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Paper 1

Creep studies on oriented thermoplastics

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CREEP STUDIES ON ORIENTED THERMOPLASTICS

1. Introduction

The enhancement of many of the mechanical properties of thermoplastics which may be achieved by orienting the molecules has been known for some time. It has been exploited in the production of textile fibres and oriented films. Molecular orientation also occurs during processes such as extrusion, moulding or forming. Here, unless carefully controlled, it may well cause a deterioration in the properties of the finished article. In view of this a systematic study on the anisotropy of the mechanical properties of thermoplastics, resulting from molecular orientation, is being carried out at present in these laboratories. The purpose of the study is two-fold:

(1) to provide useful data on the magnitude of the anisotropy and obtain precise ways of characterising it.

(2) to relate the measured properties to molecular structure. In the case of semi-crystalline polymers it is felt that the oriented state may possess a simpler structure than the isotropic state.

We shall only discuss the first of these objectives here.

Up to the present time the investigation has been restricted to the relatively simple case of transversely isotropic material produced by hot or cold drawing, particular emphasis being placed on the creep behaviour of the materials. In order to characterise such materials it is necessary to carry out measurements on specimens cut at 90° to the axis of symmetry (i.e. the draw direction). In some cases this limits the overall size to 4 cm. Measurements of lateral contraction during tensile creep are also required. As these and other requirements could not be met by existing creep apparatus, the necessary creep equipment was developed in these laboratories. Details of the apparatus are given in section 4.

Creep measurements have been carried out on an oriented semi-crystalline polymer (low-density polyethylene) and an oriented amorphous polymer (polymethyl methacrylate) in an attempt to establish trends of behaviour. In addition to tensile creep, some attention has been paid to the creep rupture and load-extension (constant extension rate) behaviour of the materials. Where appropriate these results are included with the creep results in section 6.

2. Theory

For the special case of uniaxial symmetry, or transverse isotropy the classical theory of elasticity gives the following relations[1]

$$\frac{1}{E_\theta} = \frac{1}{E_{90}}\ (\sin^4\theta - 1) + \frac{4}{E_{45}}\ (\sin^2\theta\cos^2\theta) + \frac{1}{E_0}(\cos^4\theta - 1) \qquad (1)$$

and $$\nu_{t_\theta} = \left[\frac{\nu_{t_0}}{E_0}\cos^2\theta + \frac{\nu_{t_{90}}}{E_{90}}\sin^2\theta\right] E_\theta \qquad (2)$$

where E_θ is the Young's Modulus, and $\nu_{t\theta}$ the Poisson's ratio (thickness direction) of a strip of material cut at an angle, θ, to the draw direction. The measurement of the five constants, E_0, E_{45}, E_{90}, ν_{t_0} and $\nu_{t_{90}}$ is sufficient for a complete description of the tensile behaviour of a transversely isotropic elastic solid when subjected to infinitesimal strains.

In the present work we assume that similar relations hold, with E_0 replaced by $E_0(t)$ etc. The reduction to five time dependent quantities is not completely demonstrable but we shall take it to be a useful hypothesis at this stage. For the time dependent case $\nu_{t\theta}$ is regarded as the contraction ratio for the thickness direction (i.e. the ratio of thickness contraction strain to longitudinal strain at the same instant of time during a tensile creep test on a specimen cut at an angle θ to the draw direction).

3. Materials and Sample Preparation

3.1 Low-density polyethylene

The grade chosen was I.C.I. Alkathene WJG 11. Isotropic sheets 0.2 cm. thick were prepared from granules by compression moulding. Sheets approximately 15 cm. x 10 cm. were then cold-drawn at an extension rate of 20 cm./min. A grid marked on each sheet prior to drawing was used in the determination of the draw ratio. On removal from the drawing machine the drawn sheets underwent partial recovery, the recovery rate decreasing with time. The oriented sheets were stored at room temperature for 6 months prior to test, when the draw ratio was sensibly constant and equal to 4.2 ± 0.1 (A separate sheet of draw ratio 3.8 was used for the 1000 second creep tests). Tensile specimens were then cut from the drawn sheets at known angles, θ, to the draw direction using a microtensile specimen cutter (A.S.T.M. type D.1708-59T). This gave dumbell specimens of overall length 3.8 cm. and enabled a 1.3 cm. gauge length to be used.

3.2 Polymethyl methacrylate (PMMA).

The starting material for the preparation of the anisotropic sheets was I.C.I. 'Perspex' acrylic sheet with a nominal thickness of 0.25 inch. A sheet 23 cm. x 10 cm. was drawn at an extension rate of 6 cm./min. while totally enclosed in a hot air oven at 120°C. This will be referred to as sheet 'A'. The drawn sheet was allowed to cool to room temperature before being released from the grips. No contraction of the sheet was detected after the cold specimen had been released. A second sheet 21 cm. x 10 cm. was oriented using the same basic procedure but with an extension rate of 13 cm./min. and a temperature of 140°C. This will be referred to as sheet 'B'. Sheet A had a draw ratio of 3.1 and a birefringence of 0.00094 while sheet B had a draw ratio of 2.8 and a birefringence of 0.00056.

Dumbell tensile creep specimens were machined from sheet A at angles of 0°, 45° and 90° to the draw direction. The overall length varied between 5 cms. and 6.6 cms. depending on the angle (smallest at 90°). This gave parallel test sections of at least 2.3 cm.; gauge lengths of approximately 1.7 cms. being used on the smaller specimens.

