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THE MECHANICAL PROPERTIES OF ANISOTROPIC POLYMERS

PROGRESS REPORT

A report of work carried out during the period 1st April to 30th September, 1966.

This report, in conjunction with that for the previous six months, forms the complete first year report for the period 1st October, 1965 to 31st September, 1966. Detailed results on the stress-strain properties of anisotropic polyethylene and the static fatigue of anisotropic polyvinyl chloride are presented. As detailed studies on the above polymers are still in progress, no detailed analysis of the results is given at this stage.

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PART I

GENERAL INTRODUCTION

A knowledge of the mechanical properties of polymers may be required for engineering design purposes and for improving the fundamental understanding of these materials. The majority of the published work in both fields has so far been concerned with the isotropic state. However, it is well known that many polymeric materials exhibit anisotropy of mechanical properties, the anisotropy arising either accidentally during normal processing or being deliberately introduced in an attempt to improve the material properties. It seems desirable therefore that the mechanical properties of anisotropic polymers should be known in detail and an attempt made to analyse the results and explain them. A certain amount of work has been carried out by Raumann and Saunders (1961) and Raumann (1962) on polythene, and by Pinnock and Ward (1966) for polyethylene terephthalate, their main interest being in Young's Moduli or shear moduli measurements.

The present work is designed to cover a wide range of mechanical properties, with special emphasis on creep in the anisotropic state. Polyethylene and polyvinyl chloride have been chosen, for the initial studies, being representative of soft and rigid thermoplastics respectively. They are also two of the most common polymers in general use. It is intended to extend the work to other polymers, such as for example, bisphenol - A polycarbonate, in the future

General Developments

In the previous progress report (CoA Memo No. 104, 1966) the usefulness of creep measurements and the design considerations for a creep apparatus were discussed. On the basis of that report an apparatus has been designed for the study of the creep properties of anisotropic polyethylene. Details of the basic machine, built in the department, are given in fig. 1.1. An extensometer system employing cross-spring pivots has also been designed and details are given in fig. 1.2. The extensometer system is based on a differential capacitor linear displacement transducer. Detailed tests of the extensometer and the loading machine have been delayed, pending the delivery of the transducers and their associated electronic equipment.

Stress-strain measurements on anisotropic polyethylene have been continued simultaneously with the development of the creep apparatus. The results of this investigation are given in Part II of the report.

Static fatigue measurements have been made on anisotropic polyvinyl chloride, full details being given in Part III of the report. During the measurements the existing automatic timing equipment was found to be unreliable. A new timing system is therefore being built before continuing these measurements.

Constant temperature enclosures have been constructed for use with the Instron tensile testing machine and two of the static fatigue rigs. The equipment will maintain a constant temperature, $\pm$ 0.2° C, in the range 18° C to 35° C. It is hoped to extend the range down to approximately 5° C in the near future.

PART II

THE STRESS-STRAIN PROPERTIES OF ANISOTROPIC POLYETHYLENE

1. INTRODUCTION

The anisotropy of Young's Modulus and the shear moduli of drawn polyethylene have been studied by Raumann and Saunders (1961) and by Raumann (1962). The variations of the moduli with draw ratio were found to be large and several surprising results were obtained. The work reported here covers a wider range of mechanical properties, but the method of preparation of the anisotropic sheets is based on that given by Raumann and Saunders. No analysis of the results is given as the work is still in progress.

2. SAMPLE PREPARATION

The grade of polymer chosen was I.C.I. 'Alkathene' WJG 11, having a melt flow index of 2.0 and a nominal density of 0.918 gram/c.c. at 23°C. It was obtained in the form of cube-cut granules. Isotropic sheets were prepared from the granules by pressing between chromium plated steel plates at 160°C. Thin Melinex sheets were used between the polymer and the plates to avoid adhesion problems when removing the pressed polymer sheets. The molten polymer was held in the press at 160°C for 15 minutes before being rapidly cooled by passing cold water through the press. This heating period was found to be necessary to remove strains caused by the pressing stage. The resulting isotropic sheets had a nominal thickness of 0.07 inches.

After the isotropic sheets had been in storage for a period of 12 to 15 days (288 to 360 hours), anisotropic sheets were prepared by selecting uniform isotropic sheets of length 15 to 24 cms. and width 6 cms. or 8 cms., and cold-drawing them in a Denison tensile testing machine. A grid of 1 cm. squares, marked on each sheet prior to the drawing process, was used in the determination of the final draw ratio. Baumann and Saunders (1961) have reported that the moduli of anisotropic samples, prepared in this way, increased slightly during the first three weeks after drawing, but then remained substantially constant. The drawn sheets were therefore stored at room temperature for several weeks before measurements of the draw ratios, or any tensile tests, were made.

Two types of specimen were used for the examination of the stress-strain properties. Specimens for the yield and ultimate measurements were prepared using a microtensile specimen cutter (A.S.T.M. designation D.1708-59T) having an overall length of 1.5 inches, a gauge length of 0.77 inches (1.96 cms.) and a width of 0.188 inches (0.478 cms.) in the test section. Parallel sided specimens were used for the initial modulus measurements, the strips being 0.4 cm. wide and 3.0 cms. long. Both types of specimen were cut from the polythene sheets with their long axes at angles of 0°, 45° and 90° to the draw direction. They were then stored at room temperature until required.

3. APPARATUS AND EXPERIMENTAL PROCEDURES

The stress-strain measurements reported below were obtained on an Instron, model TM. Type B load cell and grips (smooth faces) were used for the initial modulus measurements and type CT load cell with type C grips (serrated faces) for the measurement of ultimate properties. The majority of the yield and ultimate values were determined at room temperature (approximately 18 - 21°C), no attempt being made to provide further temperature stabilisation. For the initial modulus measurements, however, a constant temperature enclosure was built around the Instron, enabling a series of measurements to be made at 25°C ± 0.2°C.

The procedure adopted for the measurement of the initial modulus was as follows:

The parallel-sided specimen was mounted in the grips so that the separation of the grips was nominally 1.00". The exact separation of the grips was then measured with vernier callipers. A crosshead extension rate of 0.01 ins/min was selected and the load-extension curve obtained up to an extension of approximately 0.3%. The crosshead was then returned to its original position and the sample allowed to relax load free for at least 5 minutes. A crosshead extension rate of 0.05 ins/min was next selected and the load-extension curve again obtained up to an extension of 0.3%, followed by an interval of 5 minutes when the specimen relaxed, load free. This procedure was repeated for further crosshead extension rates of 0.1, 0.002 and 0.01 ins/min. The latter (repeat) run was continued up to an extension of at least 0.5%. It served as a check on the first run and indicated that the cycling procedure adopted did not affect the modulus values obtained. The modulus measured from the load extension curves was the secant modulus at a strain of 0.1%. A correction was applied to allow for the deflection of the load cell. In calculating the modulus the initial grips separation was regarded as the gauge length of the sample. (This procedure has been commented on in the previous report.) The initial grip separation was always within ± 3% of the nominal 1.00 inch; the extension rates may therefore be converted direct to strain rates without any appreciable error; the variation of modulus with strain rate being only of the order of 6% for a doubling of the strain rate.

The procedure adopted for the determination of the yield and ultimate properties was straightforward. The microtensile specimens were inserted in the Instron grips, with an initial grip separation of 2.05 ± 0.05 cms. The load extension curve was then obtained in the standard manner, using an extension rate of 1.00 in/min. for the anisotropic samples. For a sample gauge length of 0.77 in. this corresponds to a strain rate of 130%/min.

4. PROPERTIES OF THE ISOTROPIC SHEET

The density of the isotropic sheets has been measured in a density gradient column, at a temperature of 22.7°C. The results are shown in fig. 2.1. where it will be seen that the density did not reach a steady value during the tests. The variation is however very small; being less than 0.0004 gm/c.c. over the month following the first 4 days after preparation of the sheet. A density of 0.917 gm/c.c. corresponds to a crystallinity of approximately 47%.

The birefringence of each sheet was checked using a Babinet compensator. No region with a birefringence greater than 10^{-4} was detected in any of the sheets.

The mechanical isotropy of the sheets was checked by making initial modulus measurements and examining the load-extension curves (to break) for samples cut at various angles and positions in several sheets. No systematic variation of any of the properties with angle or position could be detected. The mean value of the initial modulus of the isotropic sheets was 2.08×10^9 dynes/cm^2 at a temperature of 25°C and an extension rate of 0.1 in/min/in.

The load-extension curves, at an extension rate of 1.0 in/min., for 4 samples, cut at various angles and positions in a single sheet were examined for anisotropy and reproducibility by superimposing the curves obtained. The curves were found to be practically indistinguishable, indicating the absence of mechanical anisotropy in the sheet and a good reproducibility between tests. The load-extension curves at various strain rates for a total of twenty-one samples cut from a single isotropic sheet were also obtained. A summary of the resulting yield and ultimate properties is given in table 2.1. The results of similar measurements on two other isotropic sheets are given in table 2.2. The agreement between the results for the three sheets is very satisfactory.

