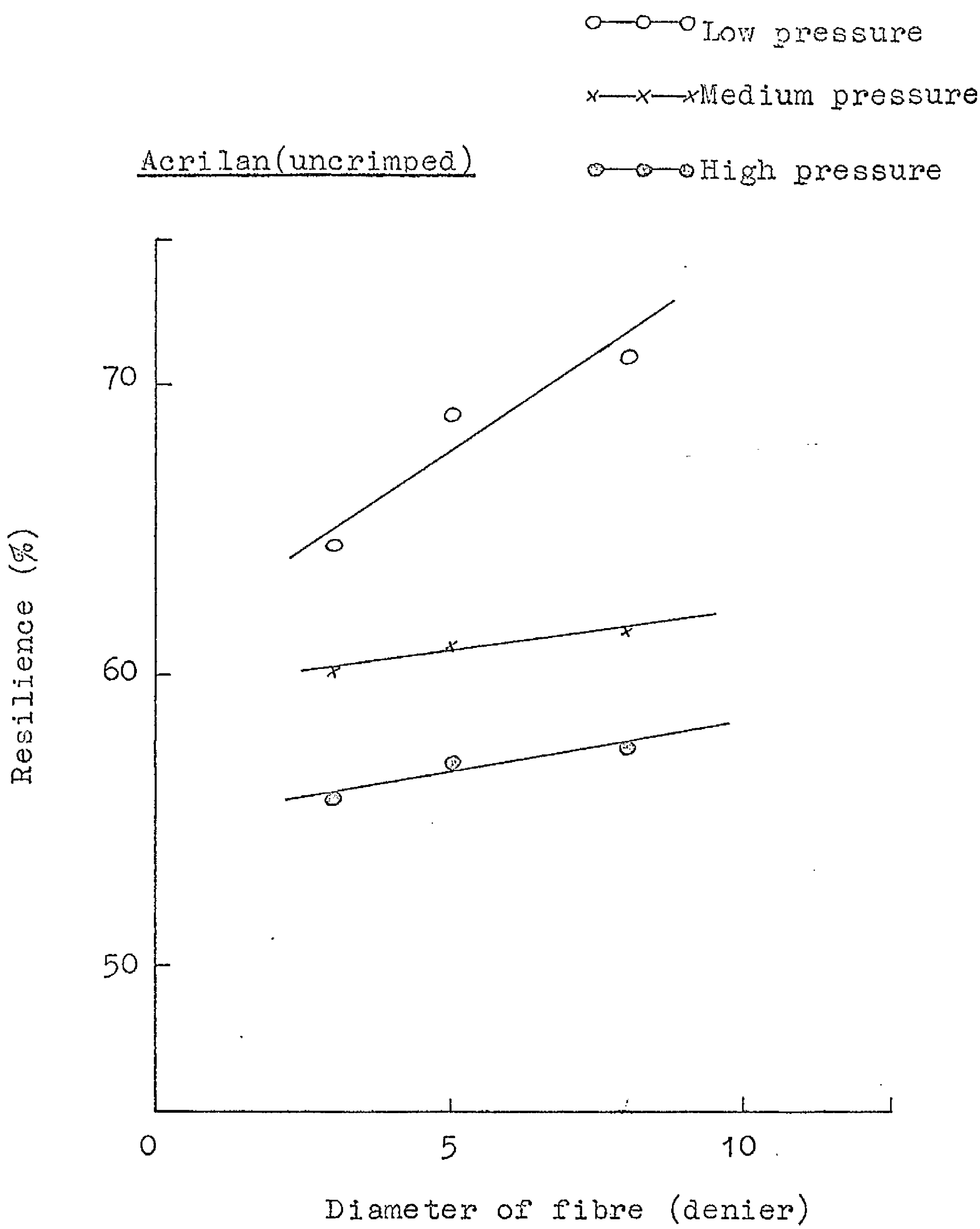


Fig. 14. Resilience vs. crimp

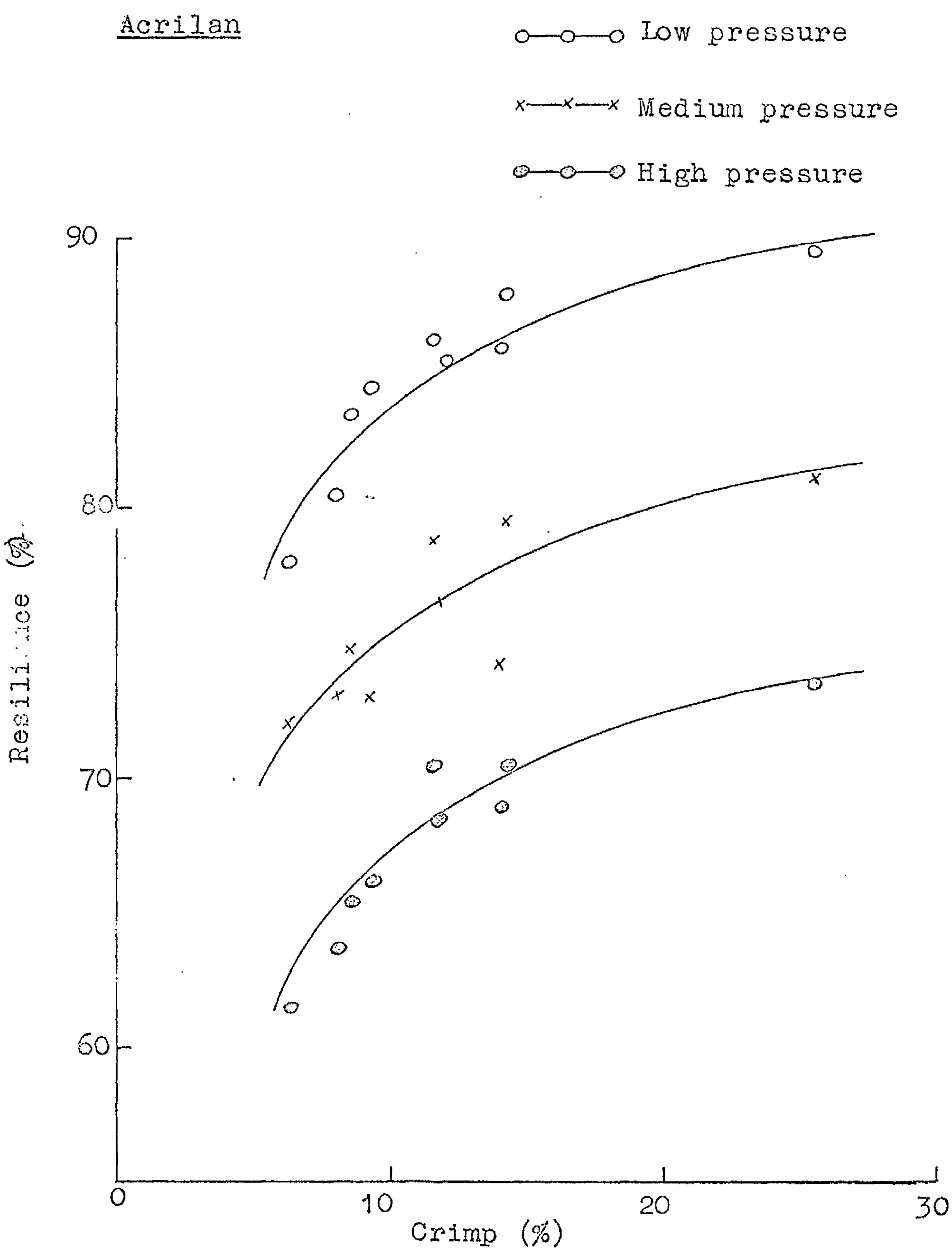


Fig.15. Resilience vs. crimp

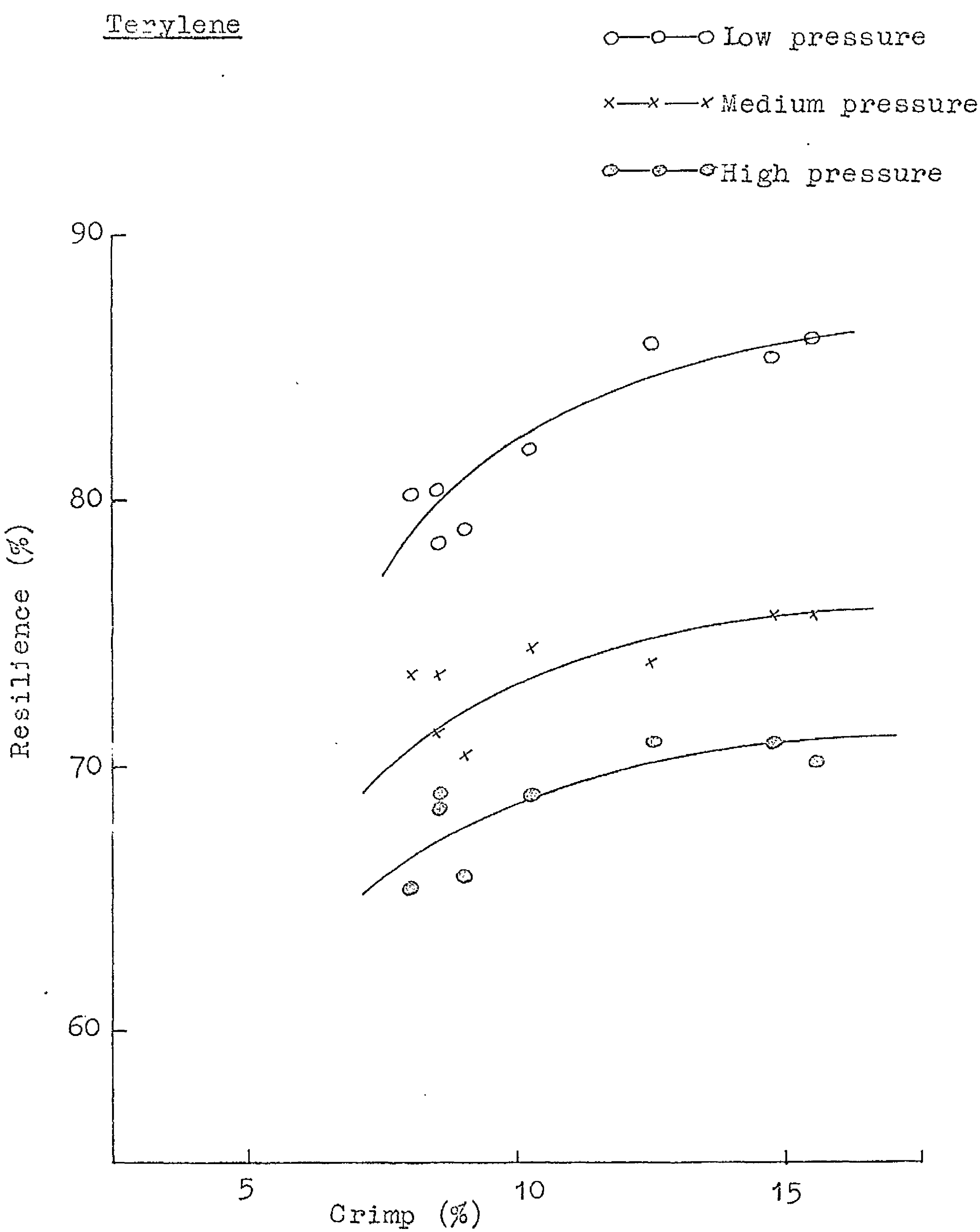


Fig. 16. Resilience vs. crimp

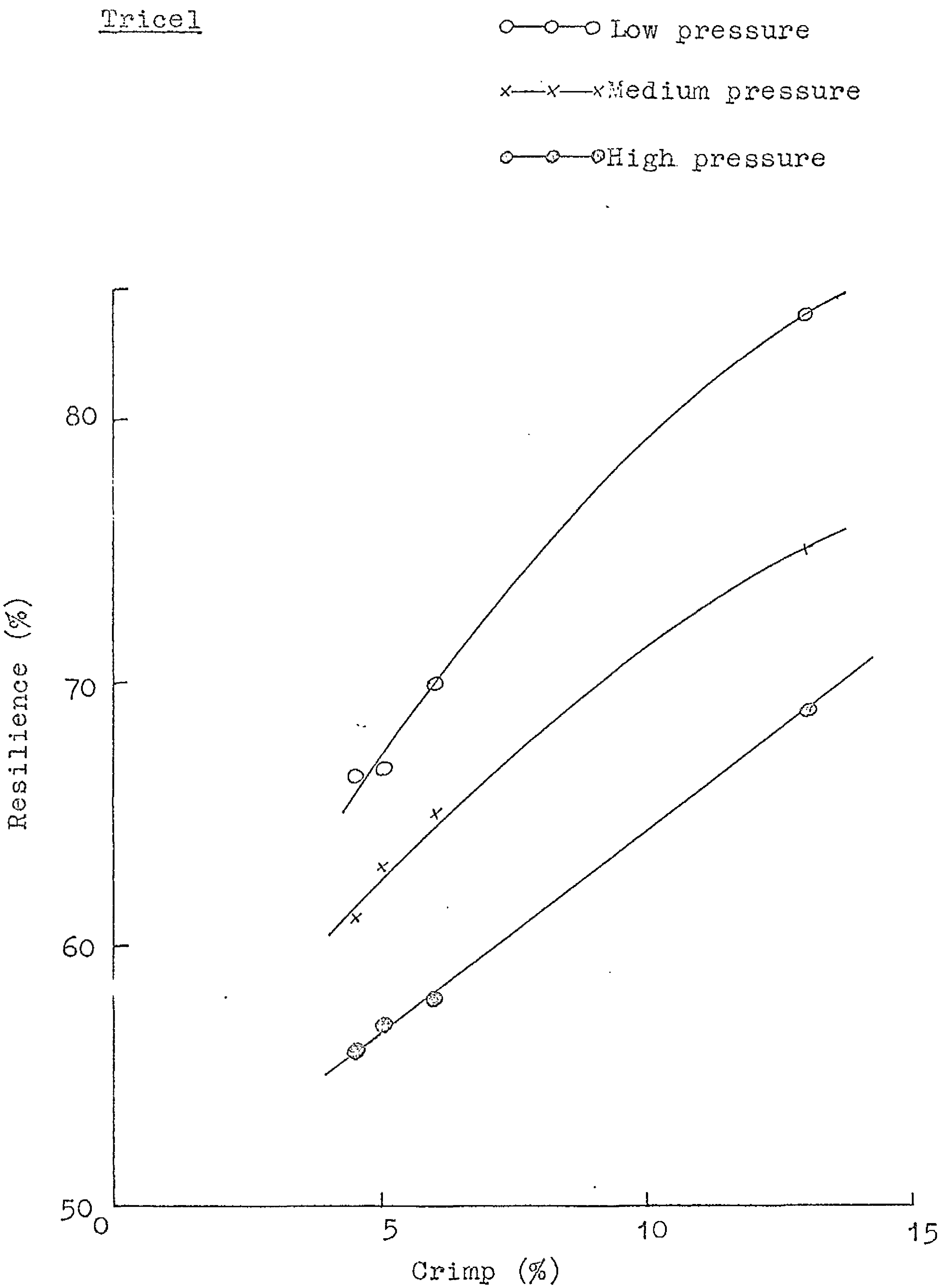