The creep rupture specimens were machined from sheet B to the pattern shown in figure 1.

4. Creep Apparatus

The basic requirements, principles of operation and performance of the apparatus are summarised here. A detailed description of the extensometers and loading machines may be found elsewhere.[2]

4.1 Measurement of tensile creep

The proposed research programme required an apparatus that would enable the creep properties of a wide range of oriented thermoplastics to be studied. It was known from previous Instron (constant extension rate) studies[3] that moduli as low as 5×10^8 dynes/cm.^{2} would be encountered with certain highly anisotropic low-density polyethylene specimens. This work also showed that the determination of strain from grip separation measurements could lead to large absolute errors, especially when small specimens were used. Unfortunately the available methods of preparation of the anisotropic sheets yielded specimens which in some instances were only 0.1 cm. thick and 4.0 cm. long. The non-linear behaviour of thermoplastics in general provided an additional complication as it emphasised the need to perform measurements at low strains.

In view of the above considerations and the normal requirements of creep apparatus the following conditions were imposed on the extensometer design:

(1) The load exerted on the specimen by the extensometer should not be greater than 20 grams.

(2) The connection of the extensometer to the specimen must not cause 'end effects' or impose lateral constraints on the specimen.

(3) No resistance to tensile extension and absence of slip-stick effects.

(4) Must be able to operate on gauge lengths down to 1.3 cm. On such a gauge length it must detect a strain of 2×10^{-5} and be able to handle strains of at least 0.05.

(5) High stability.

Conditions (1) and (4) precluded the use of existing well proven optical designs.[4] Furthermore, as many of the creep tests were intended to be of short duration it was felt desirable to have automatic data recording facilities.

The above conditions have been met using a linear displacement differential capacitor transducer having a sensitivity of 10^{-6} inch. The transducer consists essentially of a moving shaft and a fixed outer body. The shaft has a calibrated movement of 0.1 inch. Loading of the specimen by the transducer is avoided by mounting the transducer in a balanced arrangement. Two extensometer arms, pivoted at their centres on solid pivot bearings, are used. The transducer is attached to one end of the lower arm, the other end being attached to the specimen. The upper arm is also attached to the specimen at one end, while the moving shaft of the transducer rests against the other end. Balance weights are used to ensure that the extensometer arms lie in the horizontal position before a specimen is mounted in the apparatus. The load necessary to move the extensometer arms relative to one-another is never more than a small percentage of the applied tensile load.

The extensometer arms are attached to the specimen using four pointed Allan screws (one on either side of the specimen at each gauge point) which are screwed lightly into the specimen surface. These points define the gauge length. Relative movement of the gauge points is faithfully reproduced by a relative movement between the transducer moving shaft and fixed body. This movement is processed by the electronic equipment (supplied by the transducer manufacturers) and is obtained directly in inches to 10^{-5} on a digital display. Alternatively a D.C. output is available which is directly proportional to the displacement from the initial zero. For automatic recording, this output is fed into a digital voltmeter with integral printer and electronic timers are used to trigger the voltmeter to read and print the displacement at pre-determined times.

The accuracy of the extensometer is essentially that of the transducer i.e. 10^{-5} inch under normal conditions. However over a wide range of strains the reliability of the measurements is slightly worse than would be expected on the basis of this figure. This effect is most noticeable at strains below 0.002. This is probably due to slight inaccuracies in the mounting of the specimen, as the error is reduced with practice. However the main source of error is usually that of interspecimen reproducibility, particularly when oriented specimens are used. For a batch of 4 or 5 specimens this sometimes causes a spread of $\pm$ 4% in the 100 second modulus values at any particular strain, for a wide range of modulus values.

4.2 The loading machines

The loading machines are of the conventional lever-loading type; the complexity of the design depending on the intended modulus range. For the softer polymers such as low-density polyethylene a loading machine based on the design developed by Turner and co-workers is used.[4] For the more rigid plastics such as perspex, simpler loading machines have been found to be satisfactory providing care is taken in specimen preparation. On all the creep machines the loading levers are pivoted on knife edges rather than bearings.

4.3 Measurement of lateral contraction

Conditions (1), (2), (3) and (5) listed in section 4.1 also apply here. The conditions equivalent to (4) are however even more stringent in this case. Thus the contraction device has to operate on the specimen thickness which may be as little as 0.1 cm. Furthermore the device must be able to operate while the tensile extensometer is in position in order that simultaneous measurements of longitudinal extension and lateral contraction may be made. These conditions have been met by using a tensile extensometer rotated through 90° about a line parallel to the arms and altering the attachment devices on the specimen end of the arms. The new attachments are simply feelers which rest against the front and back of the specimen so monitoring the specimen thickness. The pressure exerted on the specimen can be easily controlled by springs when necessary and lateral forces reduced to a negligible level. This device has been used simultaneously with a tensile extensometer on a 1.3 cm. gauge length.

It is difficult to assess the absolute validity of the values of the creep contraction ratio obtained with this system as no material could be obtained for which a reliable value of the ratio was known. In terms of scatter and interspecimen reproducibility the results are usually consistent to ± 5% for tensile strains in the range 0.005 to 0.05 and ratio values in the range 0.35 to 0.5. The apparatus and specimen alignment are more critical for the contraction measurement than for the extension measurement and large errors in the contraction ratio values are obtained if the system is not satisfactory. Fortunately these errors are usually obvious when they occur and the results safely discarded.

5. Experimental Procedures

All the creep and creep rupture measurements were made in a room with the temperature controlled at 20.2 ± 0.7°C and a relative humidity of (50 ± 5)%. The specimens were always stored in the room for at least several days prior to test.

