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The Mechanical Properties of Anisotropic Polymers

Progress Report No. 5

A report of work carried out during the period 1st October, 1967, to 31st March, 1968.

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Contents

PART 1

General Developments

A general survey of the work carried out in the period October, 1965, to September, 1967, was given in Progress Report No. 4 (September, 1967). Apart from apparatus studies, the main experimental results described in Report No. 4 were concerned with the tensile creep of highly oriented, low-density polyethylene. Despite the fact that the measurements were incomplete, several trends were apparent in the results and details of proposed methods of analysis were given. Of great interest were the preliminary results on the simultaneous measurement of longitudinal extension and thickness contraction during tensile creep. These not only enabled a complete description of the pseudo-elastic constants of the material to be given, but also gave support to a deformation hypothesis by showing that a sample cut at 45^{o} to the draw direction underwent negligible thickness contraction during tensile creep.

In view of the extreme usefulness of the combined extension and contraction measurements mentioned above, an attempt was made to improve the methods of measurement before completing the polythene study. Details of these apparatus developments are given in part II.2 of this report.

On completion of the required apparatus, the polyethylene study was continued; greater emphasis than before being placed on the combined measurement of extension and contraction. The new results are described in part III. These results complete this phase of the study on polyethylene. A summary of the investigation has been written, with the intention of submitting it as a letter to Nature. It is at present being examined at the Ministry of Technology. A detailed report is also being prepared at present.

In preparation for creep studies on rigid thermoplastics, preliminary trials of a 'heavy-duty' creep rig were carried out in the previous period. (See Report No. 4, page 5). A slightly modified version of one of the creep rupture rigs, described in Progress Report No. 3 (March, 1967), was used, but was found to be unsatisfactory. Improvements have now been made to the apparatus and satisfactory test results obtained. These are described in part II.3 of this report. A simple two-transducer extensometer for use with the heavy-duty creep rig is described in part II.4.

Preliminary trials of a shear rig have also been made, but will not be described in this report. (See part II.1).

PART II

Apparatus Studies

1. Introduction

The basic tensile creep rig for work on polyethylene and other low-stiffness materials (referred to as the 'polythene creep rig') was described in the previous progress report. (October, 1967). The results of detailed apparatus trials were also given. As these were extremely satisfactory, no further modifications have been made to the creep rig or the tensile extensometer used with it. However an addition has been made to the apparatus to enable the thickness contraction of a specimen to be measured during tensile creep; the tensile extension being measured in the normal manner at the same time. The combination can be used on specimens with a gauge length of only 0.5 inch and an overall length of 1.5 inch. The new apparatus, and a few trial results, are described in section 2. A perspex enclosure has also been built to completely cover the apparatus. A hinged front section allows easy access to the specimen. The enclosure helps to keep the apparatus dust free and has a stabilising effect on the temperature of the air near the specimen.

Details of a creep rig developed for use with rigid thermoplastics (referred to as a 'heavy-duty creep rig') are given in section 3. A simple device for the simultaneous measurement of thickness contraction during tensile creep tests on this apparatus is described in section 4. This device may be used, instead of the single-transducer type described in section 2, when the gauge length exceeds 0.8 inch. It is very much simpler to construct but requires two transducers.

Preliminary trials on a shear creep rig (built in the previous period) have also been made in the period under review. A vibrator had to be used to avoid stiction problems. Isotropic polyethylene was used for the trials, specimens being 0.5 inch wide and 0.07 inch thick. A drastic dependence of the modulus on clamping pressure was found, and the trials were discontinued. Details of the apparatus will be given when further trials have been made on anisotropic material.

2. A Single-Transducer, Contraction Extensometer

(a) Design.

When the normal tensile extensometer is used on a sample with 0.5 inch gauge length, there is no room between the extensometer arms through which to pass a transducer. (See fig. 2.1). A tweezer type arrangement, with thin feelers resting against the specimen, was therefore considered to be necessary. The feelers had to be thin enough to pass between the specimen faces and the extensometer arms, yet sufficiently rigid to avoid bending or twisting movements as these would alter the transducer reading. It was considered that a normal tensile extensometer (with modified arm ends), rotated through 90°, could satisfy the above requirements as well as those normally required for strain measurements. (See previous discussions on tensile extensometers). The extensometer was mounted on a substantial support which was bolted direct to the base of the 'polythene' creep rig. The normal 'polythene' attachments on the extensometer arms were replaced by mild steel feelers with a partial box section. Small brass contact pieces were fitted to the flat ends of the feelers. The contact pieces were slightly rounded and highly polished. Details of the arrangement may be inferred from figs. 2.1 and 2.2. The external spring on the transducer shaft provided the pressure necessary to keep the brasses in contact with the specimen.