Fig. 17. Resilience vs. fibre friction

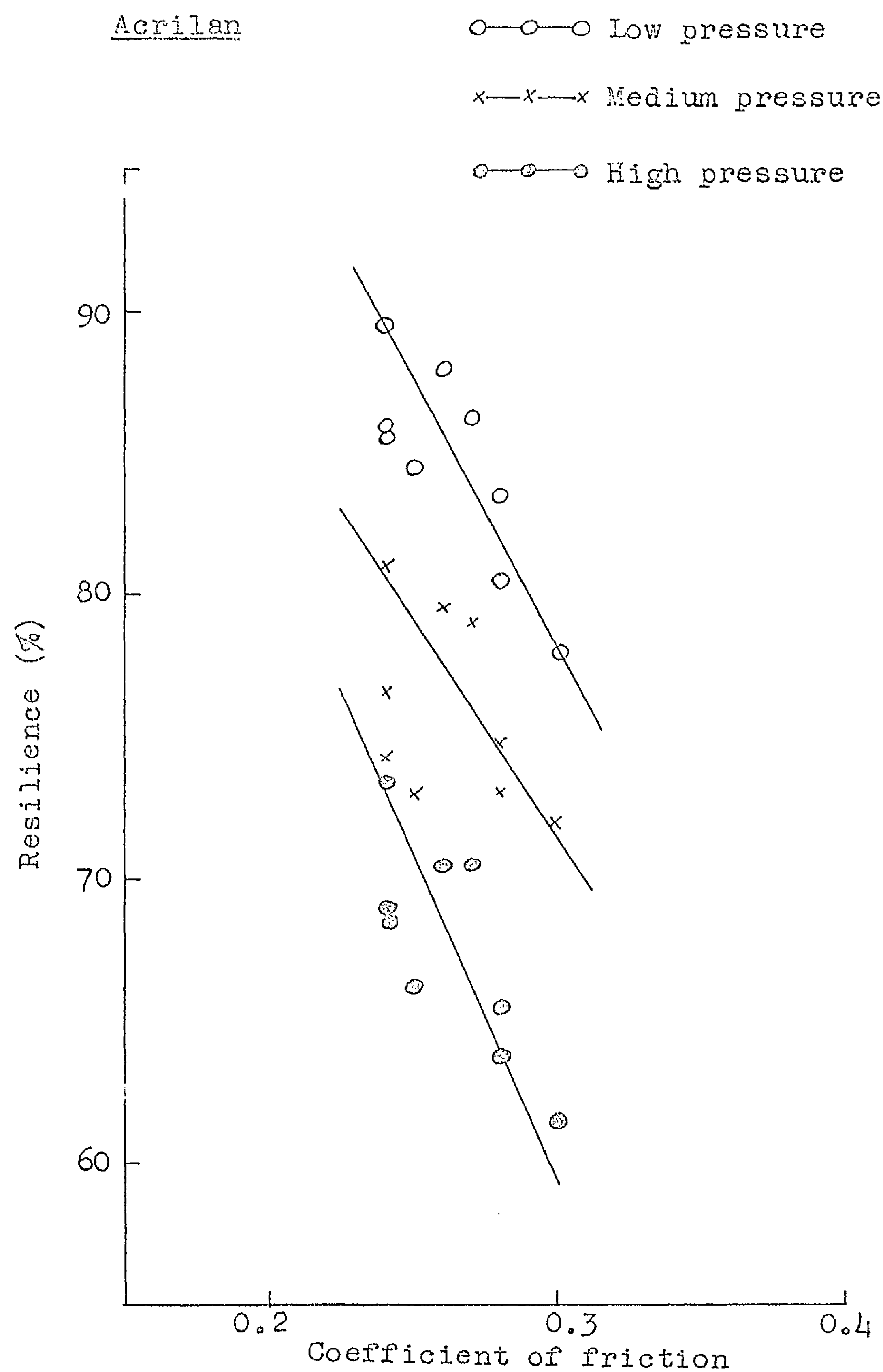


Fig. 18. Resilience vs. fibre friction

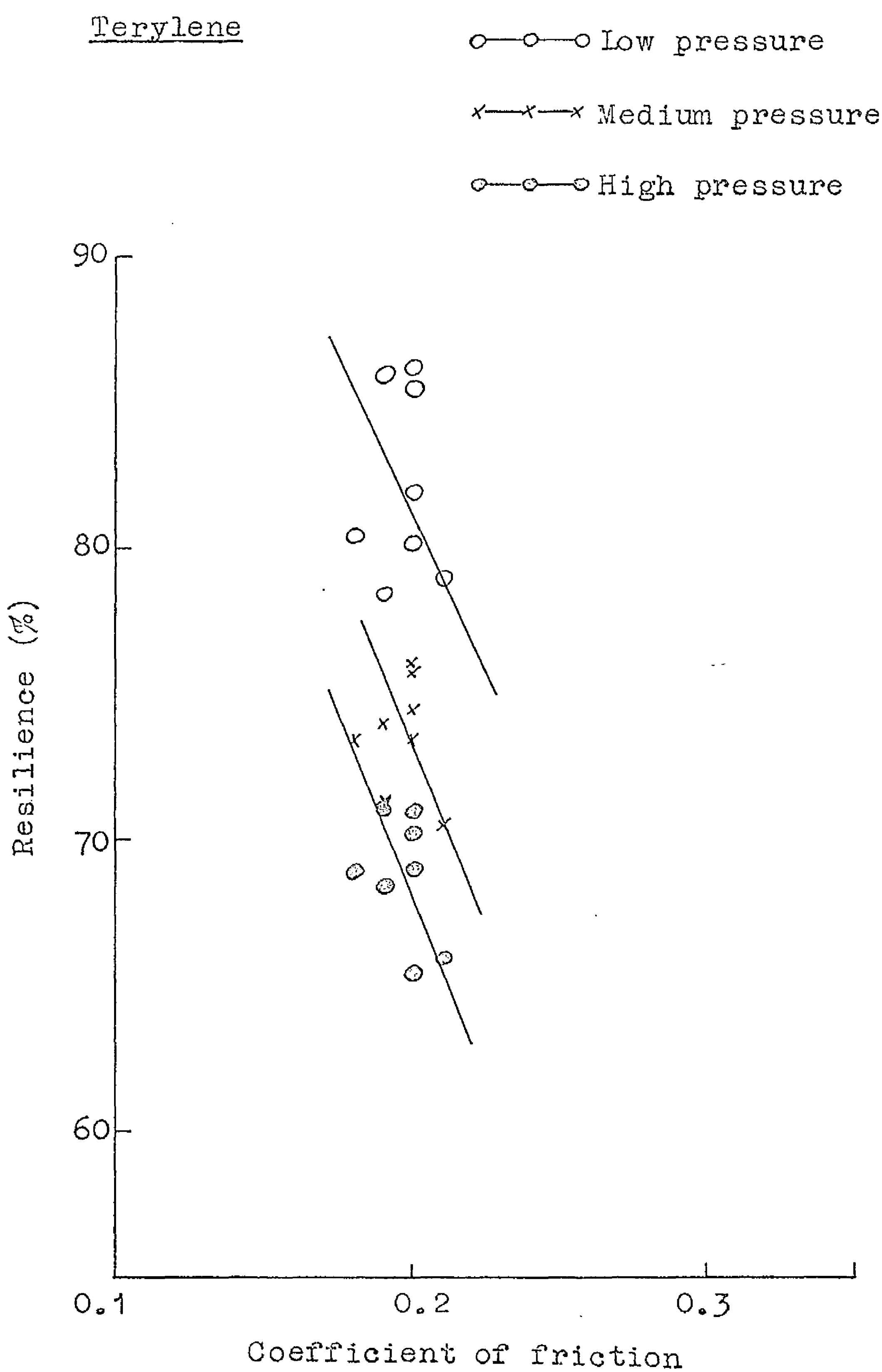


Fig.19. Resilience vs. fibre friction

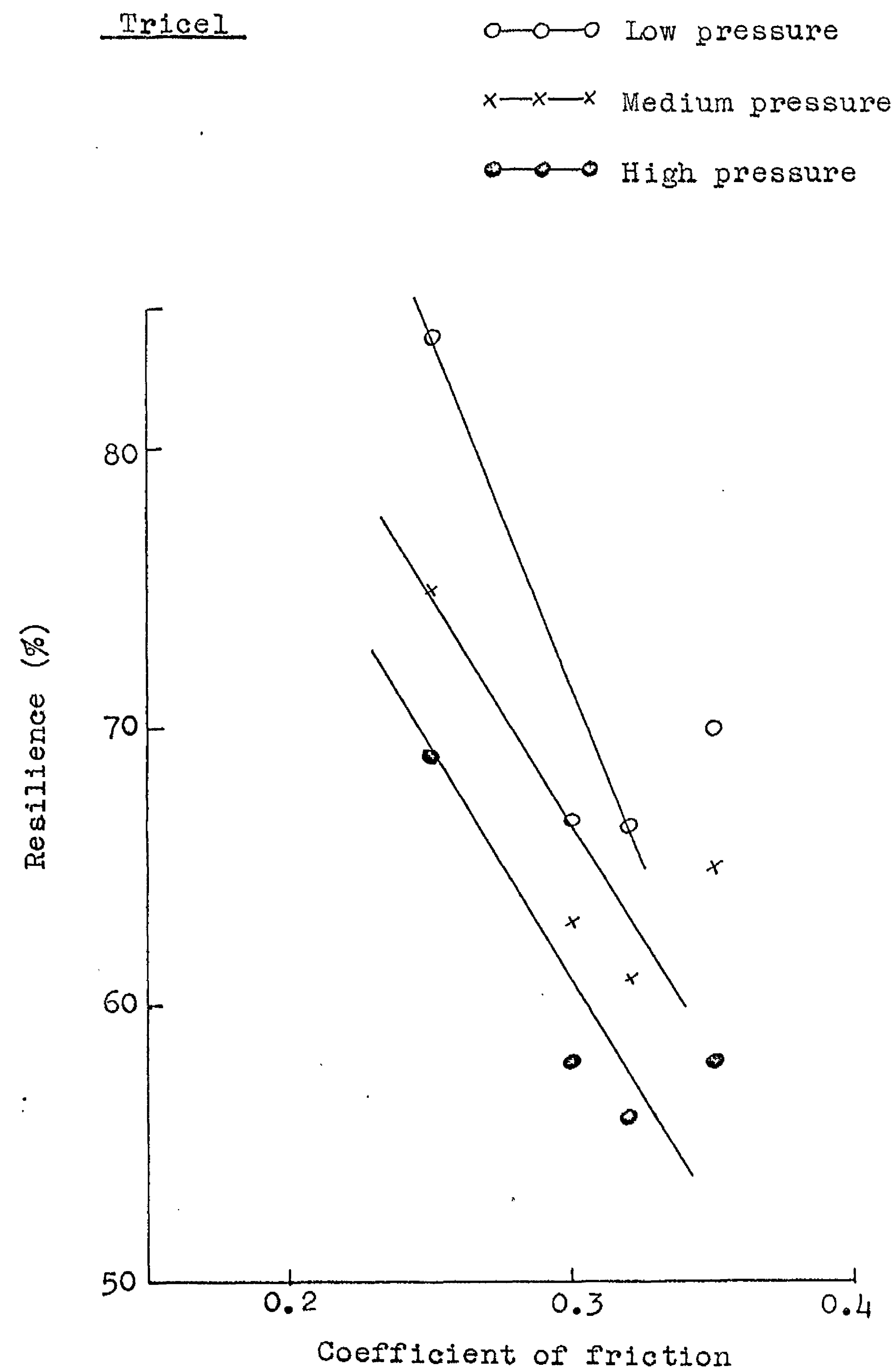