The variation of the yield strength, ultimate strength and extension at break with testing speed can be seen by examining tables 2.1 and 2.2 and the typical load-extension curves shown in fig. 2.3. The results indicate a definite increase in yield strength with testing speed. The reproducibility of the yield strength results is illustrated in fig. 2.4 (a), where all the results have been plotted. From table 2.1, the ultimate strength appears to have a peak value at 1.0 in/min, while the break extension increases steadily with extension rate. However, the ultimate properties show a much greater scatter than the yield properties, and any trend is within the experimental error. This may be seen in figs. 2.4(b) and 2.5, where the results for the variation of ultimate strength and elongation with extension rate are plotted. The large scatter in the results for the Ultimate properties is probably due to the poor surface finish imparted to the sides of the specimen by the cutters.

5. PROPERTIES OF THE ANISOTROPIC SHEET

The variation of density with draw ratio was determined from measurements on several anisotropic sheets, approximately 1,000 hours after they had been cold drawn. The results are shown in fig. 2.2, where it will be seen that the variation is very small, being only 0.001 gm/c.c. over the range of draw ratios from 1.1 to 3.7. For isotropic polyethylene this would correspond to an increase in crystallinity of only 0.5%. It seems probable therefore that changes in crystallinity with cold drawing are very small.

The variations of initial modulus, yield strength and ultimate properties with draw ratio and angle have been investigated for the anisotropic polyethylene sheets. The results are described separately below.

(a) Initial Modulus.

The measurements were performed approximately nine weeks after preparation of the anisotropic sheets. As preliminary tests had indicated that the modulus measurements were very temperature sensitive, a constant temperature enclosure was built around the Instron and a suitable constant temperature control system designed and built. The measurements were then made at a temperature of $25.0 \pm 0.2^{o}C$. Extension rates of 0.002, 0.01, 0.05 and 0.1 ins/min. were employed in order to investigate the variation of modulus with the rate of extension. Draw ratios from 1.1 to 3.7 were investigated; samples cut at angles of 0^{o}, 45^{o} and 90^{o} to the draw direction being used. It was found that plots of the initial modulus against log (Extension Rate) were linear within the experimental error, for all angles and draw ratios, the modulus increasing as the extension rate increased. The results obtained are therefore presented in this form in figs. 2.6, 2.7 and 2.8. Careful examination of the graphs reveals that, for each angle, the lines tend to become more nearly horizontal as the draw ratio increases, i.e. the modulus becomes less dependent on testing speed at the higher draw ratios. This decreasing time dependence is reflected in the typical load-extension curves shown in figs. 2.9 and 2.10, which were obtained at an extension rate of 0.01 ins/min. It will be seen that the curves for a draw ratio of 3.7 or 2.9 (fig 2.10) are nearly linear up to strains of 0.5%, while the curves for a draw ratio of 1.3 are noticeably non-linear. However, care must be exercised in interpreting this result as two separate effects contribute to this type of load-extension curve: non-linear behaviour (i.e. Hooke's law not obeyed -

Modulus is a function of the stress applied) and time-dependent behaviour (i.e. creep, stress relaxation). All that may therefore be said at this stage is that the above effects definitely decrease with increasing draw ratio. Creep measurements would be useful for distinguishing between the two effects.

The variation of initial modulus with draw ratio is plotted for angles of 0^o, 45^o and 90^o in fig. 2.11. Extension rates of 0.002 and 0.1 ins/min are illustrated.

The following observations on the results may be made:

(1) For all angles and draw ratios the initial modulus (E) increases with increasing extension rate. However the slope of the modulus - Extension Rate lines decreases as the draw ratio increases.

(2) At constant extension rate,

$E_o < E_{90}$, for draw ratios up to approximately 3.4

but $E_o > E_{90} > E_{45}$ for draw ratios > 3.4

(E_o is the initial modulus at an angle of 0^o, etc.).

(3) At constant extension rate, E_{45} decreases continually as draw ratio increases. However the exact shape of the curve depends on the extension rate. Thus it will be seen from fig. 2.11 that, at a crosshead extension rate of 0.1 in/min., $E_{45} > E_{90}$ up to a draw ratio of 1.3, but at an extension rate of 0.002 in/min., $E_{45} < E_{90}$ for all draw ratios. The transition between these two results may be seen by comparing the lines for E_{90} and E_{45} at a draw ratio of 1.1, in fig. 2.6.

(4) The difference between $(E_o)_{1.1}$ and $(E_o)_{3.7}$ decreases as the test speed increases. This also applies to (E_{90}). But the difference between $(E_{45})_{1.0}$ and $(E_{45})_{3.7}$ increases as the test speed increases. This is a direct consequence of (1) above. It would therefore appear that at very high test speeds, increasing the draw ratio has little effect on the value of E_o and E_{90}, but a large effect on E_{45}, i.e. at very high test speeds

$$(E_o)_{3.5} \doteq (E_o)_{1.0}$$

and $$(E_{90})_{3.5} \doteq (E_{90})_{1.0}$$

but $$(E_{45})_{3.5} \ll (E_{45})_{1.0}$$

where $(E_o)_{3.5}$ is the modulus of a specimen cut at an angle of 0^o to the draw direction in a sheet of draw ratio 3.5.

Finally, the effect of temperature on the measured value of the initial modulus may be examined by comparing the results in table 2.3 (obtained at 18.5^oC) with those for a draw ratio of 1.1 in figs. 2.6 and 2.7 (obtained at 25^oC). The effect of a 1^oC rise in temperature is to lower the modulus by approximately 4%. This illustrates the importance of temperature control during the measurements.

(b) Ultimate Properties and Yield Strength

The yield strength and ultimate properties were deduced from complete load-extension curves obtained on the Instron tensile testing machine, the measurements being carried out approximately five weeks after the preparation of the anisotropic sheets. All experiments were performed at a crosshead extension rate of 1.0 inch/min. and a temperature of 18 - 19^oC. No temperature stabilisation was available during these measurements. Draw ratios from 1.1 to 3.7 were investigated. The results obtained are listed in table 2.4, and typical load-extension curves for draw ratios of 1.1, 1.8 and 3.7 are given in figs. 2.12, 2.13 and 2.14.

The anisotropic samples cut at 90^o to the draw direction exhibited necking behaviour of the type associated with the isotropic samples when cold drawn, (See Stuart, 1956). For the 0^o samples, necking was apparent at low draw ratios, but gradually disappeared as the draw ratio was increased. For the 45^o samples, the ends of the neck, at the completion of the necking stage, made an angle of approximately 45^o with the specimen length, the effect becoming more apparent at the higher draw ratios. The contraction of the width and thickness of the anisotropic specimens during the load-extension tests was also of interest. At low draw ratios the contraction appeared to be in accordance with that expected for the isotropic samples. However, the 90^o specimens at high draw ratios exhibited a large reduction in width but only a small reduction in thickness. It is hoped to analyse these variations quantitatively in the near future.

The various tensile properties are dealt with separately below.

Yield Strength. (Y)

The variation of yield strength with draw ratio and angle is shown in fig. 2.15. For the 0° specimens the yield strength increases steadily, with draw ratio, from the isotropic value, while, for the 45° and 90° specimens, the yield strength has its highest value in the isotropic state. The yield strength for the 45° specimen decreases slowly from draw ratio 1.0 to 3.7. However the behaviour of the 90° specimens is rather different in that an initial small decrease in yield strength is followed by a small increase, as the draw ratio increases. Thus, between the draw ratios of 1.0 and 2.0, $Y_{90} < Y_{45}$, but above a draw ratio of 2.0, $Y_{90} > Y_{45}$. This behaviour is emphasised by the gradual development of a very sharp peak at the yield point for the 90° specimens, illustrated in figs. 2.12 to 2.14. No such peak is present in the 0° and 45° curves.

Ultimate Strength.

The variation of ultimate strength with draw ratio and angle is shown in fig. 2.16. For the 0° specimens, the ultimate strength increases steadily with draw ratio, in a manner similar to that found for the yield strength. However the ultimate strength of the 90° specimens shows a continuous, gradual decrease with increasing draw ratio, which is a marked difference from the yield strength curve. The ultimate strength of the 45° specimens also decreases with increasing draw ratio, but the shape of the curve is a little uncertain.

The unusual necking process for the 45° specimens made the estimation of the effective original gauge length extremely difficult and uncertain. Any alteration of the gauge length would obviously alter the effective rate of strain of the sample. At present no results are available on the variation of ultimate strength with strain rate for the anisotropic state but results for the isotropic state show little variation with strain rate. However, the possibility that the shape of the curve for the 45° specimen (fig. 2.16) has been affected by the unusual neck shape remains.

Elongation at Break.

The variation of elongation at break (or 'break extension') with draw ratio and angle is shown in fig. 2.17. The 90° break extension increases and the 0° break extension decreases as the draw ratio increases. The existing results for the 45° specimens (see table 2.4) cannot be plotted in this way as the method depends on the fact that all the samples have the same initial gauge length. This condition is definitely not satisfied by the 45° specimens, as mentioned in a previous section.