(b) Trials and Discussion.

Unfortunately no material was available for which reliable values of the tensile creep modulus and creep contraction ratio, ν, were known. (The latter is defined as the ratio of lateral contraction strain to longitudinal tensile strain at any given time). Test specimens cut from isotropic polythene sheets (B.S. 903 - type E cutter) were therefore used for convenience. This gave a specimen 0.07 inch thick, 3.0 inch long and 0.15 inch wide in the gauge length section. The gauge length used was 0.5 inch.

Preliminary tests showed that a vibrator was again necessary for the elimination of slip-stick effects in the contraction extensometer. For these tests the specimen loads were chosen to give a tensile strain in the region of 1%. The transducer control unit and digital voltmeter ranges were selected to enable units of 10^{-6} inch to be displayed. The small contractions (approximately 300 micro-inches) could then be read to better than 1%. It was found, however, that the scatter in the results between different specimens was far greater than that due to lack of reading accuracy or specimen reproducibility. Thus values for ν ranging from 0.37 to 0.49 were obtained. Despite this the reproducibility between tests at the same load for any one specimen was always good, providing the apparatus was not touched between tests. Thus a typical set of values for ν, obtained in succession, were 0.38, 0.39, 0.40, 0.39. The recovery after a test was also satisfactory in most cases.

It was realised that an inherent fault with the system described above was that, as the specimen extended, it actually travelled through the brass contact pieces of the contraction extensometer. Thus changes in specimen thickness due to surface defects would be inseparable from genuine specimen contraction caused by extension under load. As the scatter in the preliminary results was initially attributed to this, the effect of pulling a polythene sample through the brasses (load free) was studied. It was found that, providing obvious surface flaws were avoided, the changes in contraction extensometer reading, as the specimen was pulled a small amount through the brasses, were not sufficient to cause the scatter obtained in the values for ν.

Other possible sources of error were considered to be:

(1) Geometry of contraction device, i.e. that it required accurate positioning with arms parallel to each other and to the back plate of the creep rig. (It was later found that this setting was not as critical as was first expected).
(2) Specimen bending, i.e. the specimen straightens out on application of the load but returns to its original shape when load removed. This could easily affect the contraction measurements more than the tensile ones.

The latter error itself could be due to one or all of the following:

(1) Contraction extensometer - pushing on specimen due to pressure from transducer lead.
(2) Uneven spring pressure from tensile extensometer attachments.
(3) Poor specimen.

All the above points were taken into consideration during the second series of trials, and the geometry of the specimen, after mounting in the apparatus, was always carefully checked by eye. The complete apparatus was examined and an effort made to eliminate all slack. Five polythene specimens were used in these trials. The first specimen gave poor results ($\nu \sim 0.49$) but the others gave results that were in good agreement with one another. (The pressure exerted on the specimens by the contraction extensometer was reduced after the tests on specimen 1, by means of an elastic band which pulled against the transducer spring). For a 1% tensile strain, the final 4 specimens gave

$$\nu = 0.43 \pm 0.02 \quad \text{(at 100 seconds)}$$

It was noted that high values were obtained for ν (~ 0.45) if a test was carried out within approximately 1 hour of attaching the contraction extensometer. If, after assembly, the system was left overnight before testing, values of 0.41 to 0.43 were obtained. Furthermore, tests carried out at tensile strains of 4.7% gave

$\nu = 0.44$ to 0.455 (at 100 seconds)

irrespective of the value of ν at 1% strain. (Four runs on three samples).

Experience gained during the measurements on anisotropic polythene (reported in Part III) showed that the use of a pre-load improved the reproducibility of the measurements. As a major effect of a pre-load is to straighten out the specimen and generally align the system before the zero positions are noted, it would appear that visual inspection of the sample prior to test is not sufficient when contraction measurements are to be made. This may also explain the time effect mentioned above. Thus, any sample mounted in the apparatus is certain to have a small pre-load on it. If the specimen bend is purely a sample defect it is conceivable that, in time, the pre-load may remove the bend by a type of creep recovery process.

From this discussion it will be seen that the measurements described above give, as probable values at 100 seconds:

$\nu = 0.42$ at 1% tensile strain
$\nu = 0.45$ at 5% tensile strain

On the above performance the apparatus was considered to be satisfactory for comparative studies of ν_t in anisotropic polythene, where large variations of ν_t with angle were expected. However, it was recognised that isolated absolute measurements of ν could not be made with certainty with the existing apparatus. Possible future developments are discussed in section 5.

(c) Procedure Developed.