Fig. 20. Resilience vs. fibre friction

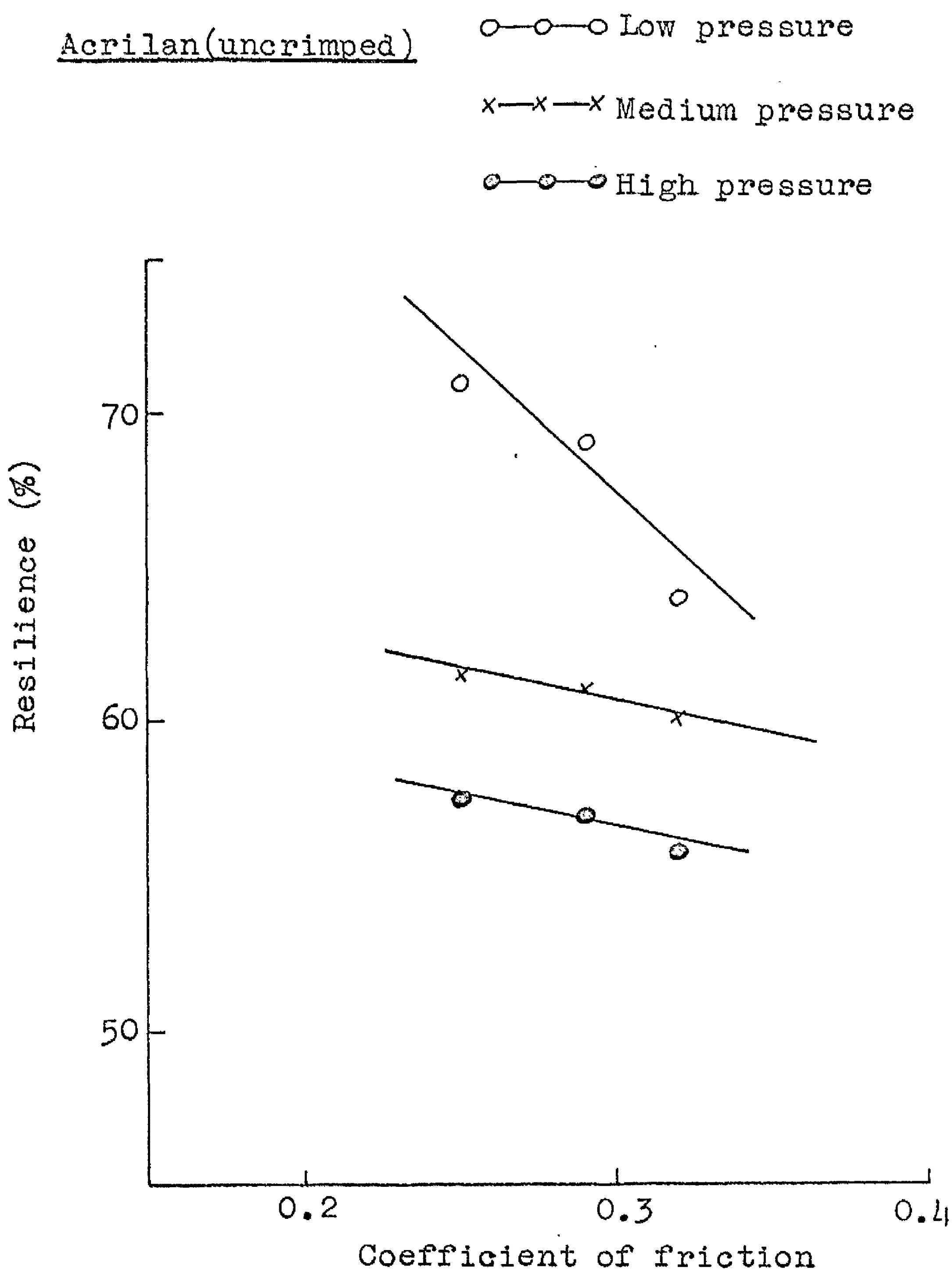


Fig.21. Resilience vs. elastic recovery

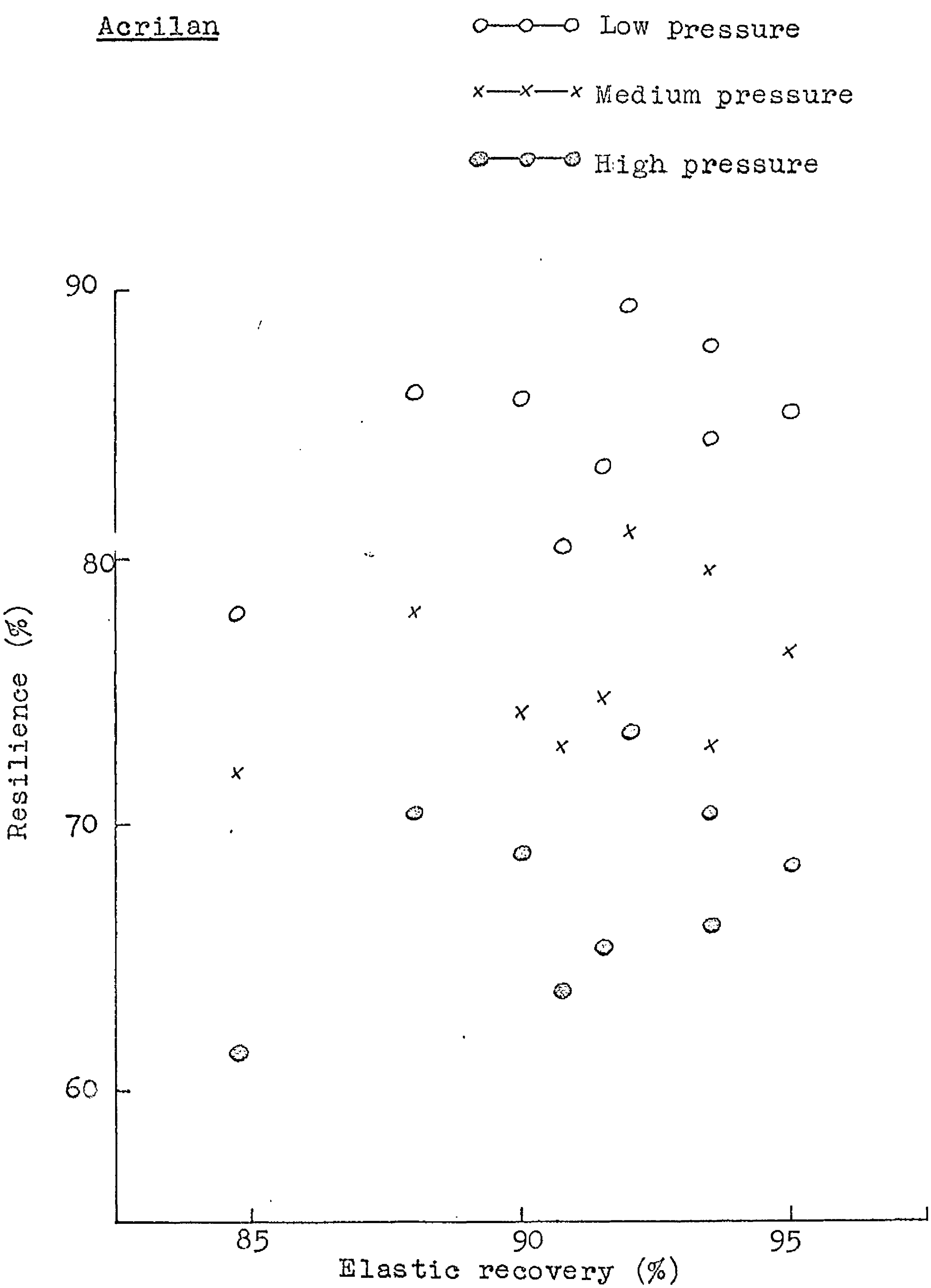


Fig. 22. Resilience vs. elastic recovery

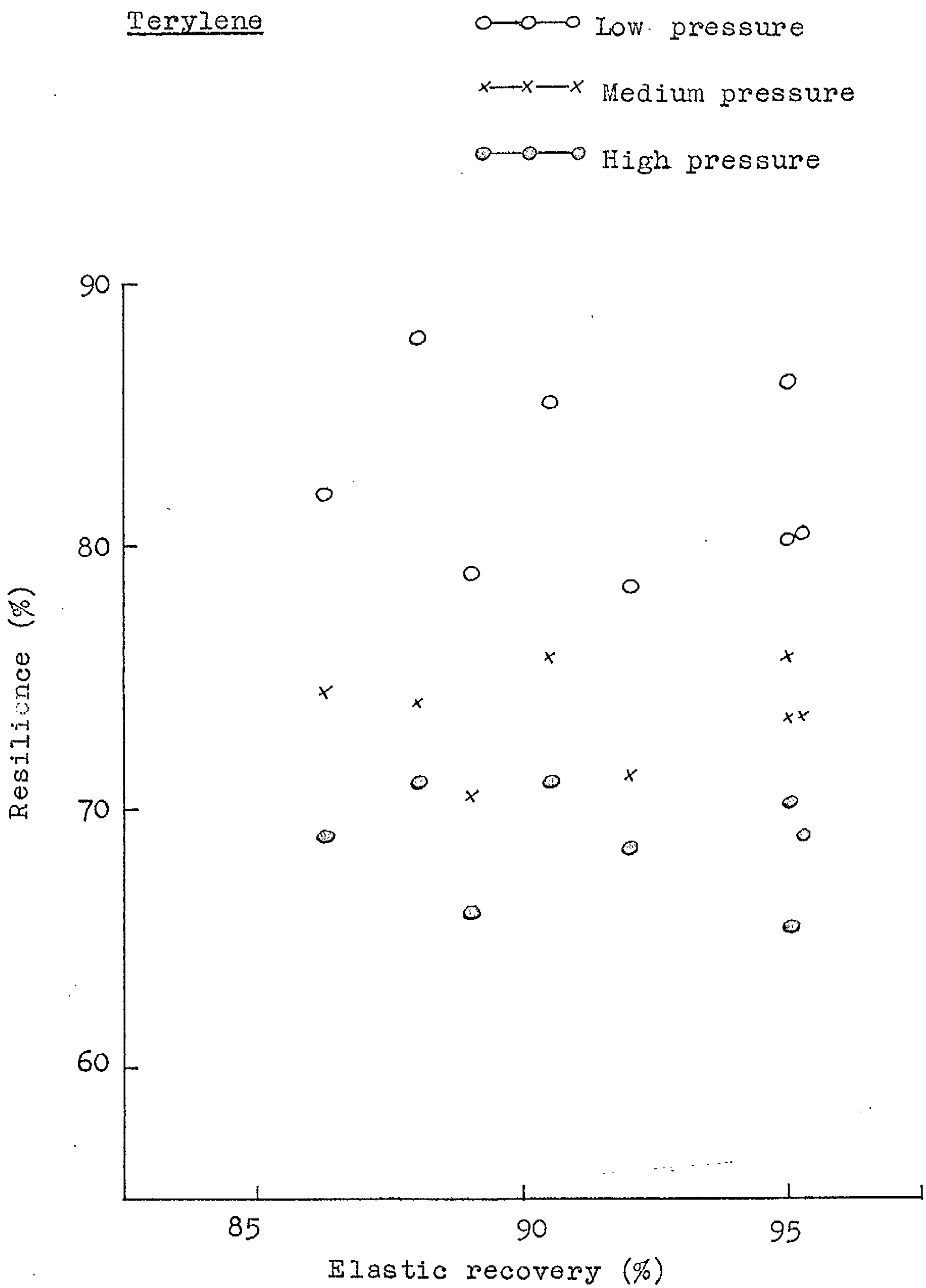


Fig. 23. Resilience vs. elastic recovery