PART III

CREEP RUPTURE OF ANISOTROPIC P.V.C. SHEET

1. INTRODUCTION

An exploratory study of the mechanical properties of anisotropic polyvinyl chloride has been carried out by Gibbs, (1966) as a student in the Department of Materials. The results obtained were submitted as a College of Aeronautics thesis. The work reported here was intended as an expansion of the above investigation. The main part of Gibbs' results was concerned with the creep rupture (or 'static fatigue') of P.V.C., but yield strength and Young's Modulus were also studied in some detail. Anisotropic sheets of draw ratio 1.5 and 3.0 were submitted to creep rupture tests, while draw ratios of approximately 1.5, 1.8, 2.1, 2.4, 2.7 and 3.0 were used for the Yield and Modulus studies. All three properties were found to exhibit anisotropy, the variation of fatigue life with angle and draw ratio being particularly large.

It was hoped to extend the fatigue measurements by carrying out tests on anisotropic sheets of draw ratio approximately 1.25 and 5.0. Measurements at the former draw ratio are reported here. Difficulty is being experienced at present with the preparation of sheets with a draw ratio greater than 3.0, although results reported by Pinner (1965) indicate that it should be possible. Further investigations on this point are in progress at present.

2. SAMPLE PREPARATION

The polymer chosen was I.C.I. 'Darvic', natural grade 110. It was obtained in the form of sheets, 6 ft. by 3 ft. and 0.25 inch thick. This grade of 'rigid' P.V.C. contains no plasticiser or pigment but does contain small quantities of stabilisers and lubricants. A more detailed discussion of the polymer has been given by Gibbs who estimated that the polymer had a number average molecular weight of about 50,000. This is relatively high for P.V.C.

The method used for preparing anisotropic P.V.C. sheets is that used by Gibbs. Only a brief outline will therefore be given here. Blanks of size 9 ins by 4 ins were cut by band saw from the sheet obtained from the manufacturers. A grid of 0.5 inch squares was marked out on one side of each blank using a ball-point pen, the grid lines being parallel to the edges of the blank. Two blanks at a time were heated on a glass plate in an electric oven for a period of 0.5 to 0.75 hour at an oven temperature of 120°C. Longer periods of heating were avoided because of the risk of thermal degradation. A heated blank was transferred to the jaws of a Denison tensile testing machine and drawn to a predetermined length, which varied according to the draw ratio required. The maximum extension rate of about 8.5 ins/min was used in order to complete the drawing process before the specimen temperature had dropped below a critical value, which depended on the draw ratio required. The drawn sheet was left in the grips until cold, so retaining the full extension. The exact draw ratio could then be determined from the grid dimensions.

Rectangles of size 2.1 ins by 0.6 ins were drawn on the prepared blanks at various angles to the draw direction. These were cut out of the sheet by band saw and a fatigue test piece of the type shown in fig 3.1 was machined from each piece. The width of each sample was measured with a ball-ended micrometer; a normal screw micrometer being used for the thickness measurement. Test pieces having any deep machining marks or scratches were rejected as fracture properties, such as creep rupture, were known to be sensitive to surface finish.

3. APPARATUS AND EXPERIMENTAL PROCEDURES

The creep rupture machines employed were those designed and used by Gibbs. Full details may be found in his thesis. Each machine consisted basically of a lever loading system and an electronic timer. A micro-switch located underneath the weight carrier was used to stop the timer at the moment of fracture of the sample. The stresses applied to the sample were chosen so as to obtain fracture times in the range 0.1 to 100 hours. The specimens were mounted in simple self-aligning holders attached by means of bolts through holes in the specimen ends. (See fig. 3.1). No temperature stabilisation was available for most of the work. The majority of the measurements were therefore carried out at room temperature, which varied from 17°C to 21°C.

4. PROPERTIES OF THE AS-RECEIVED SHEET

The 'as-received' sheet was taken as being in the isotropic state. It was therefore essential to carry out measurements on samples cut at various angles from the sheet in order to justify this assumption. The results of creep rupture measurements performed on samples cut at 0°, 45° and 90° to the edge of the sheet are given in fig. 3.2(a). No obvious anisotropy can be observed in the results. The scatter is however fairly large, probably due to small variations in the sheet properties caused by the manufacturing process. In order to carry out further checks, two blanks with the usual grids marked on them were heated for 0.5 hour in an oven at 120°C. They were then removed from the oven and suspended from the top jaw of the Denison machine until cold. The grids were then carefully measured by travelling microscope. Variations of up to ± 0.01 inch were detected in the 0.5 inch grid. (Preliminary checks had indicated that the grid, before heating, was accurate to ± 0.002 inch). The variations were equivalent to a draw ratio of up to 1.02. As the anisotropic sheets were subjected to the above heat treatment before being drawn, the properties of the heat treated, 'as-received' sheet were checked. Samples machined from the two blanks mentioned above were tested. The results are given in fig. 3.2 (b). It will be seen that the scatter of results was reduced by the heat treatment, and the line drawn through the results agrees very well with that drawn in fig. 3.2 (a). The heat treatment therefore appears to produce a satisfactory isotropic sheet prior to production of the anisotropic sheets and the fatigue properties of the heat treated sheet agree very well with the average values for the 'as-received' sheet.

5. CREEP RUPTURE RESULTS FOR THE ANISOTROPIC P.V.C. SHEET

Anisotropic sheets of draw ratio 1.28 were prepared as described in section 2. The sheets were stored at room temperature for a week before being cut up ready for machining. The machined fatigue specimens were stored a further two weeks before any measurements were made. The anisotropic sheets exhibited a birefringence of approximately 4.5×10^{-4} at a temperature of 19°C, in sodium yellow light. Static fatigue measurements were made on samples cut at angles of 0^o, 30^o, 45^o, 60^o and 90^o to the draw direction. The temperature during the tests varied between 17^oC and 21^oC. The results are given in fig. 3.3. It will be seen that the variation of stress with log (failure time) is linear for all angles. The strength of the material is greatest in the direction of orientation (0^o), and decreases with increasing angle to the draw direction. The fatigue strength of the 'as-received' material lies between that of the 45^o and the 60^o specimens. The slopes of the lines in fig. 3.3 appear to show a gradual increase in slope from the 0^o to 90^o specimens. The slope of the 0^o line is very shallow and small changes of the applied stress produce large changes in the time to failure.

In many of the fatigue tests the specimens underwent a large extension over a relatively short time, the extended portion assuming an opaque whitish appearance. It was found that, in general, the specimens which fractured after a short time (relatively high stress) only underwent a short extension in the region of 0.1 inch, while the specimens that took a long time to fracture (relatively low stress) underwent a longer extension, in the region of 0.4 inch. The length of time, after the extension phase, before the specimen failed also varied; the lifetime increasing as the extension increased (stress decreased). Also, some of the lower stress specimens broke during the extension stage or soon afterwards, while others lasted for a considerable time. This greatly increased the scatter of the results. As the extended specimen had a reduced area of crossection, it would appear that the extension process strengthened the material; presumably by orientation processes, The present experiments are designed to simply determine the time to fracture of the specimens. It is apparent however that the specimens have "failed" when the large extension occurs as the extension is irreversible and the nature of the material completely altered. It would be of interest in future experiments to plot the behaviour of this failure process.

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TABLE 2.1. SUMMARY OF THE ULTIMATE PROPERTIES OF ISOTROPIC POLYETHYLENE. (TEMP. 21 - 22°C). (1)

CROSSHEAD RATE (ins./min.)	YIELD (2) STRENGTH (dynes/cm^2.)	TENSILE STRENGTH (dynes/cm^2.)	BREAK EXTENSION (cms.)
0.1	0.84×10^8 (1,220)	1.39×10^8 (2,010)	11.8 (4.65)(3)
0.5	0.86×10^8 (1,250)	1.5×10^8 (2,170)	12.6 (4.95)
1.0	0.89×10^8 (1,290)	1.57×10^8 (2,270)	12.9 (5.07)
5.0	0.945×10^8 (1,370)	1.46×10^8 (2,120)	13.0 (5.12)
10.0	0.98×10^8 (1,420)	1.37×10^8 (1,990)	13.3 (5.25)
20.0	1.02×10^8 (1,485)	1.3 x 108 (1,880)	13.5 (5.3)

(1) MICROTENSILE SPECIMENS CUT AT VARIOUS ANGLES FROM A SINGLE ISOTROPIC SHEET; THREE OR FOUR DAYS AFTER PREPARATION OF SHEET. (No. G.15).

(2) NUMBERS IN BRACKETS ARE STRESSES IN lbs/in^2.

(3) EXTENSION IN INCHES.