From the experience gained in the above trials the following procedure was adopted for the study of anisotropic polyethylene, and several other subsequent measurements:

(1) Specimen mounted in creep rig, followed by tensile extensometer. Apparatus carefully checked; especially absence of bending of specimen and perfect fit of specimen grips in their hooks.
(2) Left to settle for time varying from 1 to 24 hours, according to degree of drift of transducer reading.
(3) Carried out 100 second stress-strain runs for strains of 0.1 to 0.9%.
(4) Let specimen relax. Attached contraction extensometer. Checked specimen alignment. Left for 1 to 24 hours to settle.
(5) Combined tensile extension and thickness contraction measurements made for tensile strains of 1% upwards.

From experience it seems that greater reliability is obtained if a pre-load is used during the contraction tests. When used, this is usually applied between stages (4) and (5); further time being allowed for the specimen to settle after application of the load. The magnitude of the load depends on the sample but, if possible, it should not exceed 10% of the load to be applied during the first contraction run.

From the tensile measurements in stage (3) an isochronous stress-strain curve may be drawn for strains up to 0.9%. The curve may be extended to higher strains using the tensile part of the measurements in stage (5). These results can then be used to check that the addition of the contraction extensometer did not affect the tensile behaviour of the specimen. This was done during all the anisotropic polyethylene tests described in part III.

3. A Tensile Creep Rig for Rigid Thermoplastics

(a) General Design Development.

Details of an apparatus used for a study of the creep rupture properties of rigid p.v.c. were given in Progress Report No. 3. For preliminary creep tests on a rigid thermoplastic (p.v.c) an extensometer (plus vibrator) was attached to one of these rigs. Typical results for creep times of 100 seconds were described in Progress Report No.4. The main objections to the use of such rigs for sensitive creep measurements appeared to be:

(1) Unsatisfactory alignment of the apparatus.
(2) Poor construction of the lower specimen grip.

A new rigid, adjustable lower grip assembly was therefore built, and the entire apparatus carefully aligned. Crude experiments on the thickness contraction of anisotropic polyethylene during tensile creep were carried out with this loading rig. (The results were described in Report No.4). During these experiments, friction effects originating in the ball races on the lever arm were found to be troublesome. They were therefore replaced by hardened knife edge pivots. Details of the final apparatus, which will be referred to as a 'heavy-duty' creep rig, may be inferred from fig. 2.3. A 5:1 loading lever is used. As the absolute dimensions of the apparatus are not critical, no further details are necessary. The importance of alignment for axial loading of the specimen must however be stressed. No lateral movements of the specimen can be tolerated during loading as this could alter the transducer zero.

(b) Trials and Discussion.

Two polypropylene samples taken from material characterised by I.C.I. were used. The samples were numbered 4 and 5 in the series. Sample '4' had been used in previous tests (see Report No. 4) whereas sample '5' had not been used previously. The usual 100 second isochronous stress-strain curves were obtained for both samples; strain ranges of 0.014% to 4.6% and 0.011% to 0.25% being used for samples 4 and 5 respectively. Very good agreement was obtained with the I.C.I. data. (The latter had to be extrapolated for comparison below 0.15% strain).

A long term creep test was started after the isochronous tests on specimen 5; the stress being chosen to give a 100 second strain in the region of 0.45%. The creep behaviour was monitored for 71.5 hours (2.57×10^5 seconds). The load was then removed and the recovery behaviour followed for 35 days. The final creep strain was 0.953%. After 35 days recovery, 99.6% of this strain had been recovered.

The creep result is compared with the I.C.I. curve in fig. 2.4. The result may also be compared with creep curves obtained on similar polypropylene samples using the 'polythene' creep rig. (See fig. 2.5 of Report No. 4). It is apparent that in both sets of trials our creep curves have fallen steadily below the expected curves. Our curves do however show good agreement between themselves. It has recently been confirmed by I.C.I. that, since our specimens were tested over 6 months after the I.C.I. data was obtained, such a deviation would be expected. It therefore appears that both the heavy-duty and the 'polythene' rigs are suitable for long-term creep studies. (Previously the 'polythene' creep rig had not been regarded as reliable for long term creep studies because of the deviation mentioned above - see page 9 of Report No. 4).

The main purpose of monitoring the recovery of the above sample was to check that the zero had not drifted with time. Recovery data obtained by I.C.I. were also available, but did not apply exactly to our experimental conditions. However the recovery behaviour did compare reasonably well with the I.C.I. data and showed no tendency for the specimen to recover past its original zero. Some idea of the final stability of the system may be obtained from the fact that over the last 10 days of the recovery the measuring system recorded a specimen contraction of only 2×10^{-5} inch, which was in agreement with that expected. Zero drift does not therefore appear to be a serious problem.

On the basis of the above trials the heavy-duty creep rig was considered to be suitable for the study of creep in rigid thermoplastics. This may appear surprising in view of the lack of refinement in the rig (e.g. no slide guide assembly). However, I.C.I. have recently confirmed that, for rigid thermoplastics, they have also found that such refinements are not required providing the basic alignment is correct and the specimen is perfect.