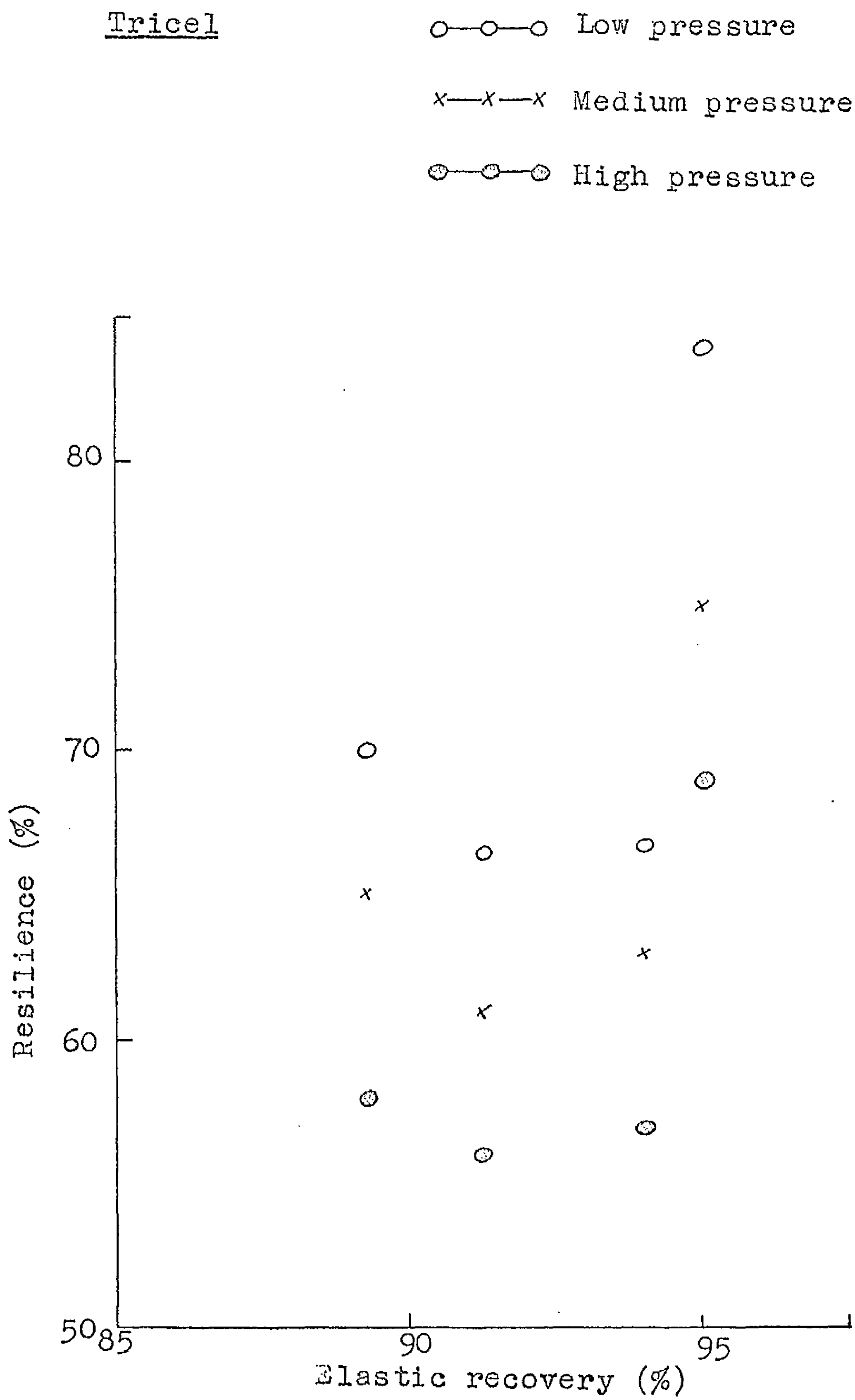


Fig. 24. Resilience vs. elastic recovery

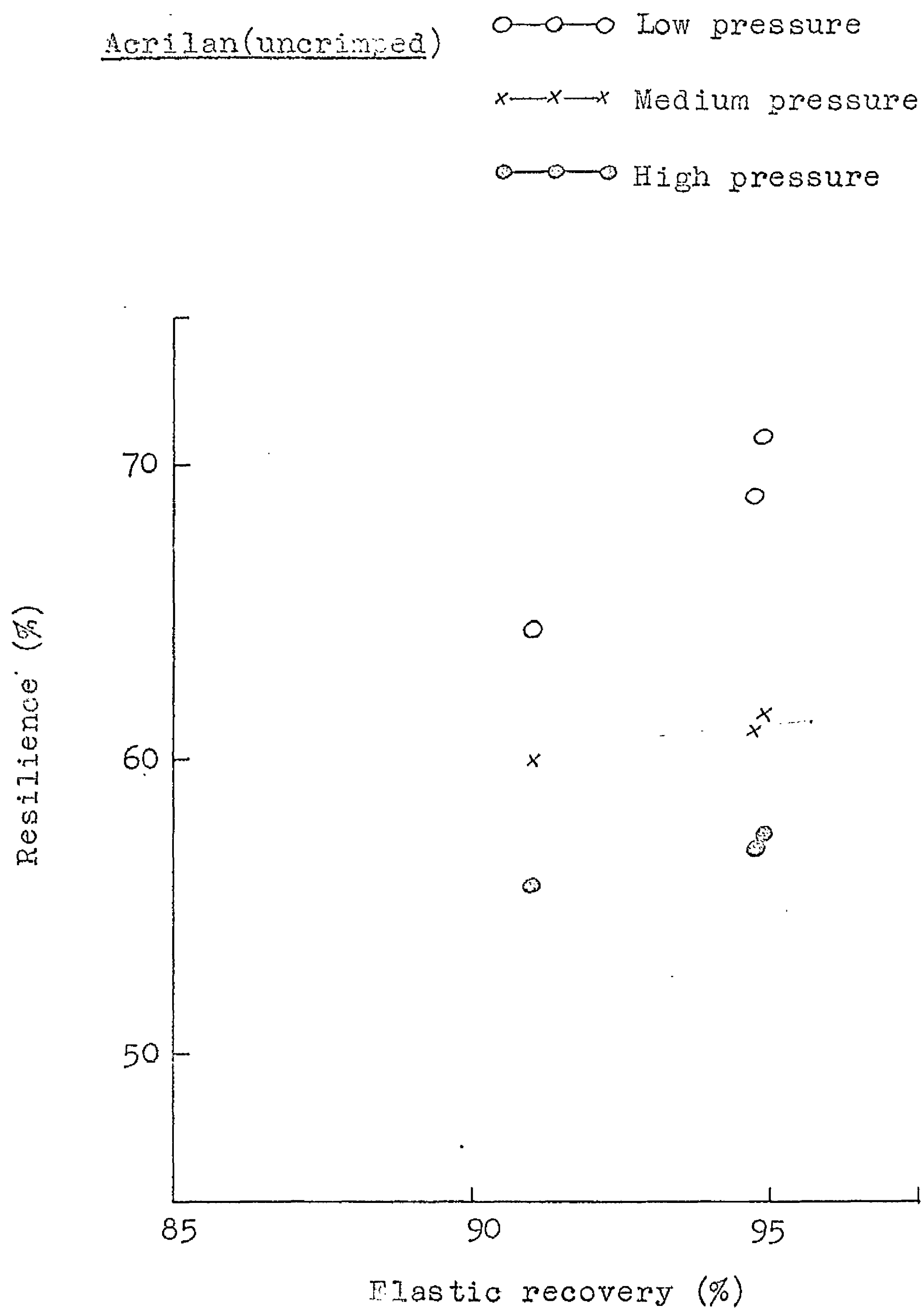


Fig. 25. Typical thickness-pressure relationship

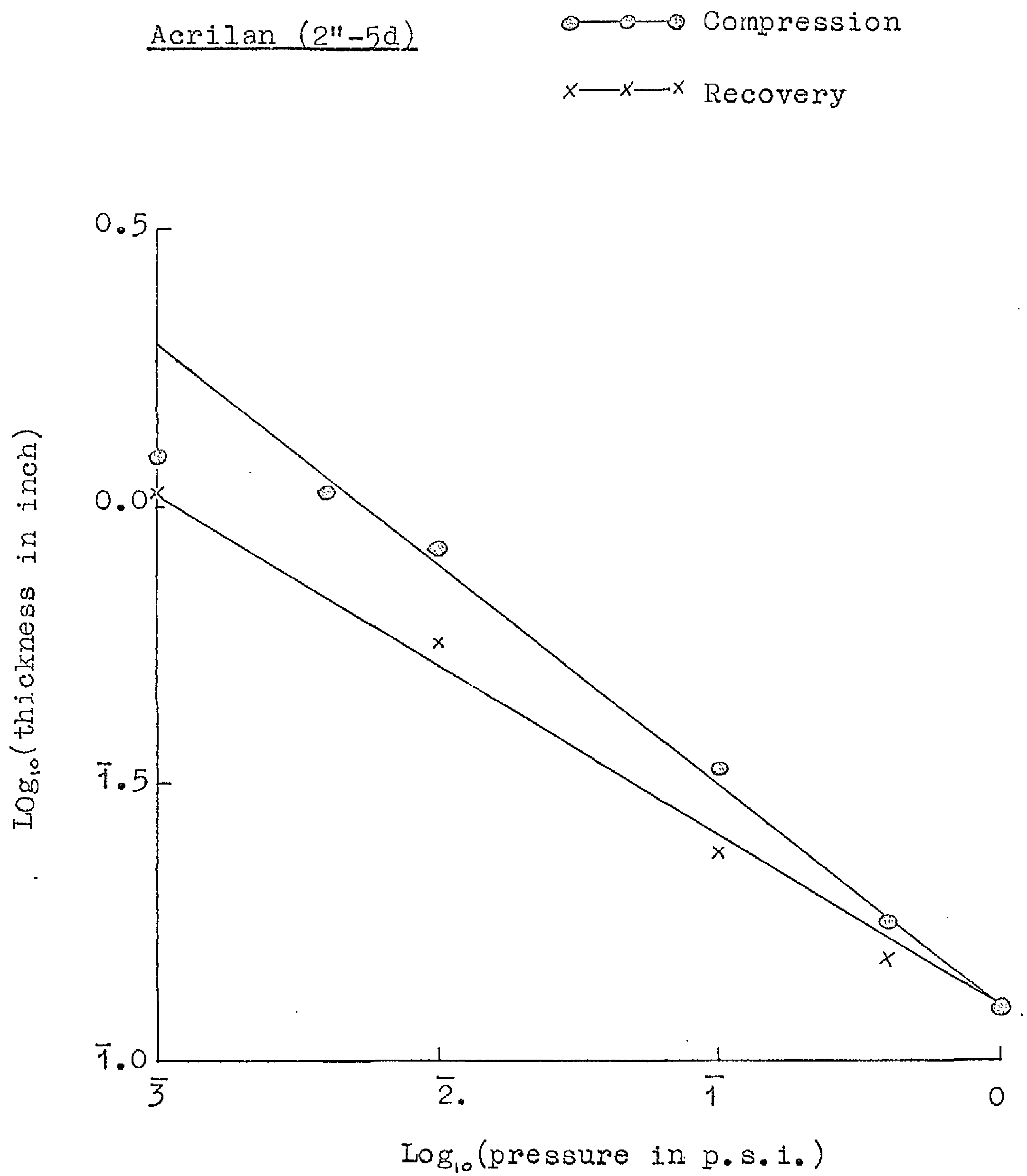


Fig.26. Resilience vs. compliance