TABLE 2.2. ULTIMATE PROPERTIES OF ISOTROPIC POLYETHYLENE: INTER-SHEET REPRODUCIBILITY TESTS (1) (TEMP. 21 - 22°C)

SAMPLE SOURCE (Sheet No.)	CROSSHEAD RATE (2) (ins/min)	YIELD STRENGTH (dynes/cm^2)	TENSILE STRENGTH (dynes/cm^2)	BREAK EXTENSION (cms.)
G.12	0.5	0.89×10^8 (1,300)	1.32×10^8 (1,910)	10.3 (4.06)(3)
	0.5	0.88×10^8 (1,280)	1.47×10^8 (2,130)	11.9 (4.67)
	1.0	0.89×10^8 (1,300)	1.59×10^8 (2,300)	13.2 (5.2)
G.13	0.2	0.86×10^8 (1,250)	1.34×10^8 (1,940)	11.2 (4.4)
	1.0	0.90×10^8 (1,310)	1.32×10^8 (1,920)	10.7 (4.2)
	1.0	0.90×10^8 (1,310)	1.45×10^8 (2,100)	11.9 (4.7)
	5.0	0.95×10^8 (1,380)	1.44×10^8 (2,090)	13.2 (5.2)

(1) Microtensile specimens: G.12 samples tested 3 days after preparation of sheet. Sheet G.13 samples tested after 7 days.

(2) Numbers in brackets are stresses in lbs./in^2.

(3) EXTENSION IN INCHES

TABLE 2.3. INITIAL MODULUS OF ANISOTROPIC POLYETHYLENE

(DRAW RATIO = 1.1, TEMPERATURE = 18.5°C)

Crosshead Rate (ins./min)	(1) Initial Modulus (Dynes/Cm^2)		
	0°	45°	90°
0.002		1.72×10^9	1.61×10^9
0.01	1.95×10^9	2.06	1.93
0.05	2.3	2.37	2.19
0.10	2.41	2.47	2.46

(1) Measured at extension of 0.1%

TABLE 2.4. ULTIMATE PROPERTIES OF ANISOTROPIC POLYETHYLENE SHEETS. (1)

DRAW RATIO	ANGLE	YIELD STRENGTH (dynes/cm.^{2})	TENSILE STRENGTH AT BREAK (dynes/cm.^{2})	EXTENSION AT BREAK (cms.)
1.1	0^o	1.08×10^8 (1.57)	1.64×10^8 (2.38)	10.7
	45^o	0.965 (1.4)	1.63 (2.36)	12.2
	90^o	0.91 (1.32)	1.45 (2.1)	12.0
1.35	0^o	1.39×10^8 (2.01)	2.1×10^8 (3.04)	8.38
	45^o	0.945 (1.37)	1.49 (2.16)	10.5
1.4	90^o	0.792 (1.15)	1.26 (1.83)	13.5
1.55	0^o	1.39×10^8 (2.01)	2.19×10^8 (3.17)	7.8
1.6	45^o	0.924 (1.34)	1.26 (1.82)	8.05
1.5	90^o	0.806 (1.17)	1.26 (1.82)	14.3
1.8	0^o	1.77×10^8 (2.56)	2.36×10^8 (3.43)	5.25
	0^o	1.75 (2.54)	2.62 (3.8)	6.22
	45^o	0.806 (1.17)	1.13 (1.64)	8.15
1.9	90^o	0.80 (1.16)	1.08 (1.57)	15.8
2.2	0^o	2.24×10^8 (3.24)	2.63×10^8 (3.81)	3.25
	0^o	2.28 (3.31)	2.76 (4.01)	3.7

TABLE 2.4. (CONTINUED)

DRAW RATIO	ANGLE	YIELD STRENGTH (dynes/cm.^{2})	TENSILE STRENGTH AT BREAK (dynes/cm.^{2})	EXTENSION AT BREAK
2.2	90°	0.855 (1.24)	FLAW DEVELOPED	
2.25	90°	0.847 (1.23)	0.985 (1.43)	17.1
2.75	0°	2.97×10^8 (4.31)	3.41×10^8 (4.94)	2.79
	0°	3.11 (4.51)	3.38 (4.89)	2.49
2.65	45°	0.737 (1.07)	1.04 (1.51)	8.25
	45°	0.73 (1.06)	1.04 (1.51)	7.87
2.63	90°	0.869 (1.26)	FLAW DEVELOPED	
	90°	0.861 (1.25)	0.875 (1.27)	18.7
2.7	0°	4.83×10^8 (7.0)	4.84×10^8 (7.02)	1.40
		4.83 (7.0)	4.86×10^8 (7.04)	1.35
	45°	0.641 (0.93)	0.896 (1.3)	8.65
		0.621 (0.90)	0.889 (1.29)	8.7
	90°	0.924 (1.34)	FLAW DEVELOPED	
		0.945 (1.37)	FLAW DEVELOPED	
		0.938 (1.36)	0.745 (1.08)	21.6

(1) MICROTENSILE SPECIMENS; STRETCHED AT A CROSSHEAD EXTENSION RATE OF 1.0 inch/min. TEMP. 18 - 19°C.

(2) VALUES IN BRACKETS ARE STRESSES IN 10^3 p.s.i.