5.1 Creep measurements

The tensile creep behaviour of the anisotropic and isotropic specimens was initially examined in the strain range 0.1% to 10% using a procedure based on that described elsewhere for obtaining isochronous stress-strain curves.[5] The creep time varied between 100 seconds (extension measurements only) and 120 seconds (extension and contraction measurements). In most cases the recovery behaviour on removal of the creep load was also recorded and the next creep load was not applied until the recovery appeared to be virtually complete. The few longer time creep tests were always carried out after several 100 second tests at lower stresses. A long term creep test or a new isochronous stress-strain run was never started until stability of the initial 'zero' was achieved.

5.2 Creep rupture measurements

Simple lever loading machines were used to apply the loads to the creep rupture specimens. Electronic timers operated by microswitches resting against the lever arms were used to determine the time to failure. No measurements of deformation were made. The nominal stress was calculated using the area of cross section at the narrowest part of the test section.

6. Results and Discussion

6.1 Low-density polyethylene

6.1.1 Isochronous extension measurements.

For an anisotropic material the variation of creep modulus with time and strain (or stress) will itself depend on angle and temperature. (The latter has not been investigated in the present work). A concise presentation of all the experimental data is therefore difficult. In the first instance we shall therefore avoid time dependence by examining the data obtained after 100 seconds of creep.

The 100 second isochronous stress-strain curves for specimens cut at various angles to the symmetry direction of the transversely isotropic polyethylene sheet are given in figure 2. The high degree of anisotropy exhibited by the material is readily apparent when the stresses at each angle necessary to produce a 100 second strain of say 0.002 are compared. (See also figure 3). A material exhibiting linear behaviour would be represented by a line of unit slope in figure 2. The solid part of each line indicates the approximate extent of linear behaviour at each angle. It will be seen that specimens in the range 0° to 45° exhibit approximately linear behaviour for strains up to at least 0.007. For specimens in the range 65° to 90° the upper limit of strain for the linear region falls progressively from 0.003 to 0.0015. In view of the large change of modulus with angle the stress at the onset of non-linearity varies in a rather different manner. Thus the 0° specimen exhibits linear behaviour up to a stress of 5×10^7 dynes/cm.^{2}, the equivalent value for the 45° specimen being only 5.5×10^6 dynes/cm.^{2}. It is of interest here to note that the isotropic material does not possess a linear region at strains down to at least 0.001. (See figure 2).

It is apparent from figure 2 that the tensile behaviour at each angle is reasonably linear for strains of up to 0.002. A 100 second tensile creep modulus, E_θ, for the linear region may therefore be calculated at each angle, θ, by using the stress necessary to give a strain of 0.002 after 100 seconds of creep. The variation of this modulus with angle is given in figure 3. The highly anisotropic nature of the drawn polyethylene sheet is readily apparent. As the results given in figure 3 are for isochronous moduli in the linear region it is useful to compare them with equation (1) obtained from classical elasticity theory. The solid line in figure 3 is obtained by using the experimental values of E_0, E_{45} and E_{90} in equation (1). The remaining experimental points are in good agreement with the theoretical line. The value of E for the isotropic material is included in figure 3 for comparison.

6.1.2 Creep behaviour

In view of the large variation of modulus with angle it is convenient initially to compare creep curves which possess similar 100 second strain values rather than those obtained under identical stress. Typical creep curves with 100 second strains in the region of 0.5% are given in figure 4. (The anisotropic sheet used for these tests had a draw ratio of 3.8). It must be emphasised that the stress used varied considerably with angle and also that there is no significance in the separation of the curves along the strain axis. The relative shapes of the creep curves are however of interest. The difference in the behaviour of the isotropic and anisotropic materials is immediately apparent, whereas the shapes of the curves for the three anisotropic specimens show little variation with angle. Similar trends are observed when the creep curves in the region of 1% tensile strain are examined. However at strains in the region of 5% the tensile creep curves show a large variation with angle, even for the short creep time of 5 to 100 seconds.

The creep curve shapes for the anisotropic material are best compared using a reduced compliance $J_R(\theta,t)$ defined as the ratio $J(\theta,t)/J(\theta,1000)$ where $J(\theta,t)$ and $J(\theta,1000)$ are the compliances at time t and 1000 seconds respectively, for a specimen cut at an angle θ to the draw direction. The curves of $J_R(0,t)$, $J_R(45,t)$ and $J_R(90,t)$ would superimpose if the shapes of the 0°, 45° and 90° creep curves (figure 4) were identical. The actual reduced compliance - time curves are shown in figure 5 (solid lines). It will be seen that the maximum deviation of the three curves is only 3%. The spread only rises to 5% if the tensile creep data in the region of 1% tensile strain are treated in the above manner. (dashed lines in figure 5). In fact the increased spread is probably mainly due to the non-linear behaviour at 90°. The above similarities lead to a considerable simplification in the description of the creep behaviour of the anisotropic material. Thus if $J_R(A,t)$ is the average value of $J_R(0,t)$ and $J_R(90,t)$ at each instant of time, then for strains in the linear region the compliance at time t for any angle, θ, is given by

$$J(\theta,t) = f(\theta,1000)\, J_R(A,t)$$

where $f(\theta,1000)$ is given by equation (1) with E_0, E_{45} and E_{90} replaced by their respective values at 1000 seconds. Thus single graphs of $J(\theta,t)$ against θ and $J_R(A,t)$ against t will completely describe the behaviour of the anisotropic polyethylene sheet in the linear region with a maximum error of ± 2%. The variation of E_0, E_{45} and E_{90} with strain is needed if the above relation is to be extended into the non-linear region.