4. A Two-Transducer Contraction Extensometer for Rigid Thermoplastics

(a) General Design.

This device has been built to enable a comparison to be made with the single transducer extensometer. It also has the advantage of being very simple to construct and use. The device is shown mounted on a heavy-duty creep rig in fig. 2.5. The transducers can slide in the aluminium blocks and are held firmly in any required position by screws. The blocks can be removed from their supporting plate when required (e.g. for insertion of the specimen).

The two-transducer extensometer has several disadvantages when compared with the single-transducer type:

(1) It can only be used on samples with a gauge length greater than 0.8 inch.
(2) The specimen contact pressure is higher and can't be easily controlled. It is therefore easy to get an out-of-balance force on the specimen faces. The amount of friction will also be higher. This renders it unsuitable for work on soft materials.
(3) It requires two transducers.

Both types of extensometer do not exert a tensile load on the specimen. As the two-transducer extensometer is intended primarily for work on rigid thermoplastics, points (1) and (2) above may not be too serious and (3) may be outweighted by the ease of construction.

This was the type of contraction extensometer used during the anisotropic polythene measurements described in part IV of Report No. 4. However, the apparatus shown in figs. 2.3 and 2.5 of this report allows simultaneous measurement of tensile extension and thickness contraction using sensitive extensometers. (The tensile extension was measured by travelling microscope in the previous study).

(b) Trials and Discussion.

Polypropylene specimens 4 and 5 were used. These trials were in fact performed on each specimen immediately after it had been used for the pure tensile tests described in section 3. No vibrator was used on the contraction extensometer as several short trials appeared to show that it was unnecessary.

The results obtained with specimen 4 are given in the table below. All the measurements were made at a time of 100 seconds after application of the load.

Tensile Strain (%)	0.26	1.1	2.2	3.65
Creep Contraction Ratio, ν.	0.46	0.43	0.43	0.44

The results at the lower strains are open to serious doubt. This may well have been caused by the fact that no pre-load was used with this specimen. Furthermore the specimen had been taken to a tensile strain of 5% in 100 seconds only 1.5 hours before the start of the above tests, and the specimen was only left to settle for 0.75 hour after the contraction extensometer was mounted.

Tests on specimen 5 were performed after the 35 day recovery run mentioned in section 3.b. The specimen was left for 1 hour after attaching the contraction extensometer. Again, no vibrator was used on the latter. (It is now considered that further checks must be made regarding the use of a vibrator). Initially, small strains of 0.24% and 0.47% were applied to the specimen by suitable choice of loads. Both tests gave 100 second values for ν of 0.36. The tensile modulus was calculated and found to be satisfactory. In view of the low value for ν (compared with the results for specimen 4), the effect of a pre-load was investigated.

A pre-load equivalent to 1.5 kg. was applied to the specimen and the system left for 0.5 hour to settle. A specimen load of 9.0 kg. was then applied for 100 seconds, giving $\nu = 0.39$ at a tensile strain of 0.6%. This seemed in better agreement with the results on specimen 4 at high strains.

With the pre-load kept on, a load of 12.5 kg. was applied to the specimen. The tensile extension and thickness contraction were monitored for 7 hours, after which time the load was removed and the recovery monitored. At a time of 100 seconds the creep values corresponded to $\nu = 0.40$ at a tensile strain of 0.9%. This value also fits with the results on specimen 4 at high strains. The use of a pre-load would therefore appear to be an advantage. The creep results are shown in fig. 2.6. The rapid increase of ν to just under 0.5 is surprising. Two points are however worth bearing in mind:

(1) The sample is anisotropic.
(2) A tensile strain of 2% (after 7 hours) is quite high. It appears that these tests should normally be carried out at lower strains.

In support of point (2) it may be of interest to note that the strains had not recovered after a recovery time of over 25 times the creep time. (A specimen strained to 1% in 3 days recovered over 99% of the final strain in a time of 10 X creep time). The specimen may therefore have suffered permanent damage. Tests at lower strains are obviously required, and are continuing at present.

5. Contraction Measurements - Future Developments

The development of the simple, two-transducer contraction extensometer will enable comparative trials to be made on the two contraction devices now available. Polypropylene is probably the most suitable material as it may be used with both systems in the same strain range without too much difficulty. Such comparative trials should help to improve the reliability of both systems. In fact, preliminary trials with a polypropylene specimen have just been completed. The results with the two-transducer extensometer and heavy-duty creep rig were reasonably consistent, giving a probable value for ν_t of 0.40 ± 0.02 at a tensile strain of 1%. The same specimen tested on the polythene creep rig, with a single-transducer extensometer, gave inconsistent results initially. However, on addition of a pre-load, a value of 0.41 was obtained for ν_t. It would seem that the apparatus alignment may be more critical for the latter system. These trials are continuing with fresh samples.