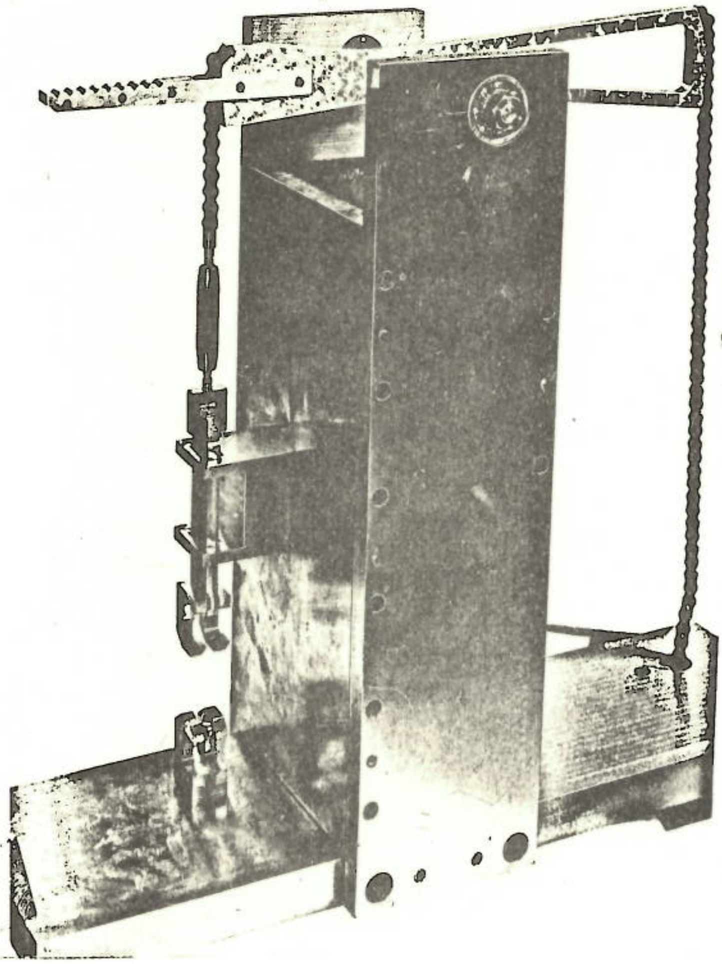

FIG. 1.1 BASIC LEVER-LOADING CREEP APPARATUS

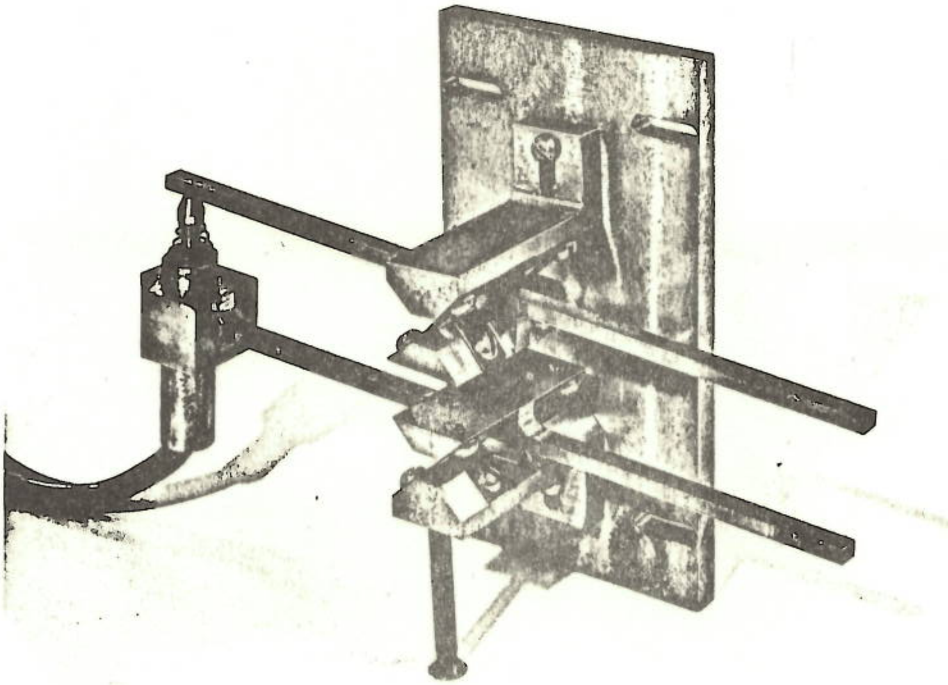

FIG. 1.2 THE EXTENSOMETER

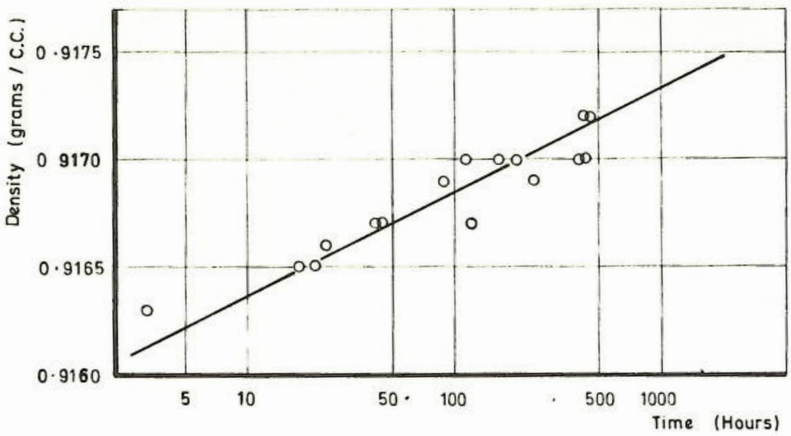

Figure. 2.1. Variation of Density with Time after Preparation for Isotropic Polythene Sheets (Temp. = 22·7 °C)

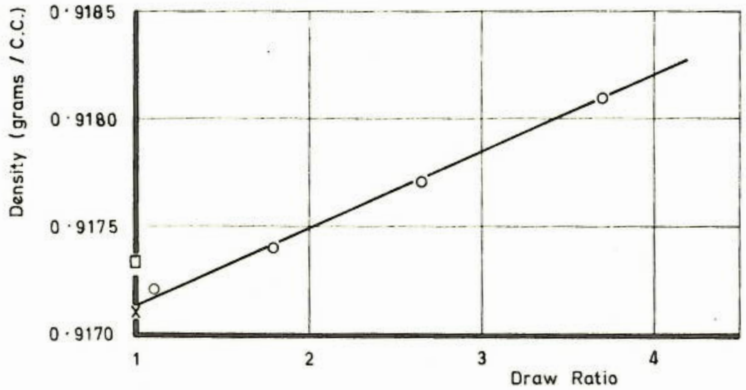

Figure 2.2. Variation of Density with Draw Ratio for Anisotropic Polythene (Temp = 22·7 °C)
Measurements made approximately 1,000 hours after Drawing
X = Isotropic Sheet when Anisotropic Sheets made
□ = Isotropic Sheet 1,000 hours later.

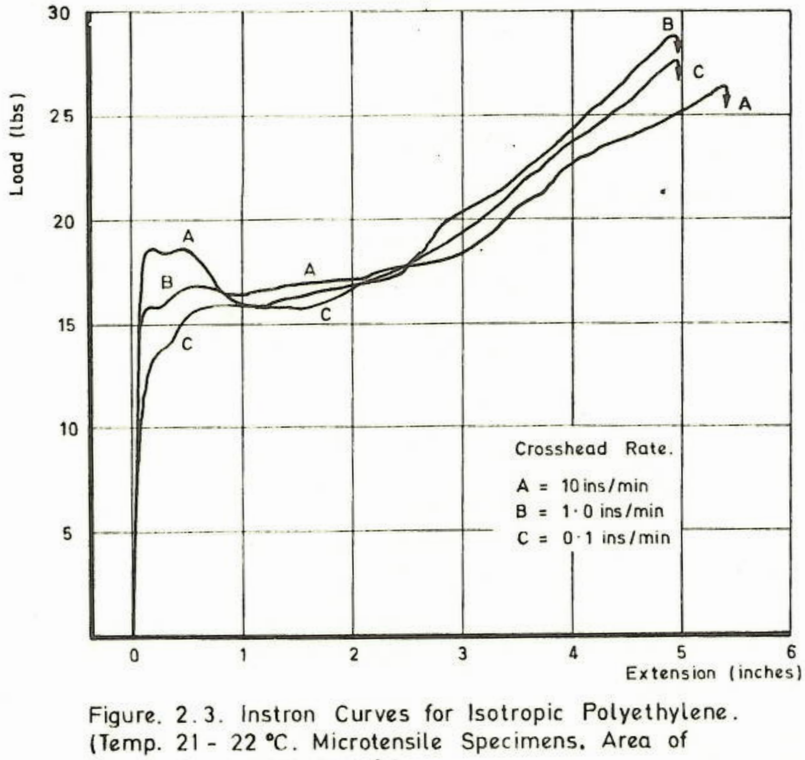

Figure. 2.3. Instron Curves for Isotropic Polyethylene. (Temp. 21 - 22 °C. Microtensile Specimens. Area of Crossection = 0·013 ins^2)

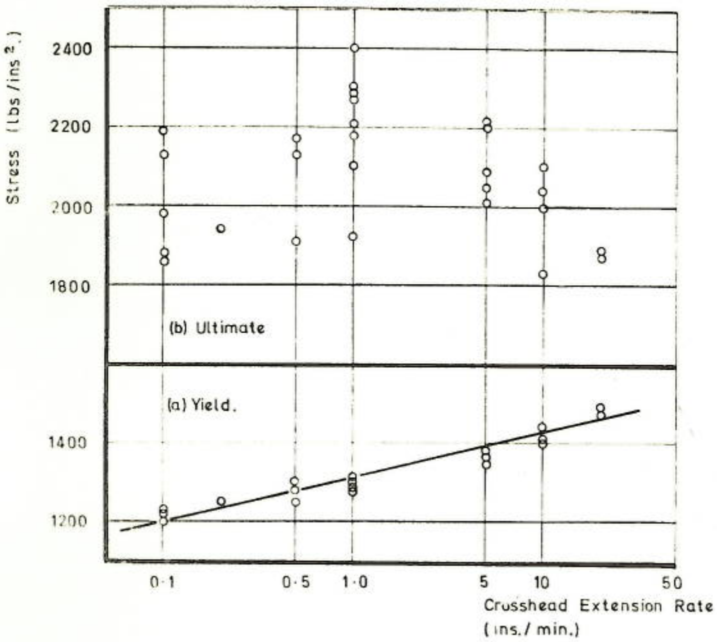

Figure 2.4. Variation of (a) Yield Strength and (b) Ultimate Strength with Crosshead Extension Rate for Isotropic Polyethylene.

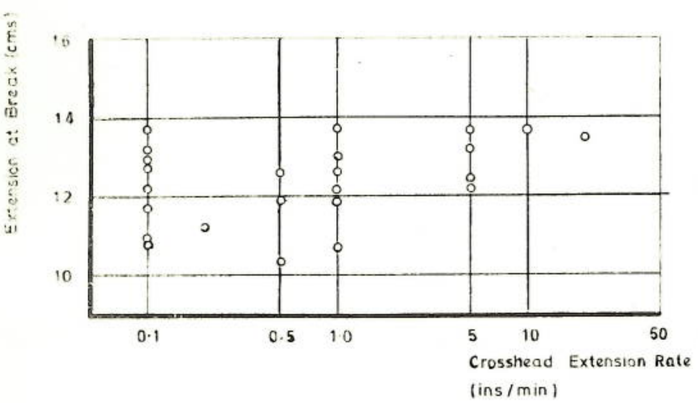

Figure 2.5. Variation of Extension at Break with Crosshead Extension Rate for Isotropic Polyethylene.

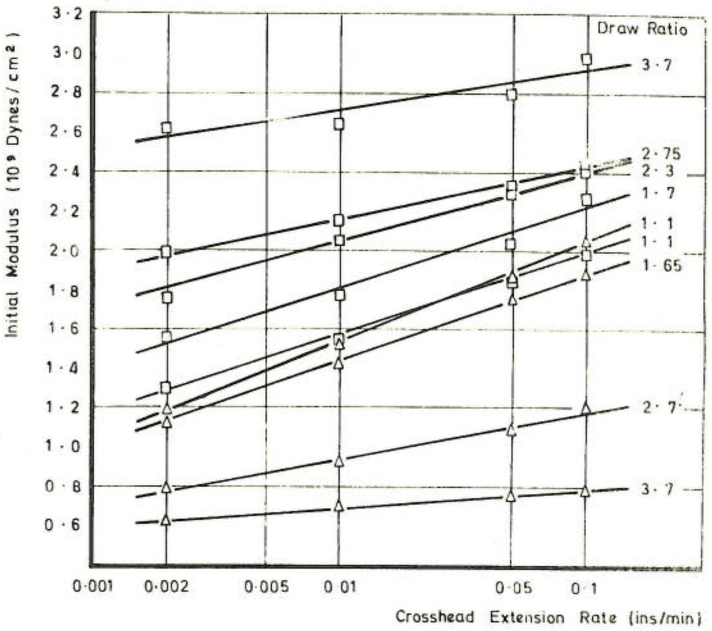

Figure. 2.6. Variation of Initial Modulus with Crosshead Extension Rate for Various Angles and Draw Ratios. (□ - 90°, Δ - 45° to Draw Direction.)