It must be emphasised that the above simplification is only valid if the creep curve has the same shape (within acceptable error) at each angle. This assumption must always be verified experimentally over the required time interval, for at least three angles (0°, 45°, 90°), as the long term behaviour at one angle cannot be predicted with certainty from its short time behaviour and the long time behaviour at another angle.

6.1.3 Lateral contraction measurements

The variation of the 100 second thickness contraction ratio, $\nu_{t\theta}$ with angle, θ, is shown in figure 6. The results were some of the first to be obtained and show rather more scatter than would now be considered acceptable. However they show clearly the large variation of $\nu_{t\theta}$ with θ. The solid line in figure 6 was obtained using equation (2), and the experimental values of E_0, E_{45}, E_{90}, ν_{t0} and ν_{t90}. Measurements in progress at present show that $\nu_{t\theta}$ increases with time and strain for angles of 0°, 45° and 90°.

6.1.4 General comments.

The creep behaviour of oriented low-density polyethylene is rather complicated. However if the similarity in the shape of the creep curves is continued at long times the problems of characterisation will be greatly simplified. The relative magnitude of E_{45} and E_{90} is surprising and there is evidence from other work[6] that it is not typical of semi-crystalline polymer, at least for infinitesimal strains. The relatively low values of E_{45} and $\nu_{t_{45}}$ are due to easy-shear parallel to the molecular chains and the behaviour of the oriented material for angles of 20° to 70° has been predicted for a wide strain range on the basis of such a mechanism.[7]

The creep rupture behaviour of the oriented polyethylene has not been studied. However studies[3] on an Instron tensile testing machine (constant extension rate tests) have shown that the yield and ultimate strength possess the same degree of anisotropy as the 100 second creep modulus.

The recovery behaviour has not been dealt with in detail here. However it is of interest to note that for tensile strains of at least 2% the anisotropic specimens recovered 98% of the final creep strain within a recovery time of 10 x (creep time).

6.2 Polymethyl methacrylate

6.2.1 Creep studies

The study of creep in oriented PMMA is still in progress. However the trends observed so far will be illustrated here as some are in marked contrast to those found in polyethylene.

The variation of tensile stress with the 100 second tensile strain for anisotropic (0° and 90° specimens) and isotropic PMMA is shown in figure 7. The curve for the 45° specimen is in close agreement with that for the isotropic material. A linear material would give a line of unit slope on such a log-log plot (dash line in figure 7). It will be seen that both the anisotropic and isotropic specimens exhibit virtually linear behaviour below a 100 second tensile strain of 0.003 and possess approximately the same form of non-linear behaviour at higher strains. Furthermore there is very little separation of the 0°, 45° and 90° curves along the stress axis which indicates a low anisotropy of the creep modulus. (See also table 1).

The results of short time (5 to 100 seconds) creep tests show that, for tensile strains up to at least 0.005, there is no significant variation of creep behaviour with angle for the oriented PMMA. Thus the curves of reduced compliance against time would superimpose (as for polyethylene): However, in marked contrast to the behaviour of polyethylene the creep behaviour of the isotropic PMMA agrees closely with that of the oriented material. Extension of the results to longer times is in progress.

Preliminary measurements of the creep contraction ratio, ν_t, at 100 seconds have been made on the isotropic and anisotropic materials. There appears to be little variation in the value of the ratio between the anisotropic specimens or between the anisotropic and isotropic materials. Thus for a 100 second tensile strain of 0.01 the value of ν_t for the three anisotropic specimens (0°, 45°, 90°) lies between 0.36 and 0.39 which may be compared with a value of 0.37 for the isotropic material. The relatively large value of $\nu_{t_{45}}$ again contrasts with the behaviour of polyethylene but would be expected on classical elasticity theory in view of the similarity in the values of E_0, E_{45} and E_{90} for the oriented PMMA.

6.2.2 Creep rupture studies

Specimens machined from oriented sheet B at angles of 0°, 45° and 90° to the draw direction were used. The applied tensile stresses were chosen to give rupture times of up to 10^4 seconds. An indication of the anisotropy of the creep rupture behaviour may be obtained by comparing the stress necessary at each angle to produce rupture in 1000 seconds. The stresses are given in column 3 of table 1. It should be noted that the fractures were always of a brittle nature. It is apparent from table 1 that creep rupture exhibits greater anisotropy than creep modulus. The difference is in fact rather more than is apparent from table 1 as the moduli were obtained from sheet A (birefingence = 0.00094) while the rupture specimens were machined from the less oriented sheet B (birefringence = 0.00056).

6.2.3 General comments

The small anisotropy of the creep modulus and the close agreement between the behaviour of the oriented and isotropic materials was rather surprising as the oriented material had exhibited a marked anisotropy during the machining of the specimens. Unfortunately the simple measurements of draw ratio and birefringence are not in themselves sufficient for predicting the mechanical anisotropy to be expected of the oriented sheet. (The values corresponding to the completely oriented material would be of assistance here. A comparison of the birefringence values of oriented sheets A and B, drawn at 120°C and 140°C respectively, shows that there is probably some loss of orientation during drawing; the loss increasing as the drawing temperature is increased. Even so, the oriented sheet shows complete recovery when heated to 118°C for less than 20 minutes. Despite these uncertainties the present measurements are extremely useful as they show that even when PMMA has been highly drawn at such temperatures it does not exhibit much anisotropy in its creep behaviour at low stresses or for short times. However the brief measurements of creep rupture behaviour show that it is probably not safe to neglect the influences of orientation when creep is occurring under high stresses or for long times.