The possibility of comparing results obtained on our apparatus with those obtained by two other investigators on the same material has just arisen. Measurements on the characterised material will be started as soon as possible.

PART III

Tensile Creep and Thickness Contraction of Highly Anisotropic, Low-Density Polyethylene.

1. Introduction

A detailed study of the tensile creep properties of highly anisotropic, low density polyethylene was initiated during the previous six-month period. The study was continued in the present six-month period and this phase of the research programme is now complete. The results obtained up to September, 1967, were summarised in graphical form in Progress Report No. 4. Two proposed methods of analysis of the results were also discussed and illustrative calculations were given. A summary of the complete work has been prepared for publication as a letter to Nature and a detailed report of the work is in preparation. The results obtained in the period under review are therefore only given in summary form below. No analysis is given.

2. Results

A full description of the specimen preparation, basic apparatus and experimental procedures was given in Progress Report No. 4. The extra apparatus and procedures used during the new contraction measurements are described in part II.2 of this report.

The creep properties of specimens cut at the following angles, θ, to the draw direction of the anisotropic sheets were studied:

1 at 0°, 2 at 12°, 1 at 65°, 2 at 80°, 2 at 90°.

Combined contraction and extension measurements were made on all the above specimens, with creep times in the region of 100 to 120 seconds. A new isotropic specimen was studied in a similar manner for comparison purposes. For convenience the extension and contraction results are described separately below.

(a) Extension.

The variation of the 100 second tensile creep modulus with angle is shown in fig. 3.1. The modulus values were calculated from the results for a 100 second strain of 0.2%, where all the specimens exhibited nearly linear behaviour. The results obtained previously are also given in fig. 3.1. It will be seen that all the results agree closely with the curve obtained using classical elasticity theory. This theory is therefore adequate for describing the form of the results, when they are presented in the above manner, i.e. avoiding time-dependence and non-linearity.

The non-linear behaviour of the new specimens is illustrated in fig. 3.2, where the 100 second tensile creep modulus is plotted against the 100 second strain on a log-log scale. In most cases, specimens at any one value of θ, were cut from different sheets. Despite this, the reproducibility of the results was extremely good. Two of the previous results are included in fig. 3.2 for comparison purposes, as in the previous report a linear modulus axis was used. It is now clear that the non-linearity changes progressively with θ.

The creep behaviour of the specimens for 100 second strains in the region of 1% and 5% is illustrated in figs. 3.3 and 3.4 respectively. Some previous results are included for comparison. As explained in the previous report, there is no significance in the separation of the curves along the strain axis. The results in fig. 3.3 show that, at 1% strain, the form of the creep curves in the anisotropic material does not vary significantly with angle. Furthermore the new isotropic results confirm that the creep rate of the anisotropic specimens is considerably less than that of the isotropic material. In contrast, the results in fig. 3.4 show that at large strains, the form of the creep curves does vary with angle. Thus, in order to reach a strain in the region of 5% (at 100 seconds) the specimens at high values of θ exhibit a far greater amount of creep than those at low θ values; the trend however only being significant between 45^o and 80^o. The 90^o specimens broke during tests aimed to give 100 second strains of approximately 1.6%. Furthermore the creep rates of the 80^o and isotropic specimens are very similar at high strains. The new creep results have thus confirmed the trends that were suspected in the original set of results.

(b) Contraction.

The creep contraction ratio for the thickness direction, ν_t, was measured in all cases (i.e. the ratio of the thickness contraction strain to the longitudinal strain at the same time). The variation of ν_t with angle, θ, is shown in fig. 3.5. The strains at 100 seconds were used in all the calculations. The value of ν_t at various strains is given, as several interesting trends in the effect of strain on the value of ν_t were observed. The previous results, obtained using a relatively crude arrangement, are also included in fig. 3.5.

The crude results were obtained at tensile strains in the range 3% to 6%. However, for angles between 25^o and 65^o, the value of ν_t is very small and is unlikely to vary significantly with strain. This is supported by the results at 65^o. Thus the results given as closed circles may, within experimental error be considered as approximately equal to the results that would have been obtained if a 1% tensile strain had been used. The theoretical line in fig. 3.5 was calculated using equation 3.4 of Report No. 4 (page 17) and the values of the constants of the compliance matrix for 1% tensile strain. In view of the experimental difficulties the agreement between the theoretical line and the "1%" values of ν_t is reasonably good.