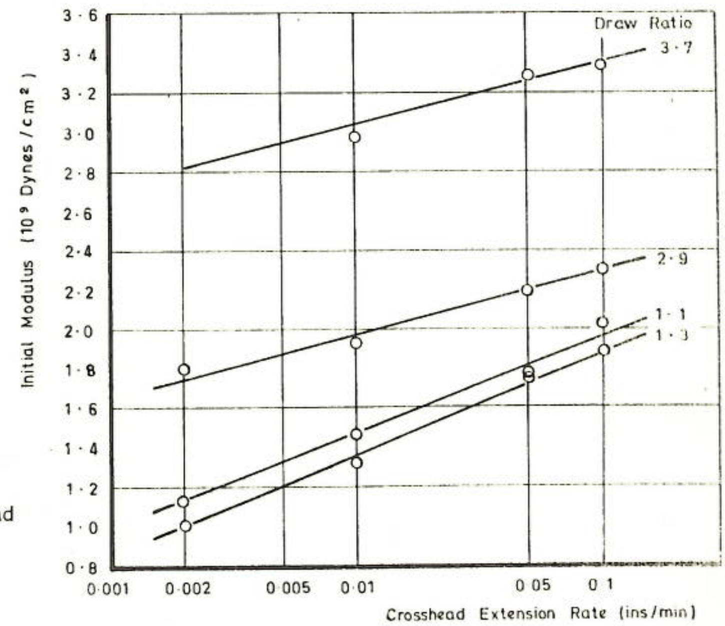

Figure. 2.7. Variation of Initial Modulus with Crosshead Extension Rate for Various Draw Ratios. (O - 0° to Draw Direction.)

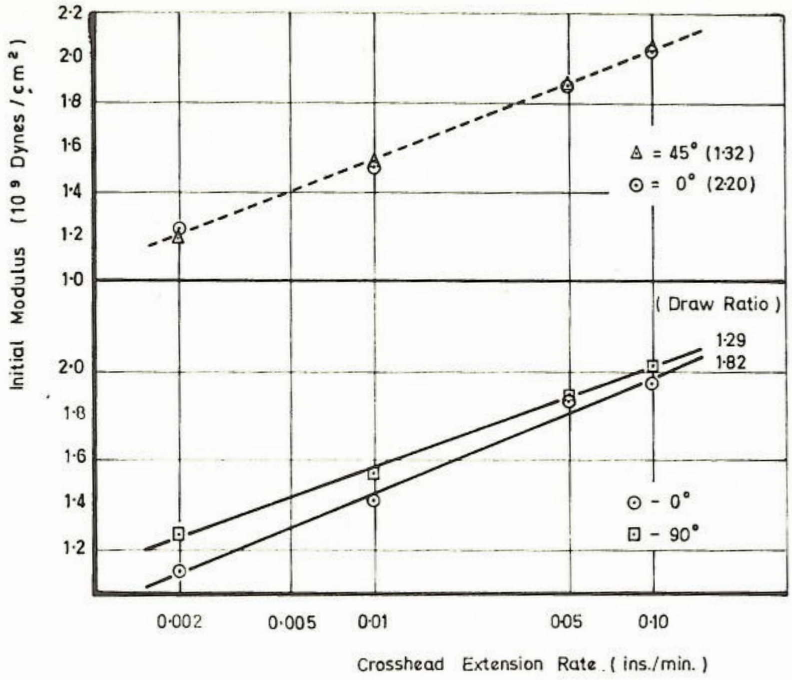

Figure 2.8. Variation of Initial Modulus with Crosshead Extension Rate for Various Angles and Draw Ratios.

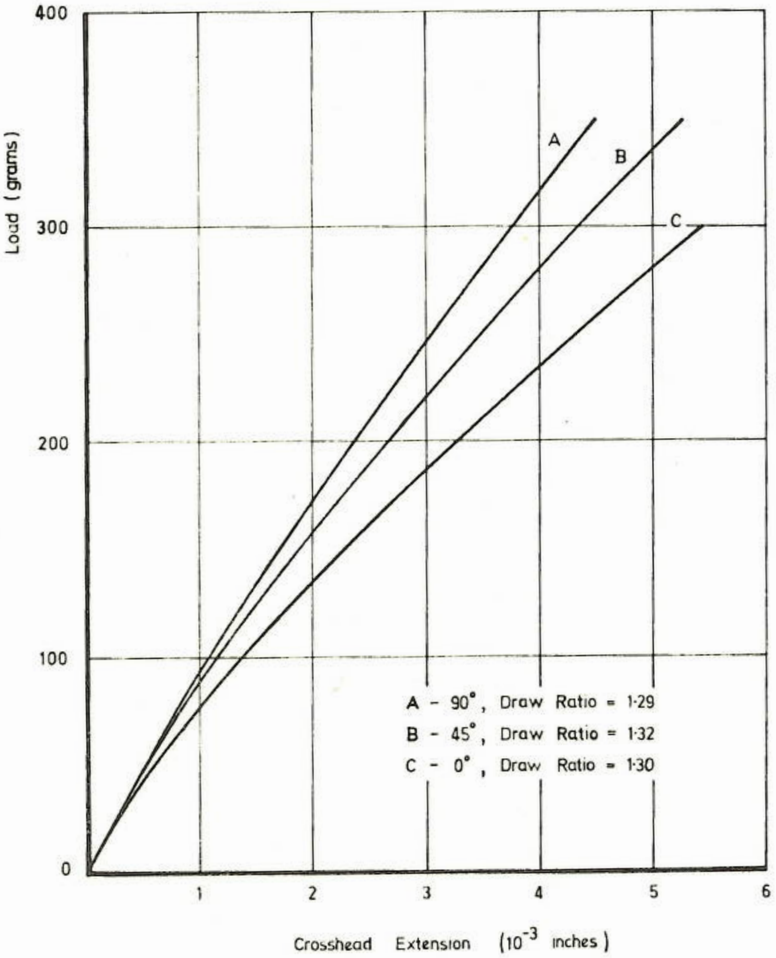

Figure 2.9. Variation of Load with Extension for Anisotropic Polythene (Instron Curves) Cut at Angles of 0°, 45°, 90° to Draw Direction (Extension Rate = 0·01 ins./min.)

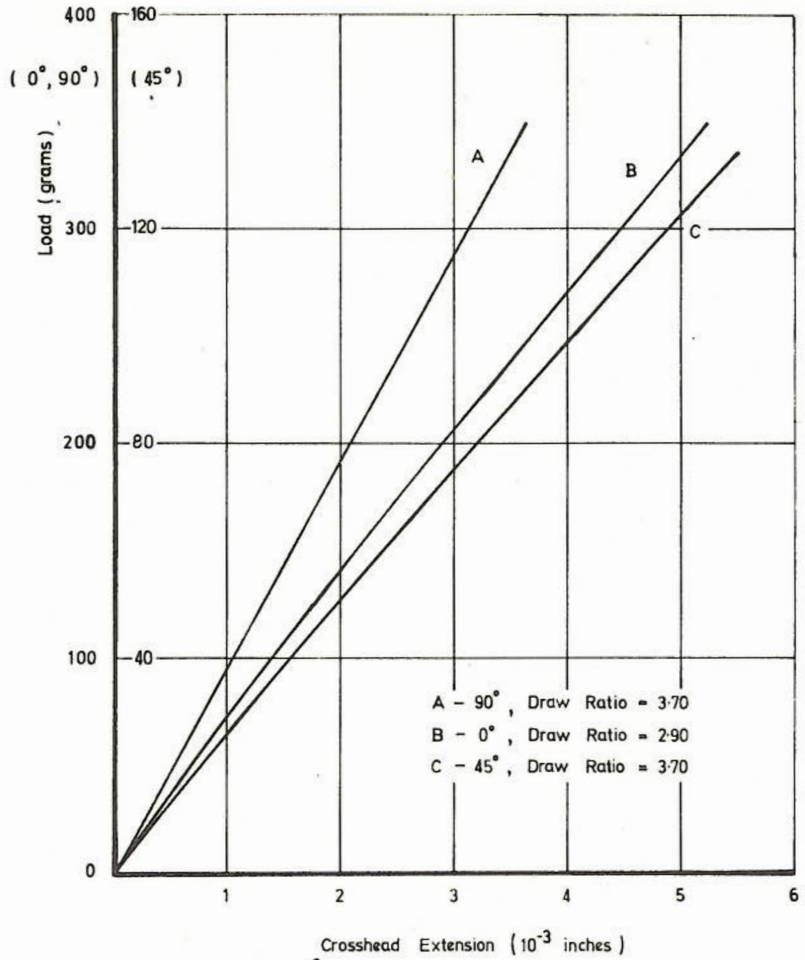

Figure 2.10. Variation of Load with Extension for Anisotropic Polythene Cut at Angles of 0°, 45°, 90° to Draw Direction (Instron Curves) (Extension Rate = 0·01 ins./min.)