7. General Conclusions

Most of the similarities and differences in the behaviour of low-density polyethylene and PMMA have been referred to in the previous sections. The use of a reduced compliance which is independent of angle represents a considerable simplification in the description of the behaviour of both polymers. It remains to be seen whether or not this simplified representation is accurate at long times.

The degrees of anisotropy exhibited by particular properties of different polymers obviously can't be compared directly. However the difference in the degree of anisotropy for several properties of one polymer may be compared with the differences exhibited by another. Thus oriented low-density polyethylene (which is semi-crystalline) exhibits a high degree of anisotropy in its tensile creep and load extension behaviour. However for PMMA (which is amorphous) the creep rupture behaviour is considerably more anisotropic than the tensile creep. It is of interest here to mention the behaviour of oriented polyvinyl chloride[8] which many regard as being slightly crystalline. For this material the difference in the degree of anisotropy exhibited by the creep rupture behaviour and an 'Instron' modulus is noticeably less than that shown by PMMA. Further work is however required before a general pattern of behaviour may be established.

8. Acknowledgments

Thanks are due to Mr. D. Clayton who obtained the 100 second tensile creep data for polyethylene. This work was supported by a grant from the Ministry of Technology.

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(4) Turner, S. British Plastics 37 (1964) 386.

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(6) Ward, I.M., Applied Materials Research (1966)228.

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Table 1. The variation of creep modulus and rupture stress (for constant rupture time) with angle for oriented PMMA.

ANGLE	MODULUS (1) (10^{10} dynes/cm.^{2})	RUPTURE STRESS (2) (10^8 dynes/cm.^{2})
0°	3.5	9.6
45°	3.25	7.0
90°	2.95	5.2

(1) for sheet A. birefringence =+ 0.00094

(2) for sheet B. birefringence = 0.00056. This rupture stress is the nominal stress necessary to produce rupture after 1000 seconds.