The "5%" values of ν_t at angles of 12° and 80° show that ν_t varies appreciably with tensile strain at these angles. At 0° the variation is very small. Furthermore ν_t increases, with increasing strain, for angles of 0° and 12°, but decreases for angles of 65° and 80°. The implications of this variation have been considered and connections have been found between it and some earlier Instron work. A discussion on this subject is to be included in the detailed report of the work.

The results for the contraction study on the isotropic sample are given below:

100 second Tensile Strain	1%(a)	1%(b)	2.6%	5%
100 second ν_t	0.45	0.42	0.43	0.44

(a) Tested soon after contraction extensometer mounted. (No pre-load.)
(b) Tested 50 hours later. (No pre-load).

The effect of a time delay after mounting the contraction extensometer is apparent. This effect, and the results of preliminary contraction measurements on isotropic polyethylene samples, are discussed in part II.2.(b) of this report.

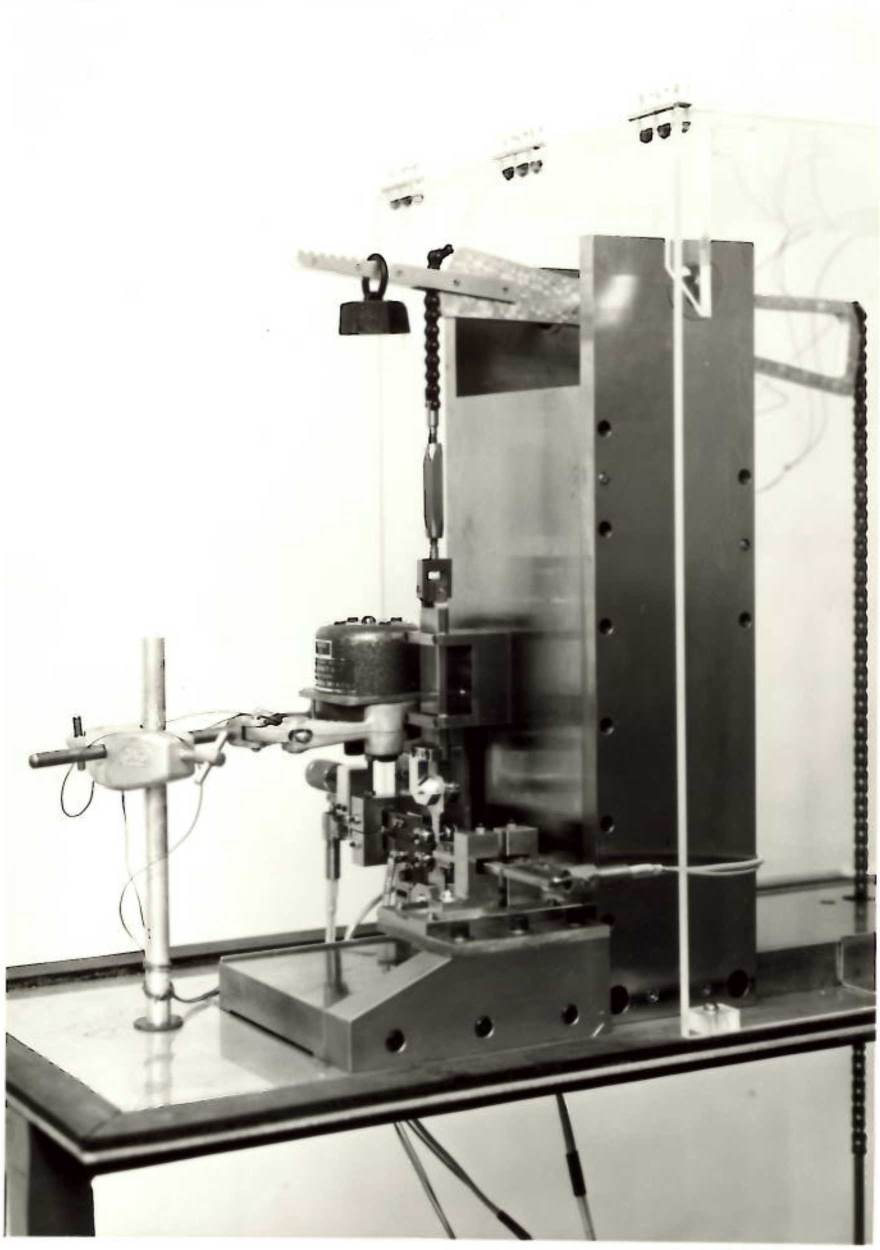

FIG. 2.1. General view of 'polythene' creep rig with balanced single-transducer extensometer for extension measurement and modified single-transducer extensometer for thickness contraction measurement.
(Vibrator on latter removed for photograph).