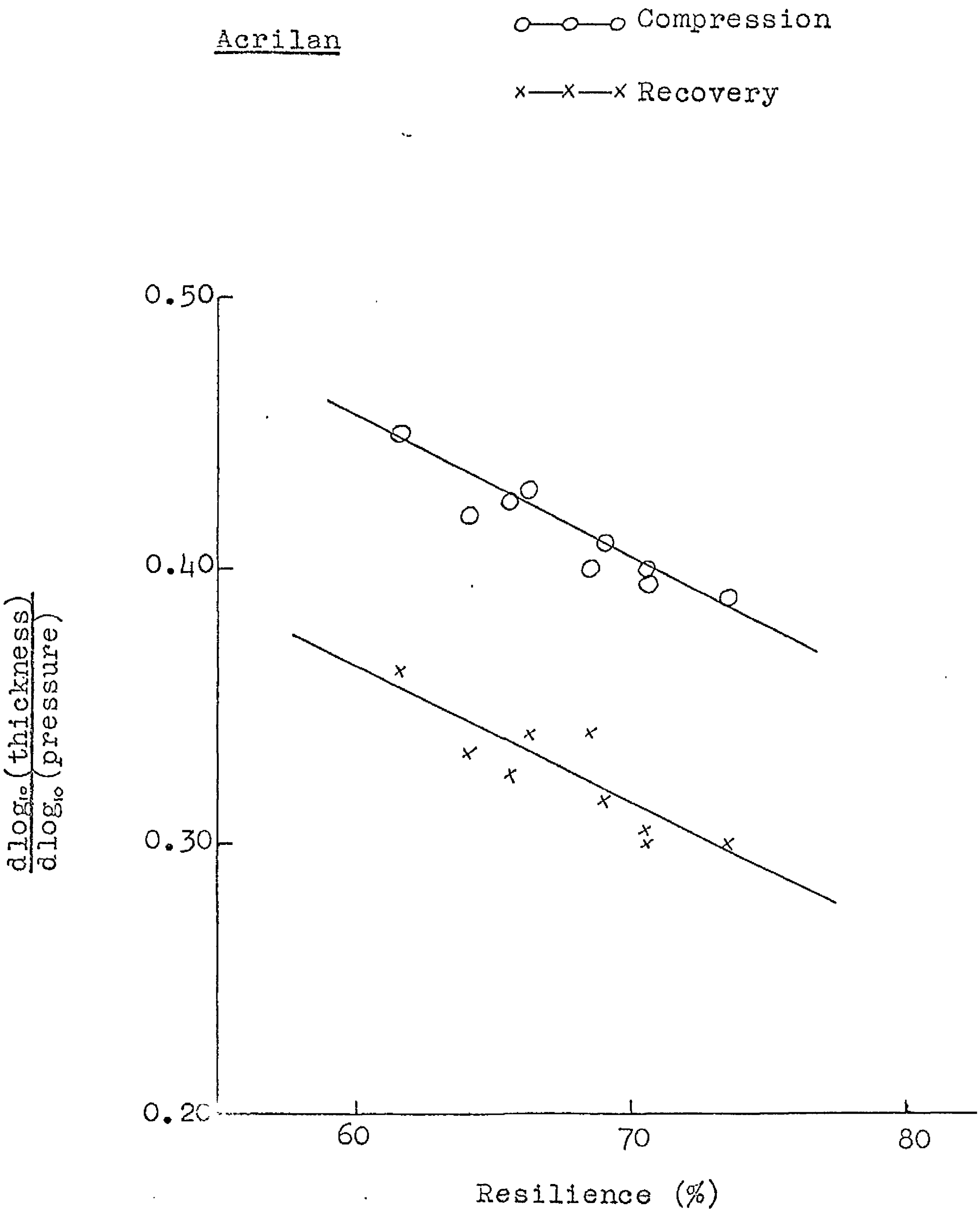


Fig.27. Resilience vs. compliance

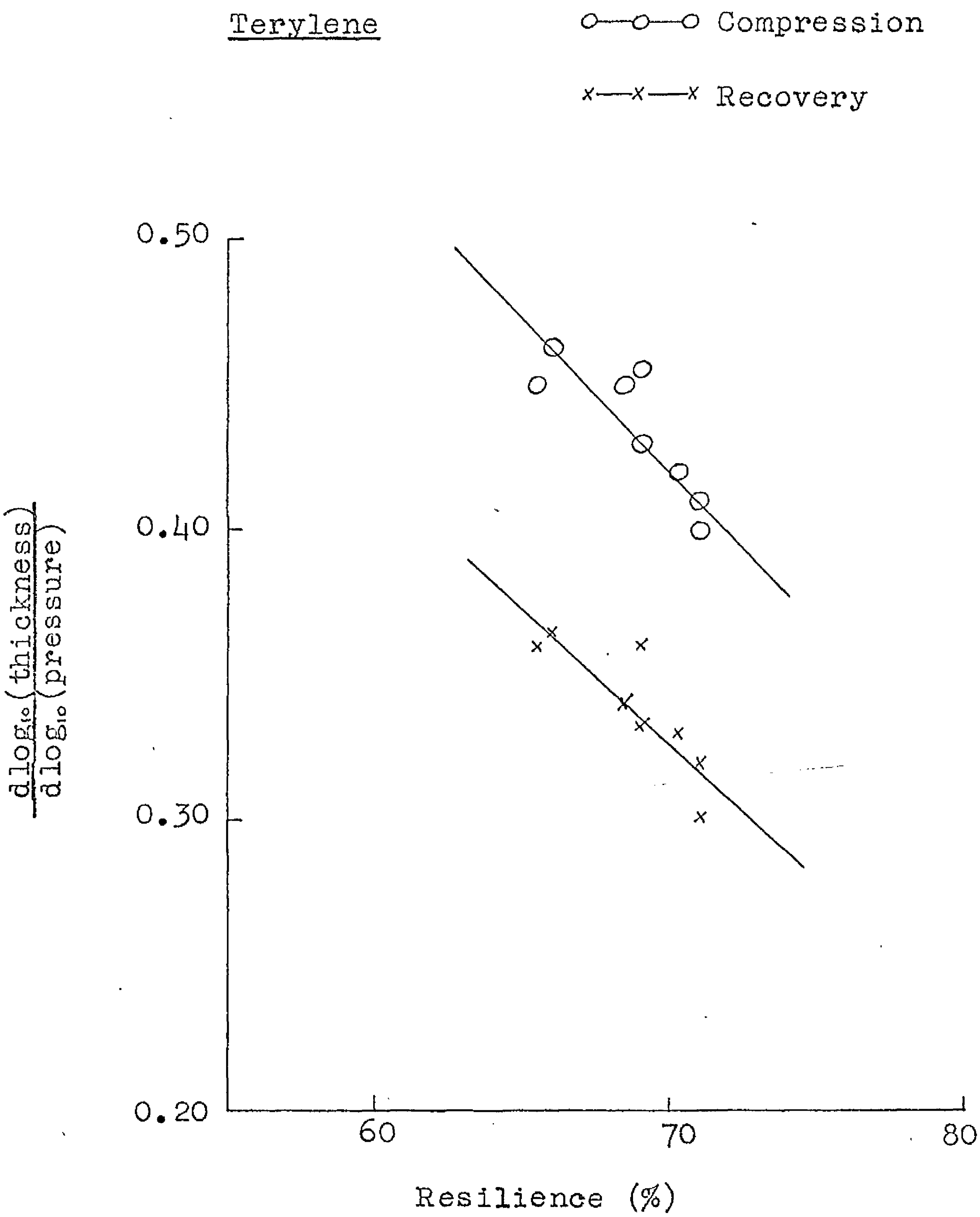


Fig. 28 Resilience vs. Compliance

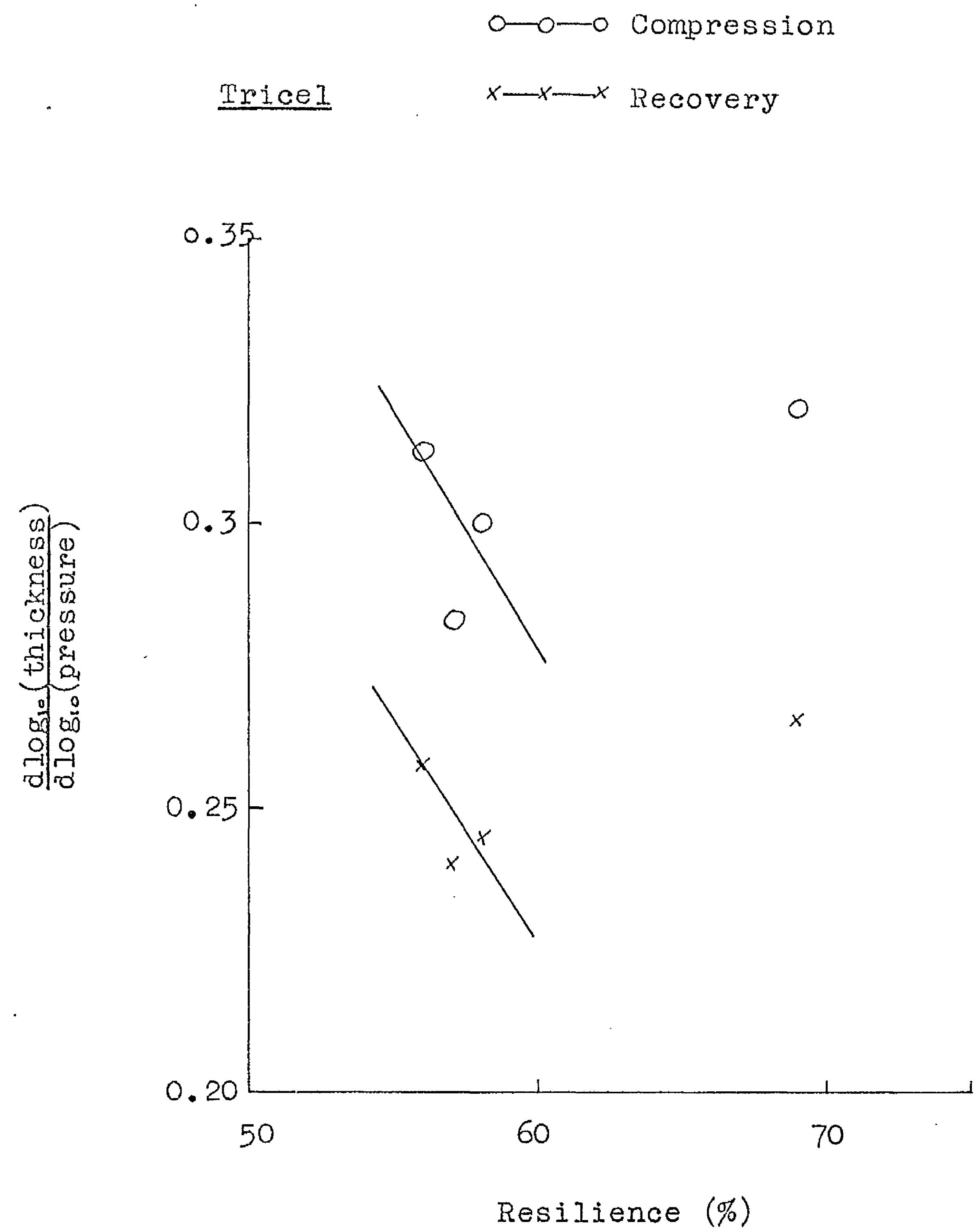


Fig. 29. Resilience vs. relative humidity

Acrilan