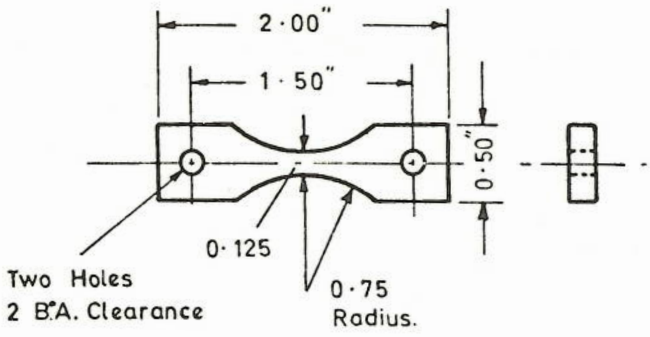

Figure.1. Creep Rupture Specimen Design

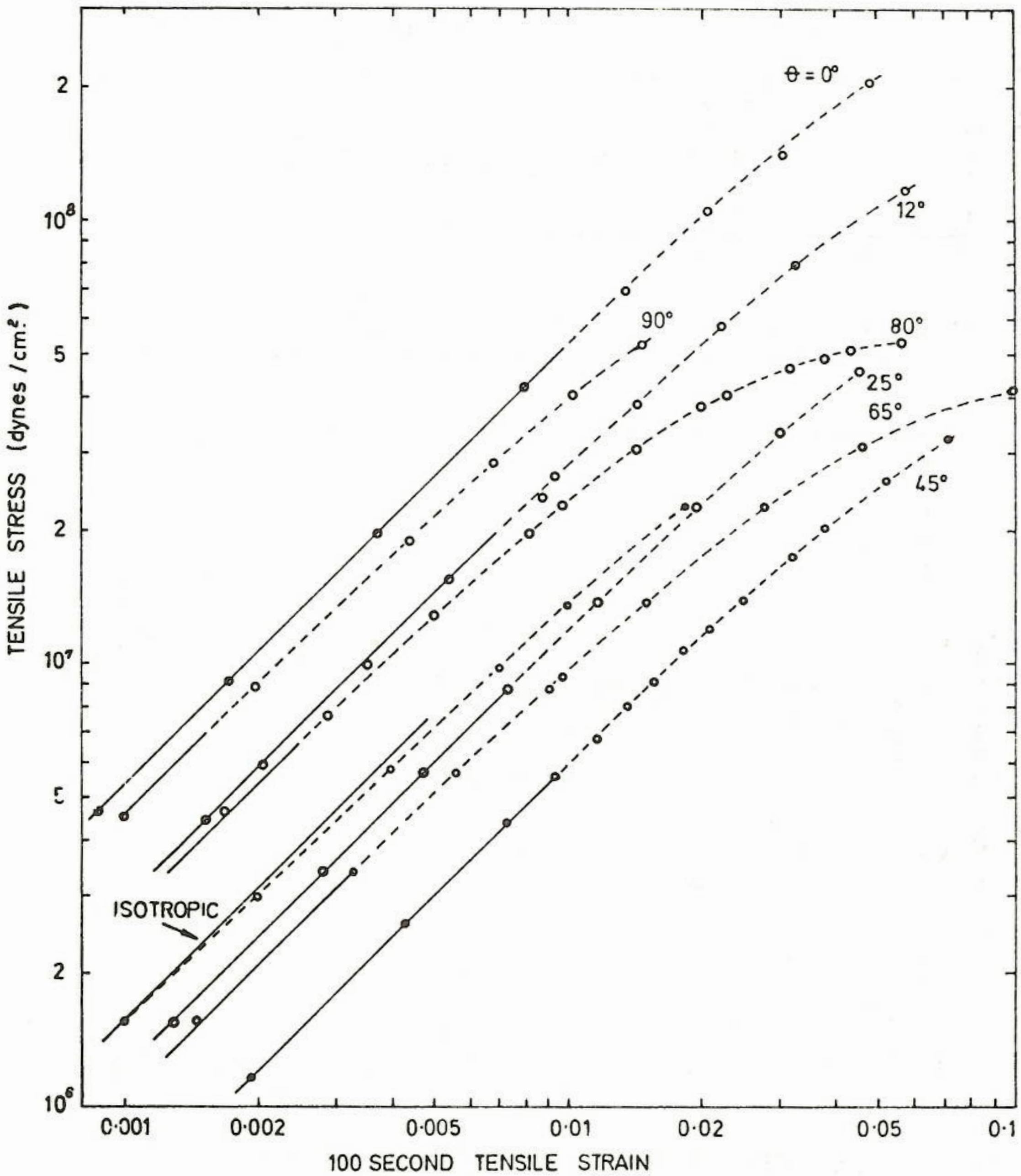

FIG. 2 VARIATION OF TENSILE STRESS WITH 100 SECOND TENSILE STRAIN FOR ISOTROPIC AND COLD-DRAWN LOW-DENSITY POLYETHYLENE.
(—— REPRESENTS APPROXIMATE EXTENT OF LINEAR BEHAVIOUR.)

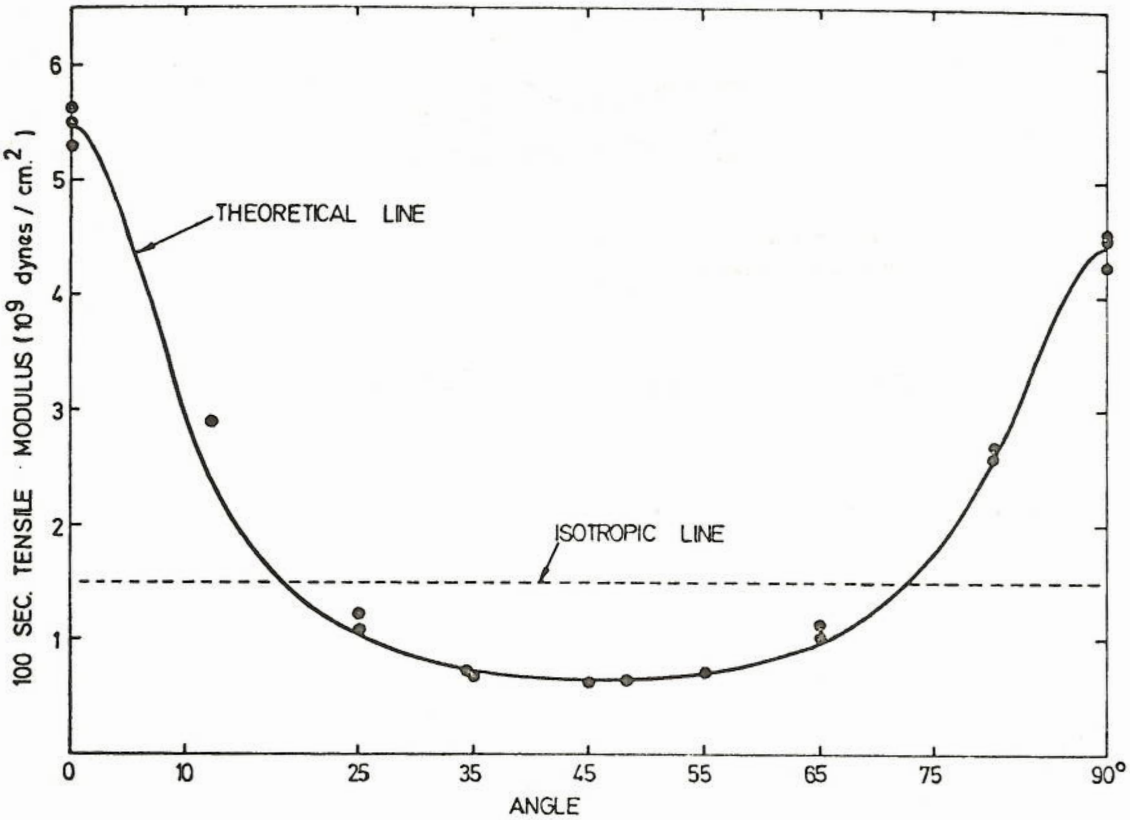

FIG. 3. VARIATION OF THE 100 SECOND TENSILE CREEP MODULUS WITH ANGLE FOR ANISOTROPIC POLYTHENE (MEASURED AT 0·2% STRAIN)