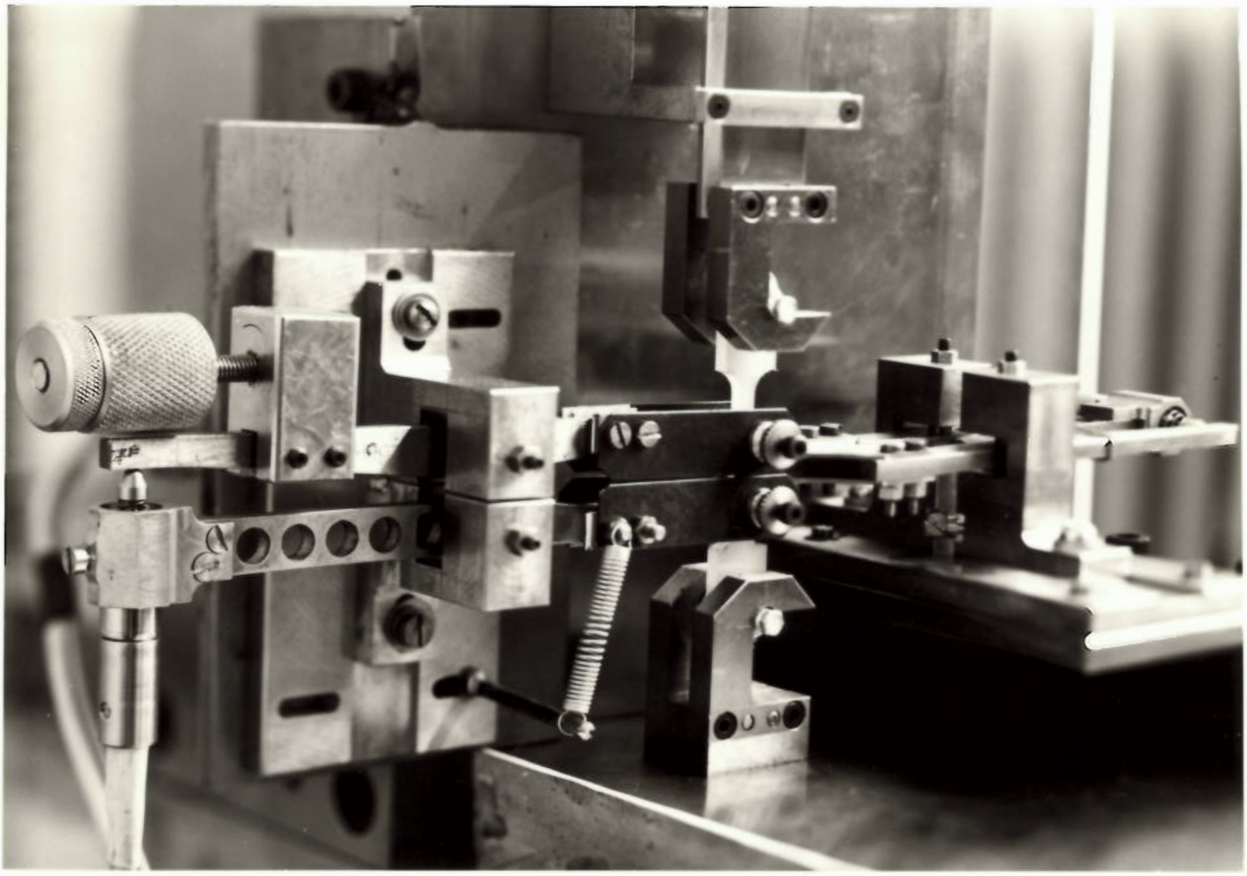

FIG. 2.2. Close-up of extensometer on 'polythene' creep rig, showing the methods used for attaching the extensometer to the specimen, and the normal method of mounting the specimen.