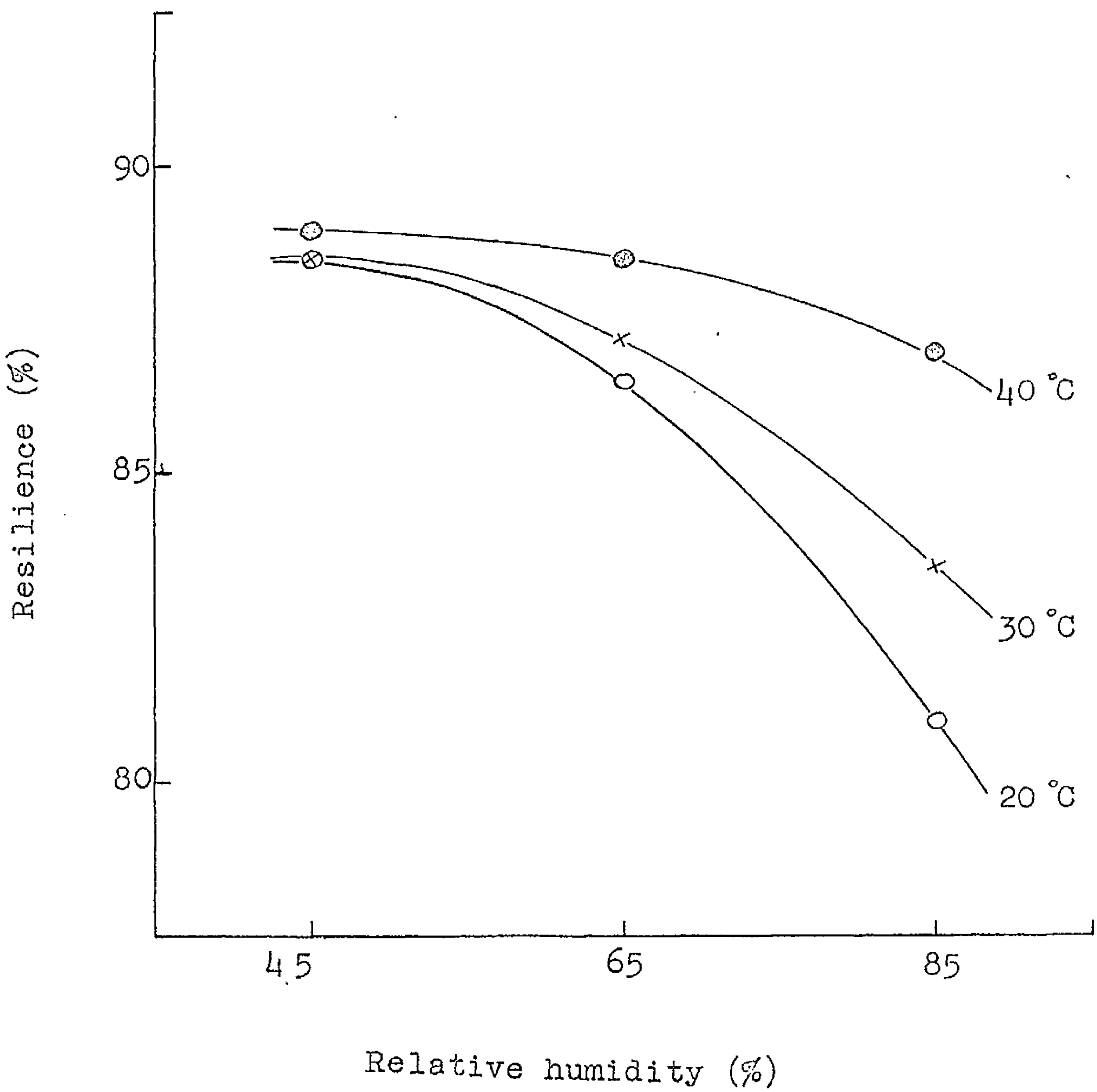


Fig.30. Resilience vs. relative humidity

<u>Terylene</u>

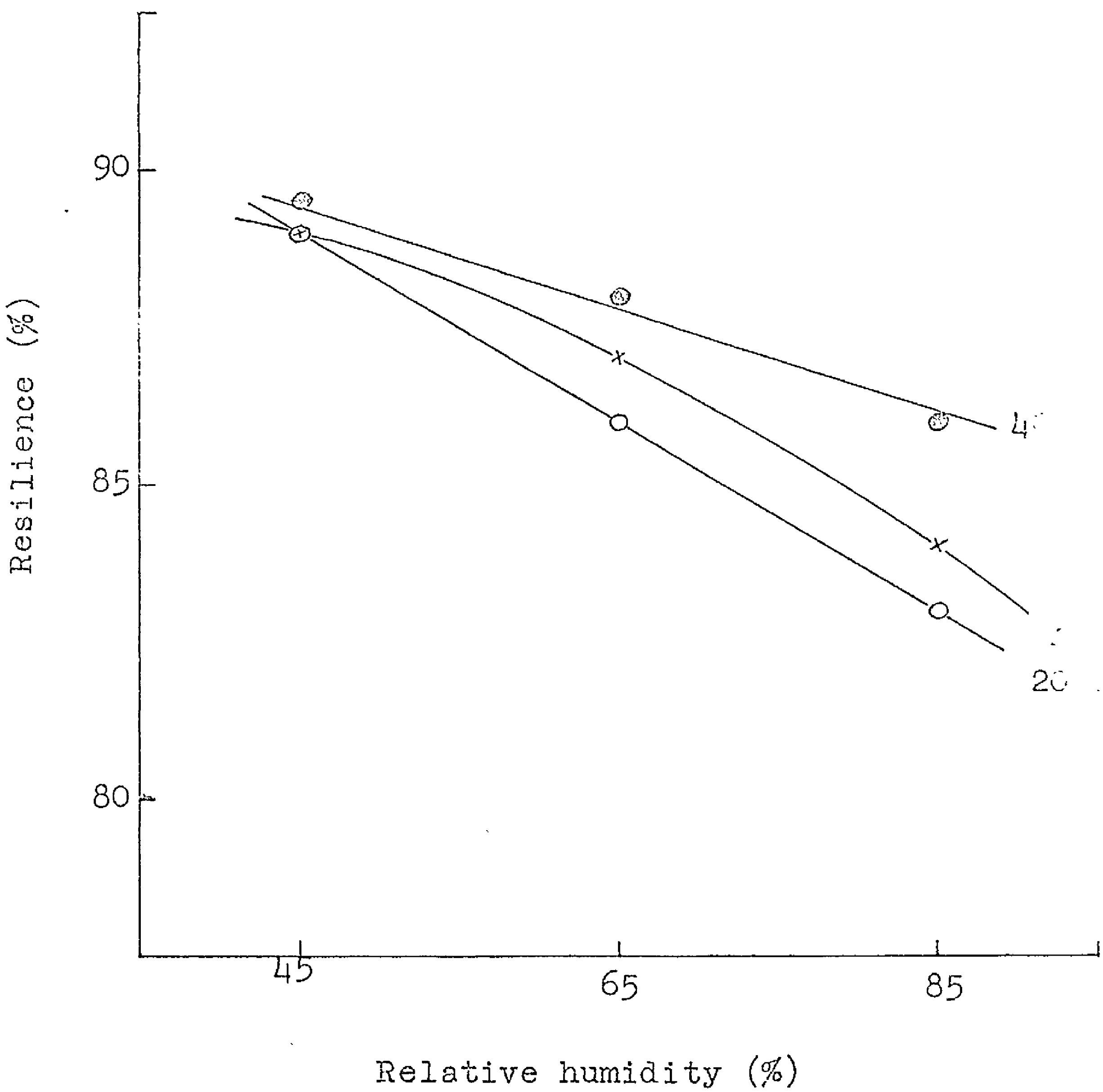


Fig.31. Resilience vs. relative humidity

Tricel

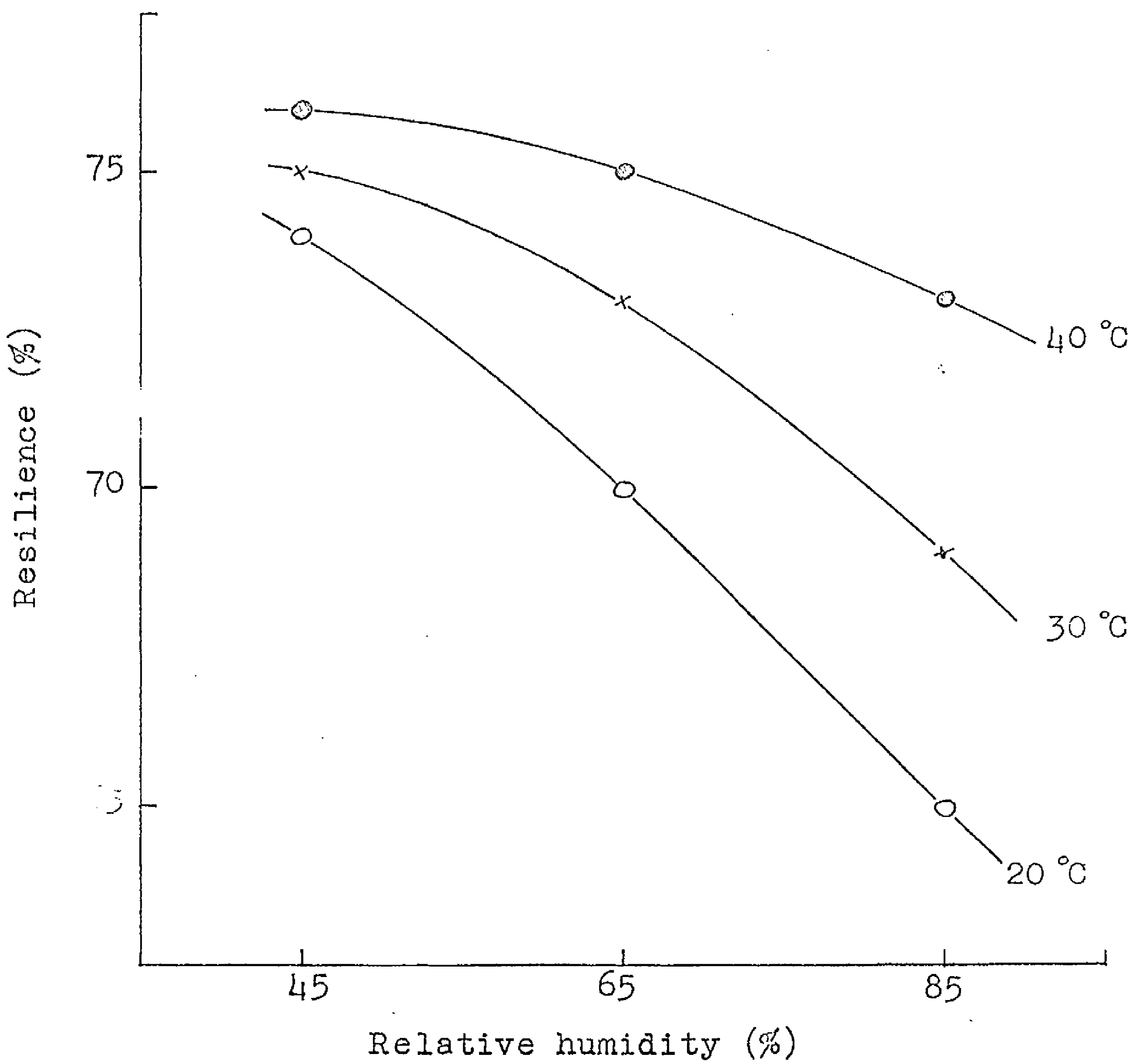


Fig.32. Resilience vs. temperature