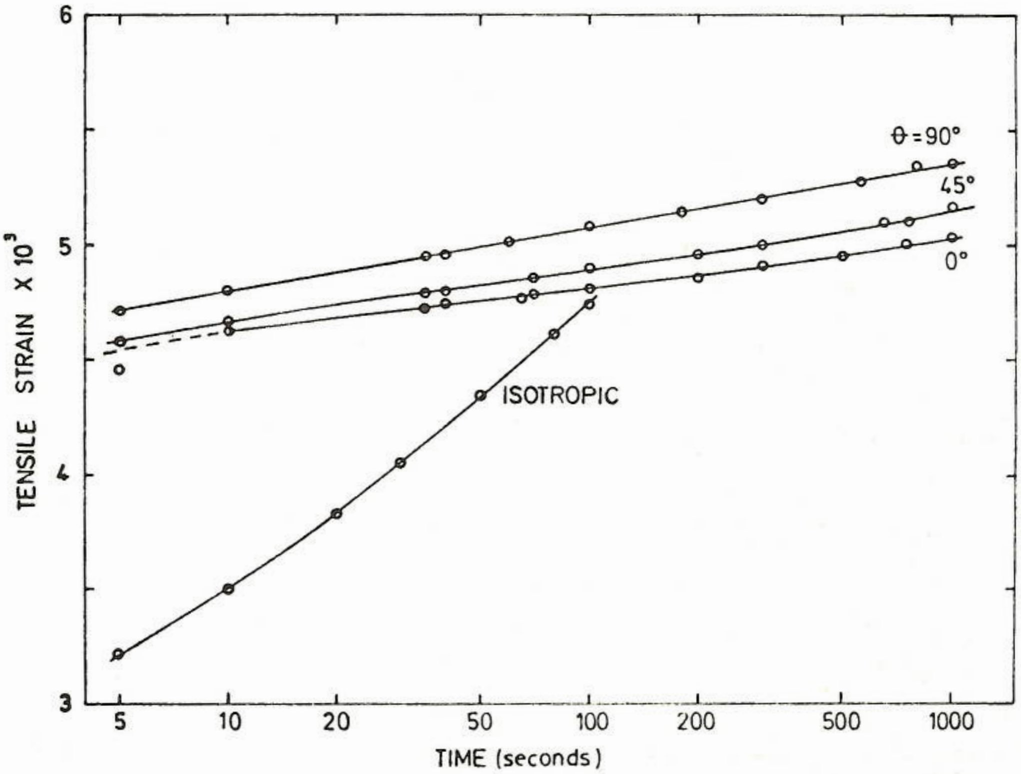

FIG 4. TENSILE STRAIN - TIME CURVES FOR ISOTROPIC AND COLD - DRAWN LOW-DENSITY POLYETHYLENE. (100 SECOND STRAINS IN THE REGION OF 0·5%).

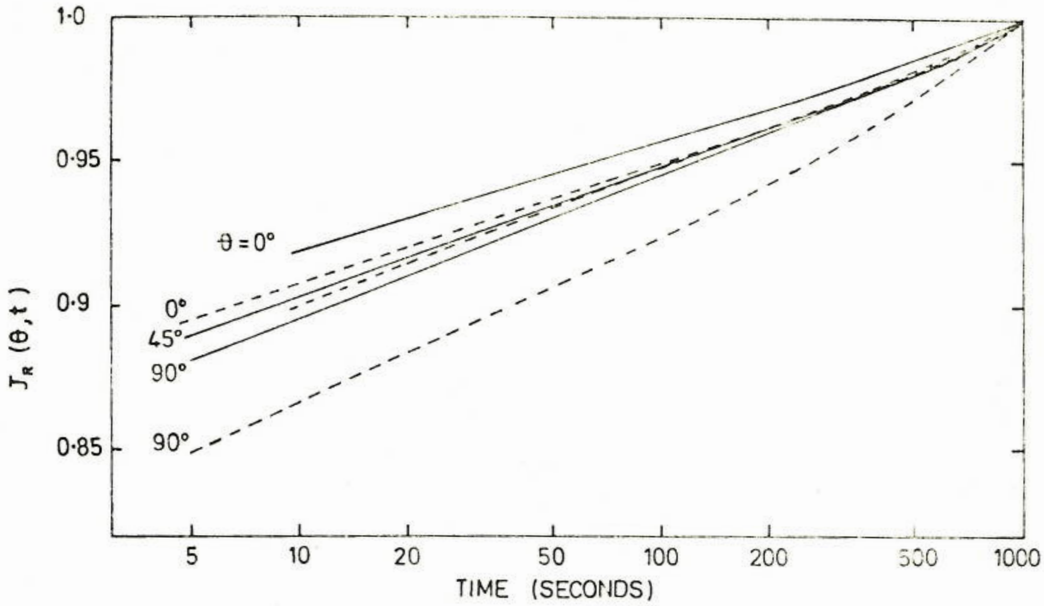

FIG.5 VARIATION OF REDUCED COMPLIANCE $J_R(\theta, t)$ WITH TIME FOR COLD-DRAWN LOW DENSITY POLYETHYLENE.