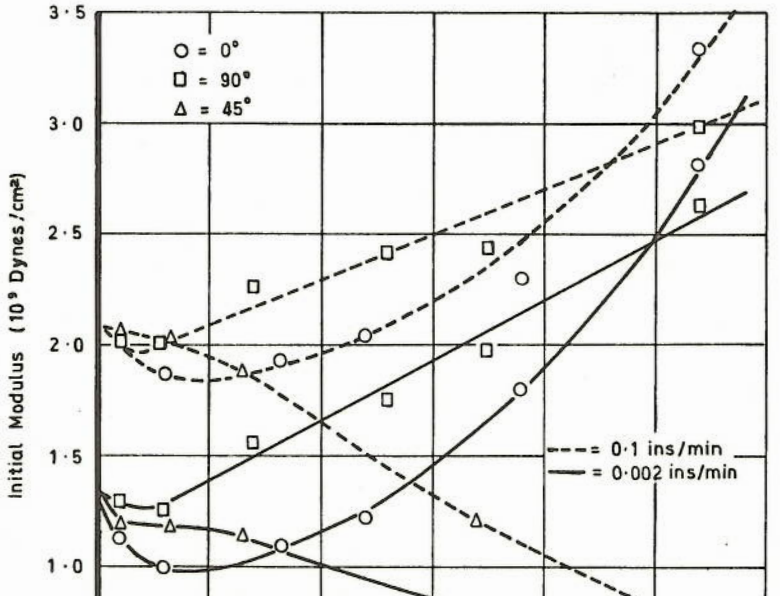

Figure. 2.11. Variation of Initial Modulus with Draw Ratio for Specimens Cut at Angles of 0°, 45° and 90° to the Draw Direction (Temp. = 25 °C.)

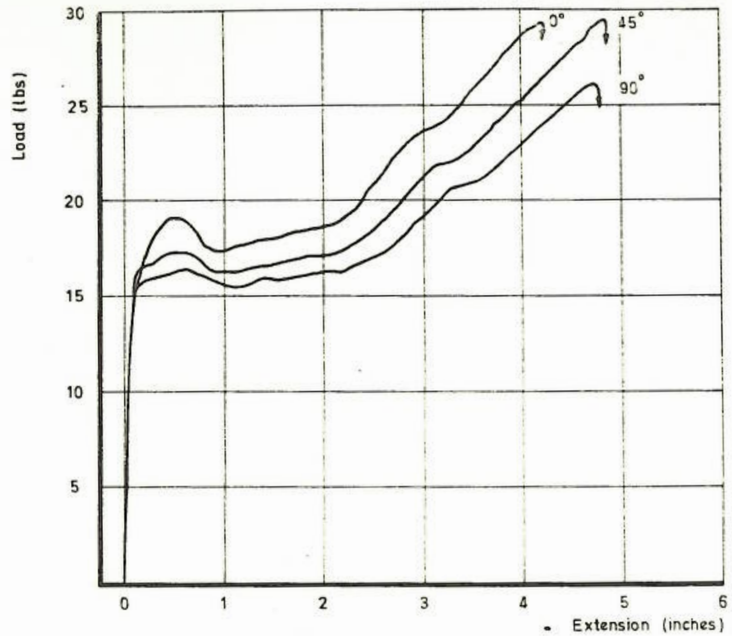

Figure. 2.12. Variation of Load with Extension (Instron Curves) for Anisotropic Polyethylene. Draw Ratio = 1·1. (Temp. 18 – 19 °C. Microtensile Specimens Area of Crossection = 0·0102 ins². Extension Rate = 1·0 ins/min.)

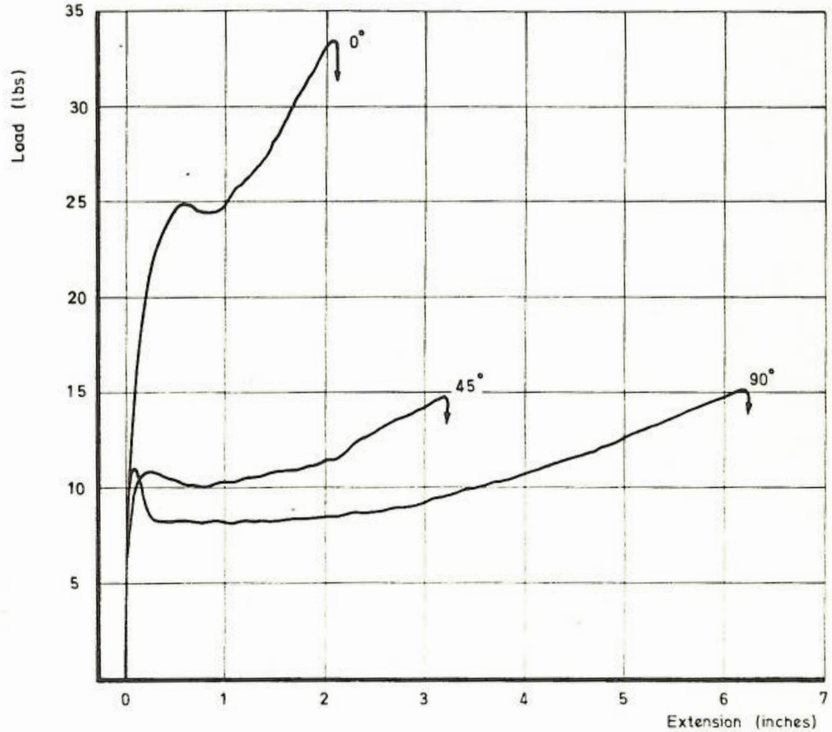

Figure. 2.13 Variation of Load with Extension for Anisotropic Polyethylene. Draw Ratio = 1 · 8. (Area of Crossection = 0 · 0082 inches.²)

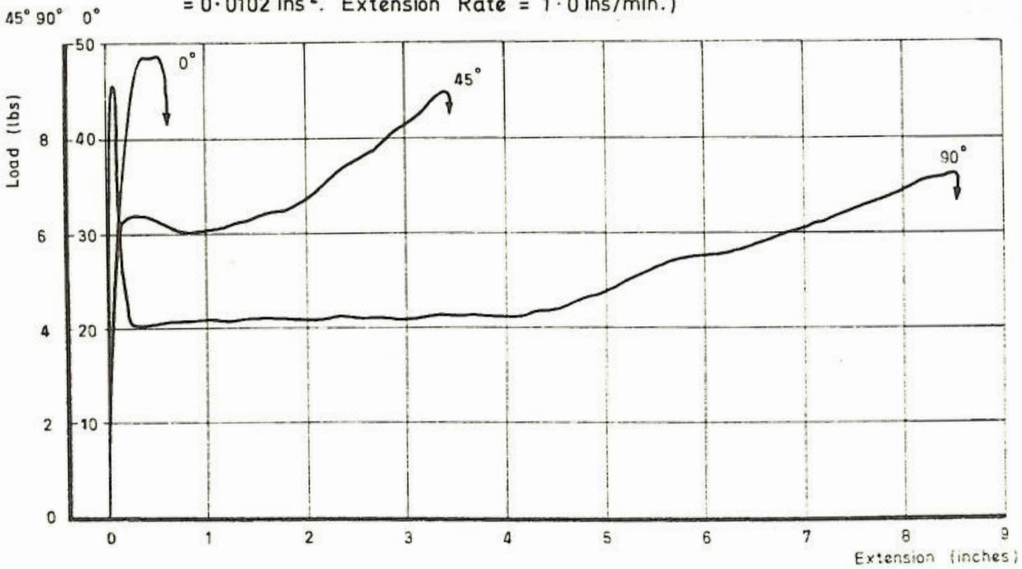

Figure 2.14. Variation of Load with Extension for Anisotropic Polyethylene. Draw Ratio = 3 · 7. (Area of Crossection = 0·0057 ins²)

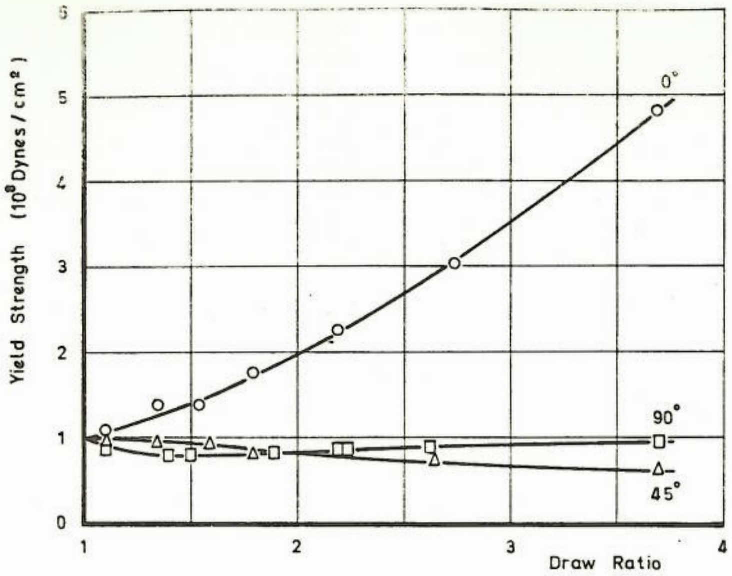

Figure 2.15. Variation of Yield Strength with Draw Ratio for Anisotropic Polyethylene Sheets.
(Temp. = 18 - 19 °C Crosshead Extension Rate = 1·0 inch/min Microtensile Specimens.)