Acrilan

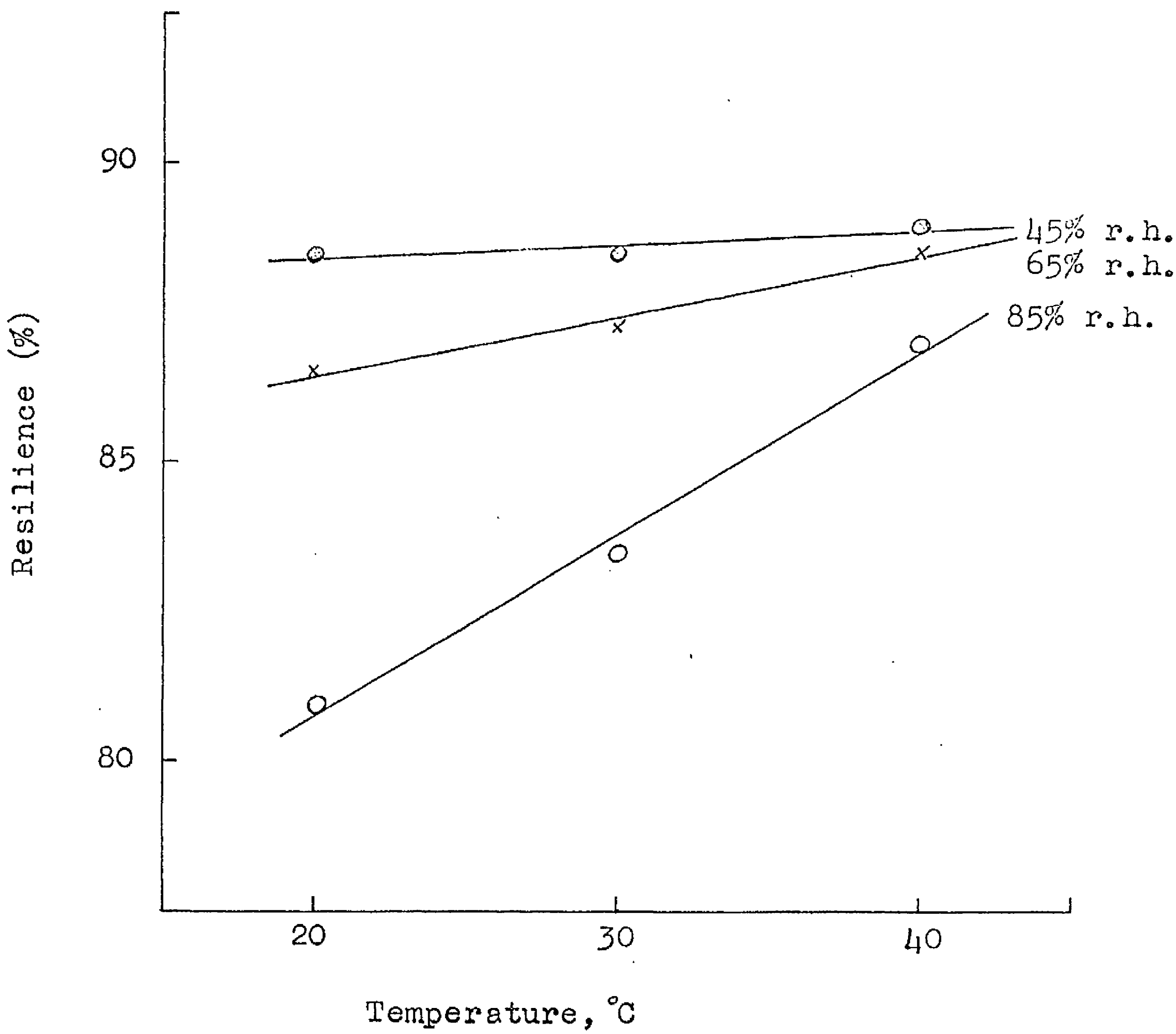


Fig.33. Resilience vs. temperature

Terylene

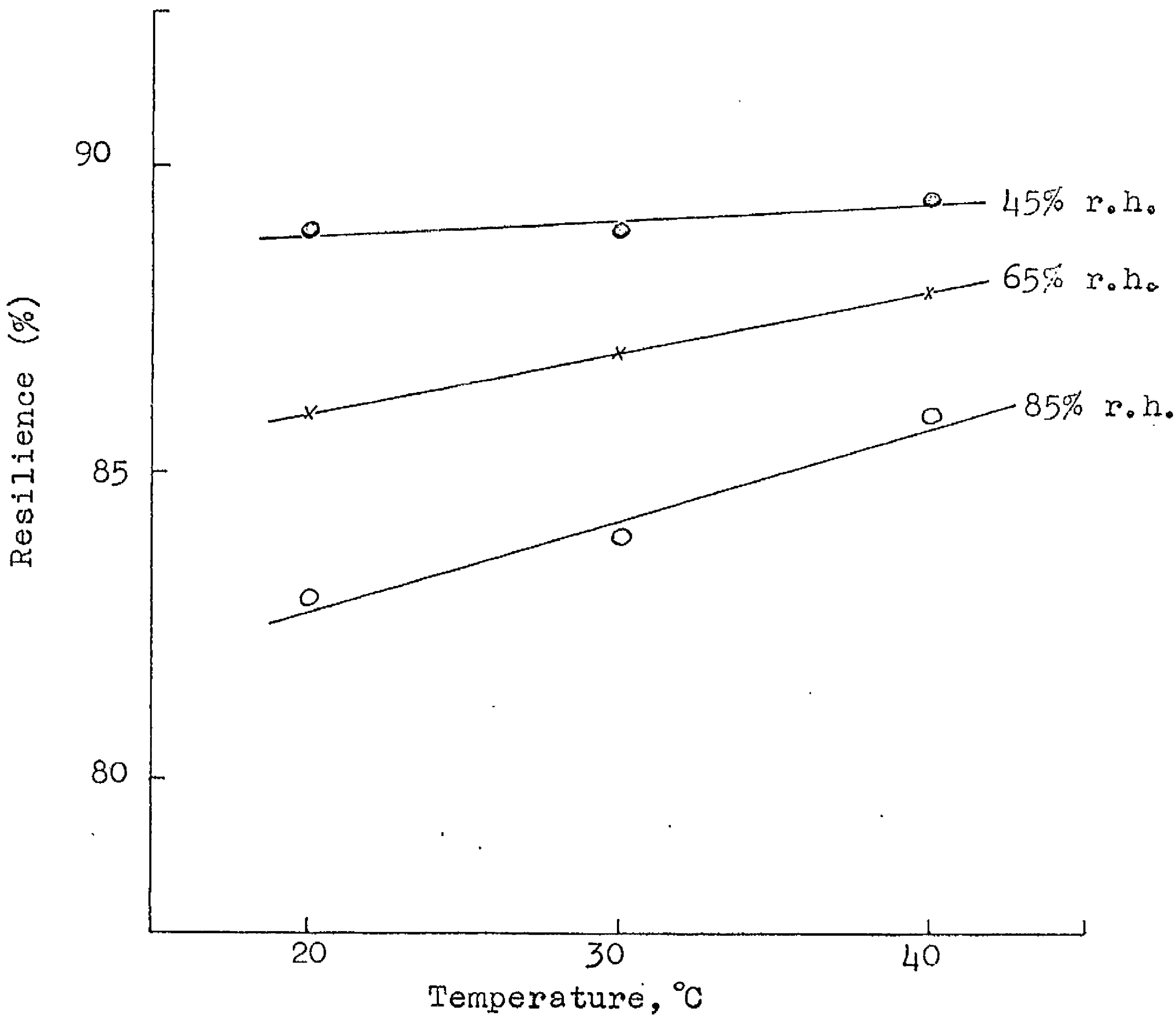


Fig. 34. Resilience vs. temperature

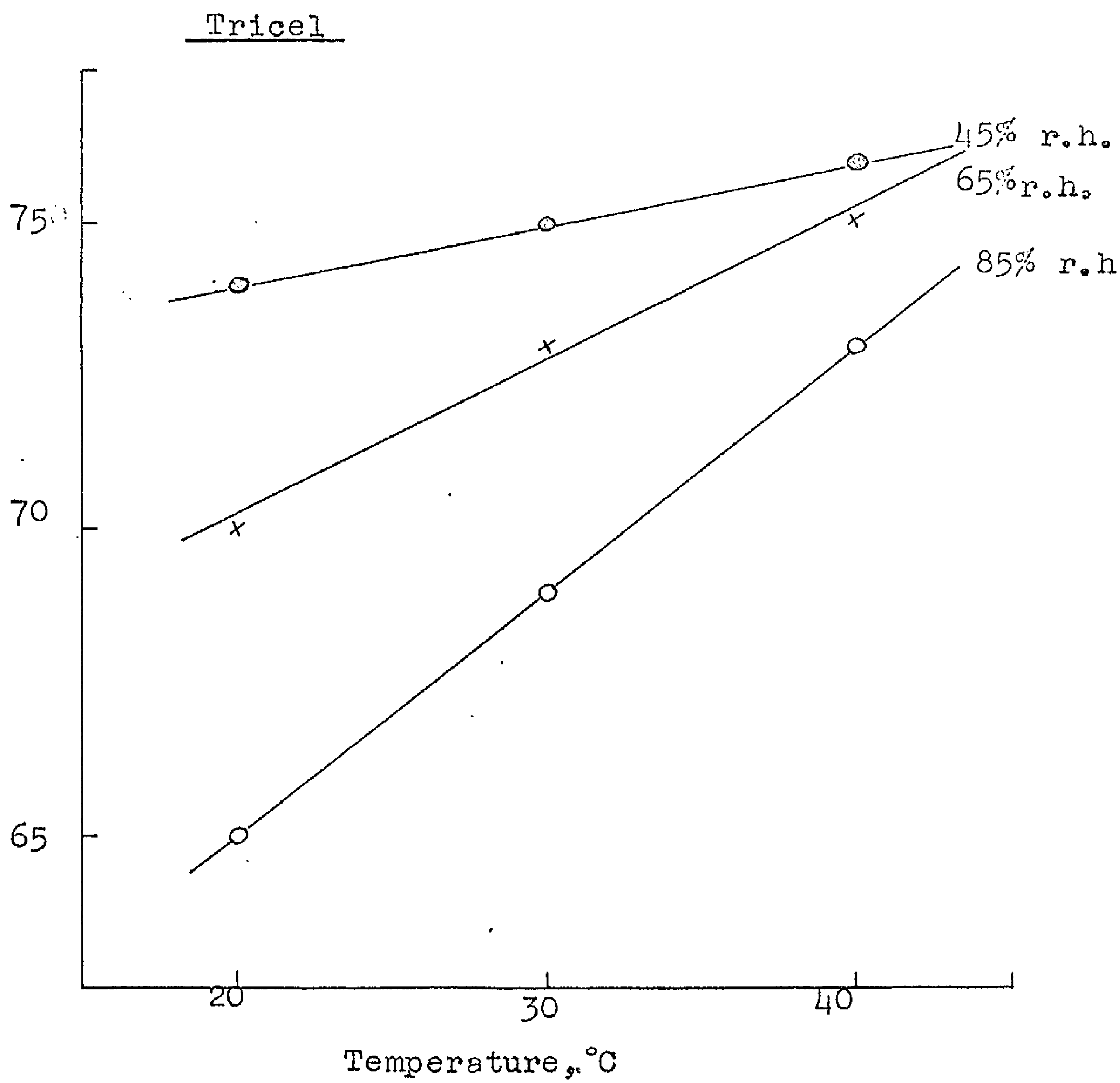


Fig.35. Fibres with various amount of finish