—— FROM CREEP CURVES WITH STRAINS IN THE REGION OF 0·5%

- - - - FROM CREEP CURVES WITH STRAINS IN THE REGION OF 1·0%

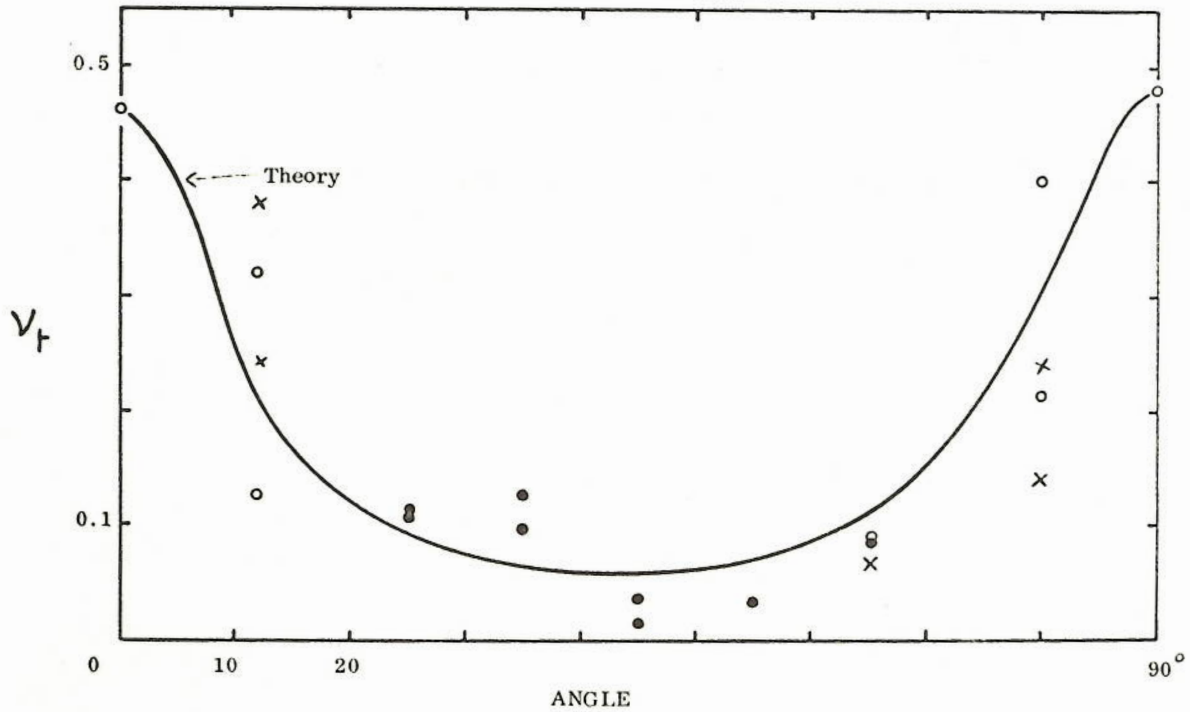

FIG. 6 VARIATION OF THE 100 SECOND THICKNESS CONTRACTION RATIO, ν_r WITH ANGLE, θ.

o - measured using two, single-transducer, extensometers (1% tensile strain).

× - as above (5% tensile strain).

• - measured using travelling microscope plus one, double-transducer extensometer. (Tensile strains in range 3% to 6%.)

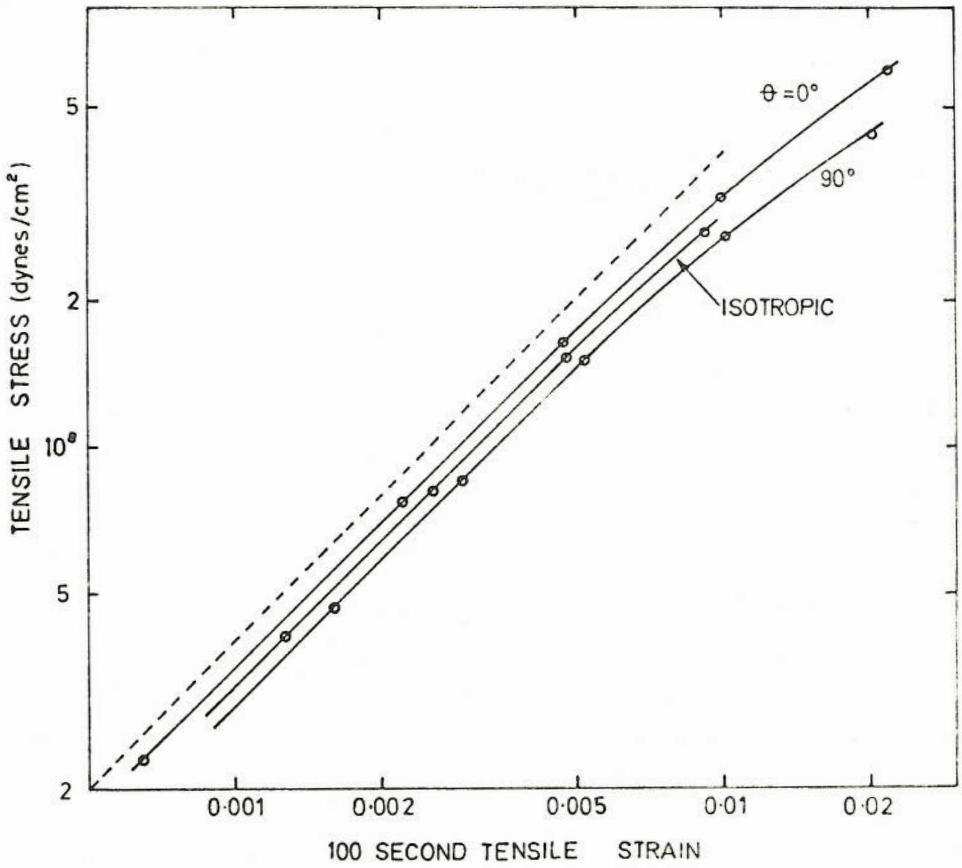

FIG. 7 VARIATION OF TENSILE STRESS WITH 100 SECOND TENSILE STRAIN FOR ISOTROPIC AND HOT-DRAWN POLYMETHYL METHACRYLATE.
(---GIVES SLOPE OF LINE FOR LINEAR BEHAVIOUR)