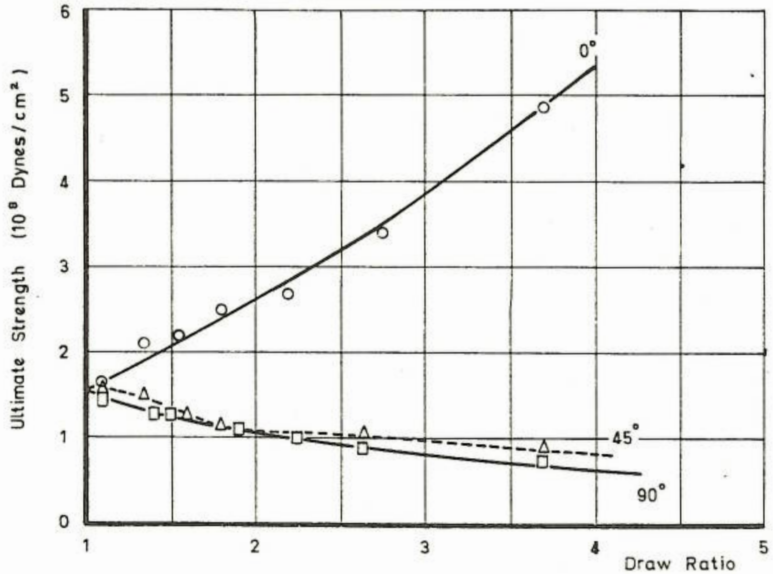

Figure. 2.16. Variation of Ultimate Strength with Draw Ratio for Anisotropic Polyethylene Sheets.
(Temp. = 18 - 19 °C Crosshead Extension Rate = 1·0 inch/min Microtensile Specimens.)

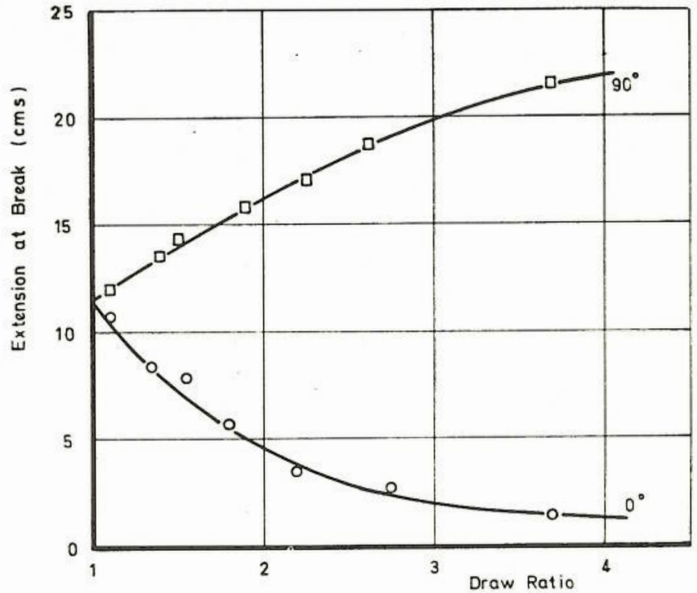

Figure 2.17. Variation of Extension-at-Break with Draw Ratio for Anisotropic Polyethylene Sheets
(Temp. = 18 - 19 °C. Crosshead Extension Rate = 1·0 inch/min. Microtensile Specimens.)

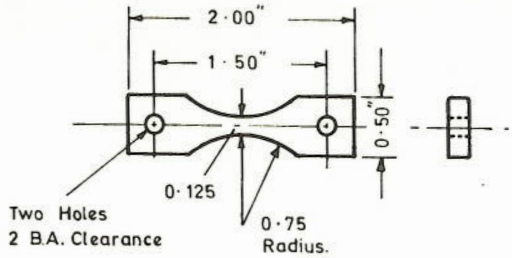

Figure. 3.1. Creep Rupture Specimen Design

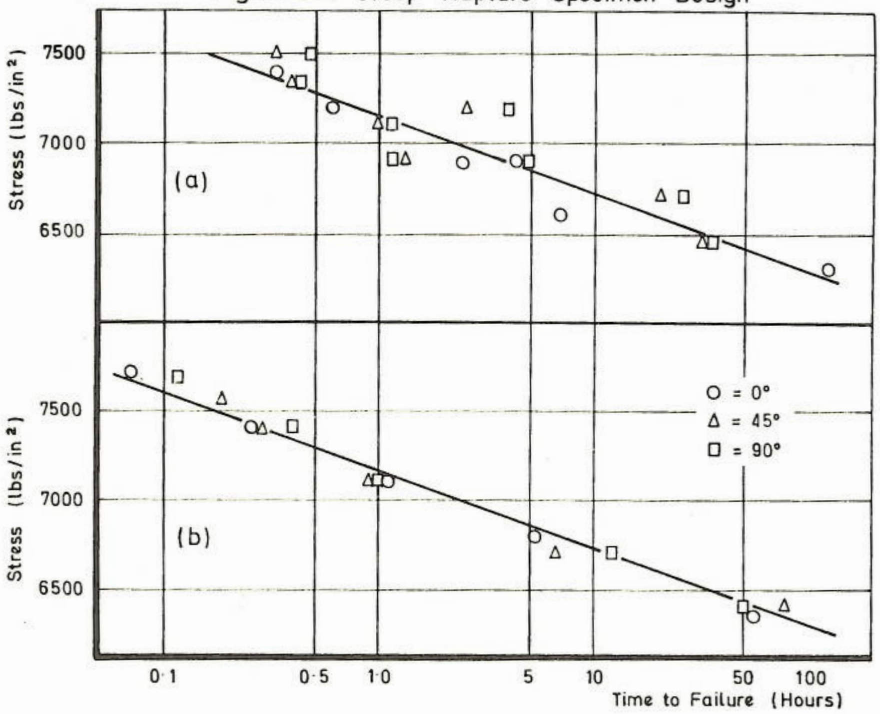

Figure. 3.2. Variation of Failure Time with Applied Stress for (a) 'As-Received' P.V.C. (b) Heat Treated As-Received P.V.C. (Temp. = 17 - 21 °C.)

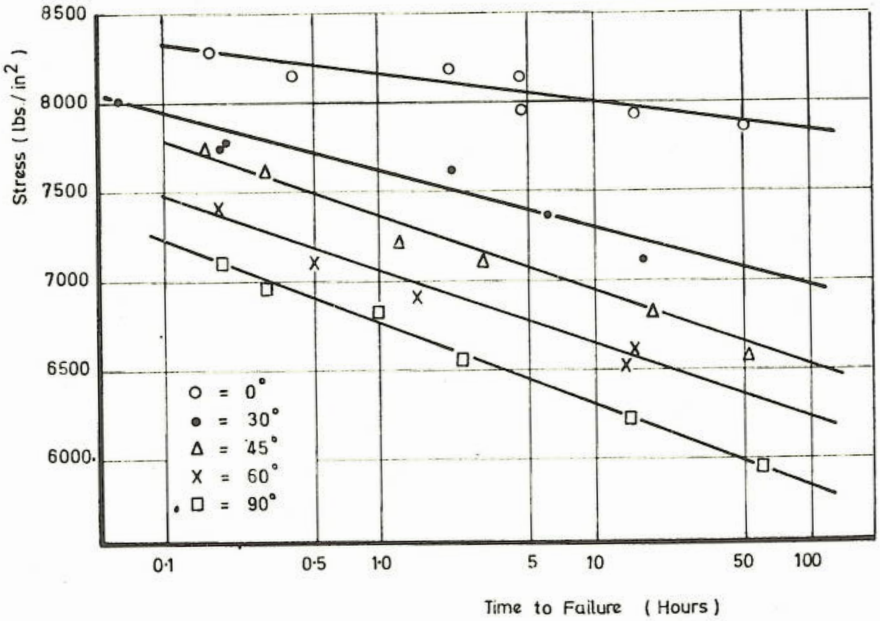

Figure. 3.3. Variation of Failure Time with Applied Stress for Anisotropic P.V.C. Sheet. Draw Ratio = 1·30 (Temp. = 17 – 21°C.)