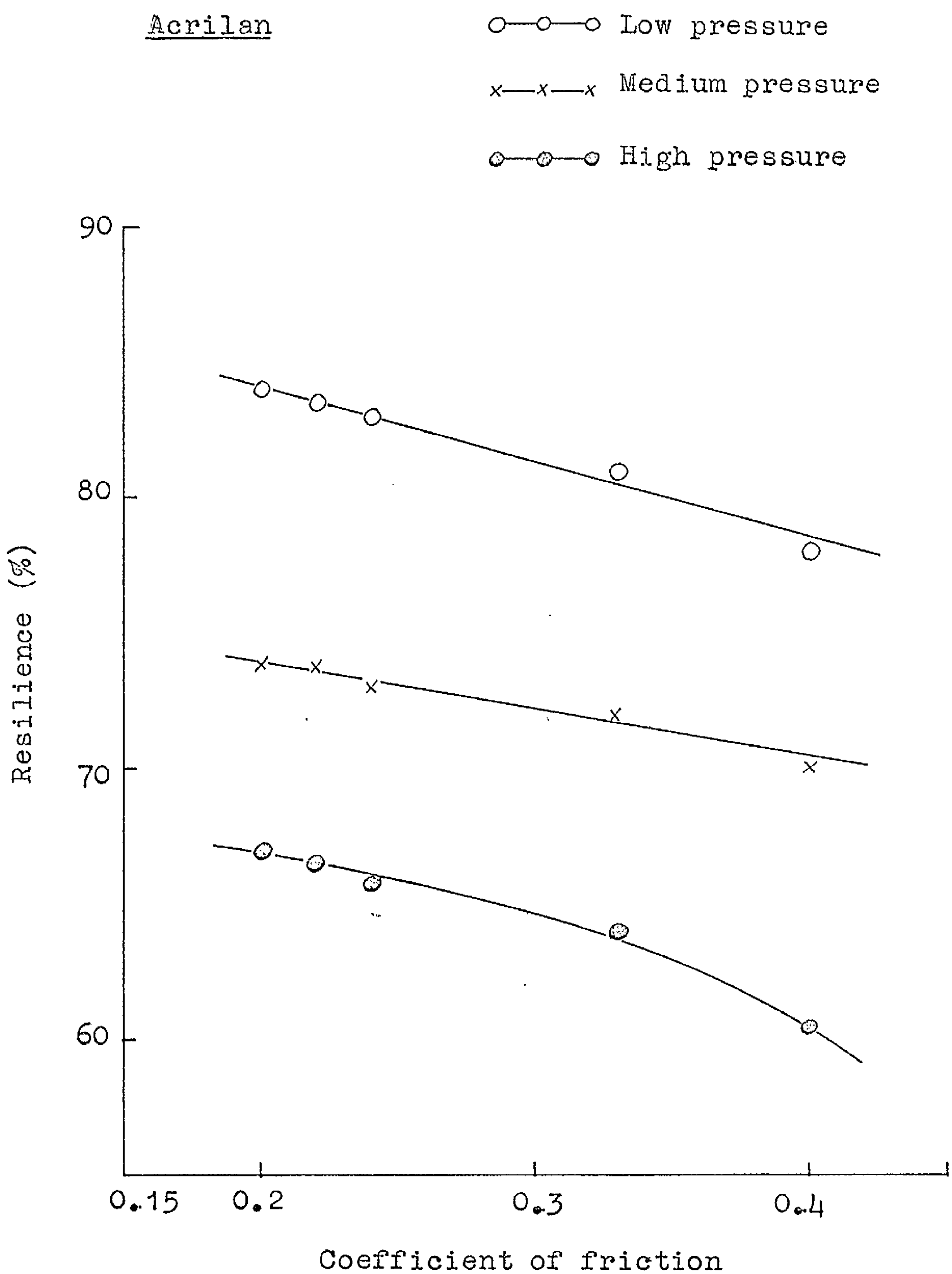


Fig. 36. Resilience vs. amount of finish

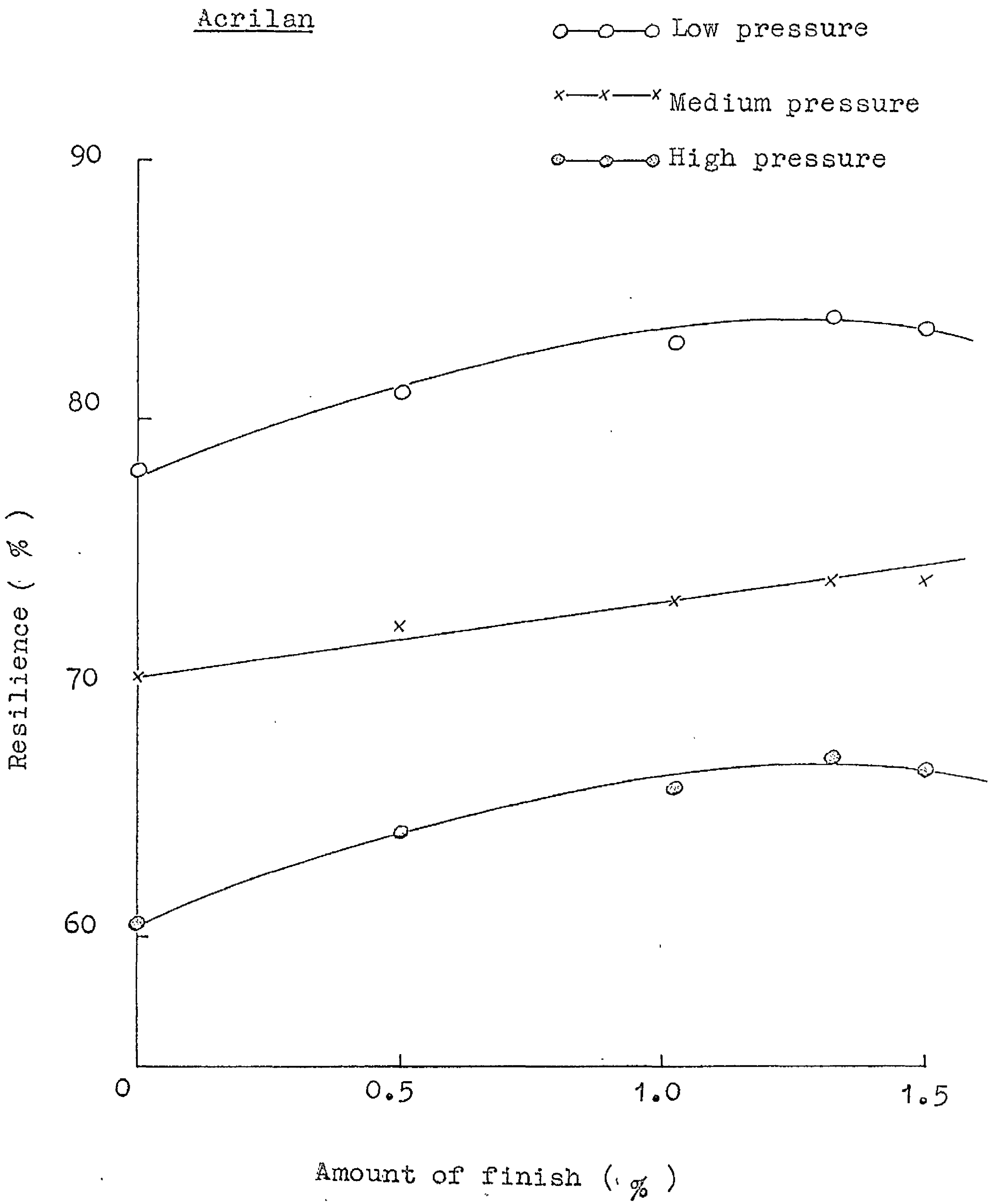


Fig. 38 Shirley Thickness Gauge vs. Instron

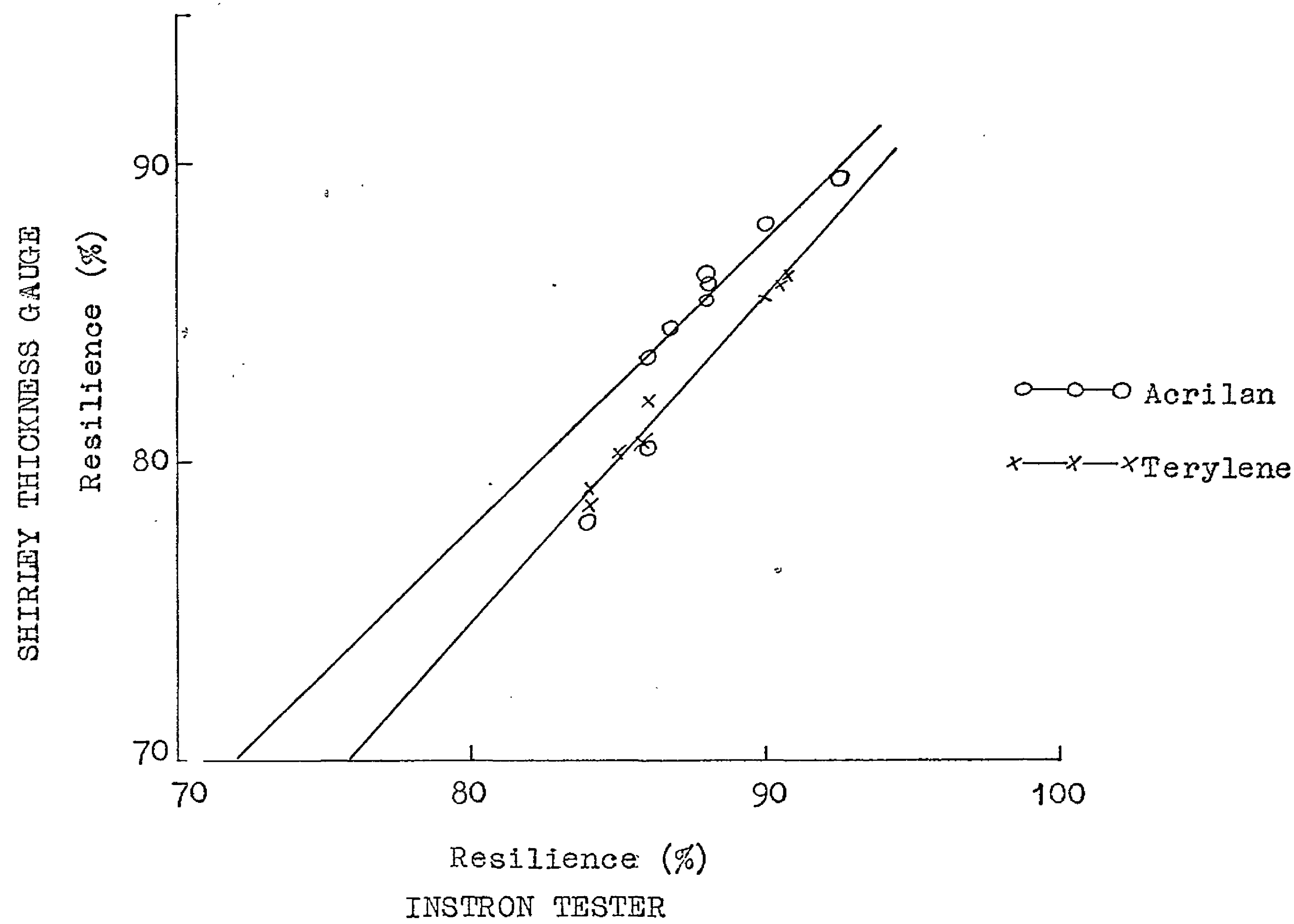


Fig. 39. Compression-recovery time cycles