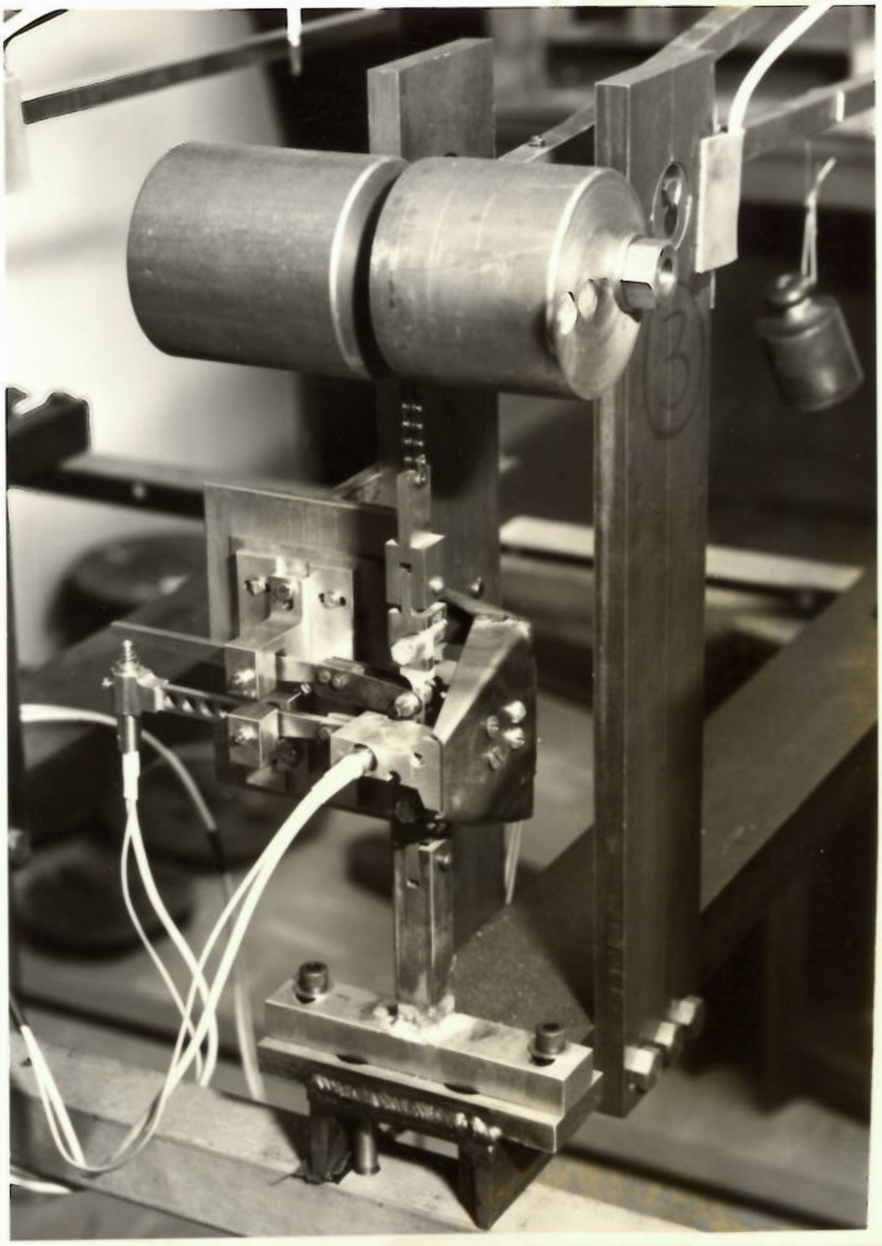

FIG. 2.3 General view of 'heavy-duty' creep rig with normal single-transducer extensometer for extension measurement and the new two-transducer device for thickness contraction measurement.

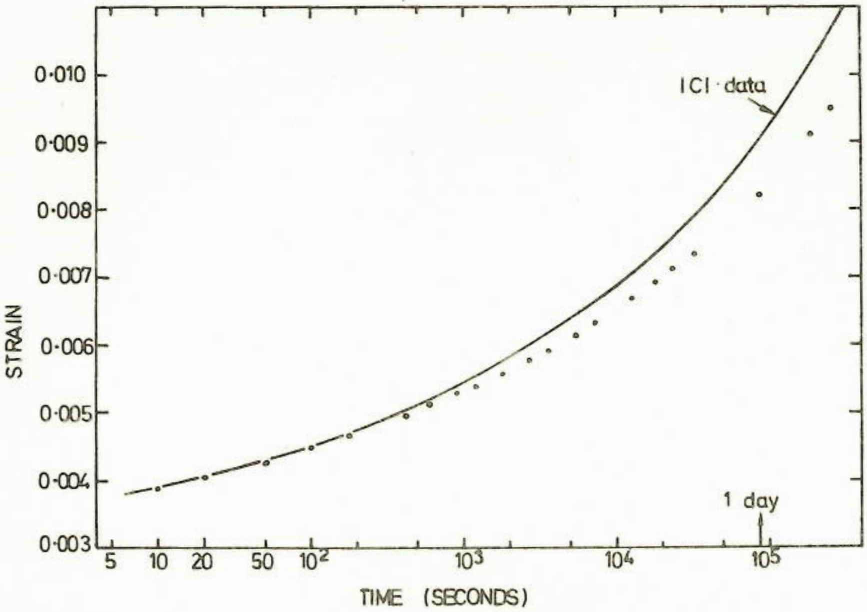

FIG. 2.4. CREEP TRIAL ON HEAVY - DUTY RIG (I.C.I. POLYPROPYLENE SPECIMEN NO. 5. Applied stress= $6{\cdot}9 \times 10^7$ dynes/$cm.^2$)

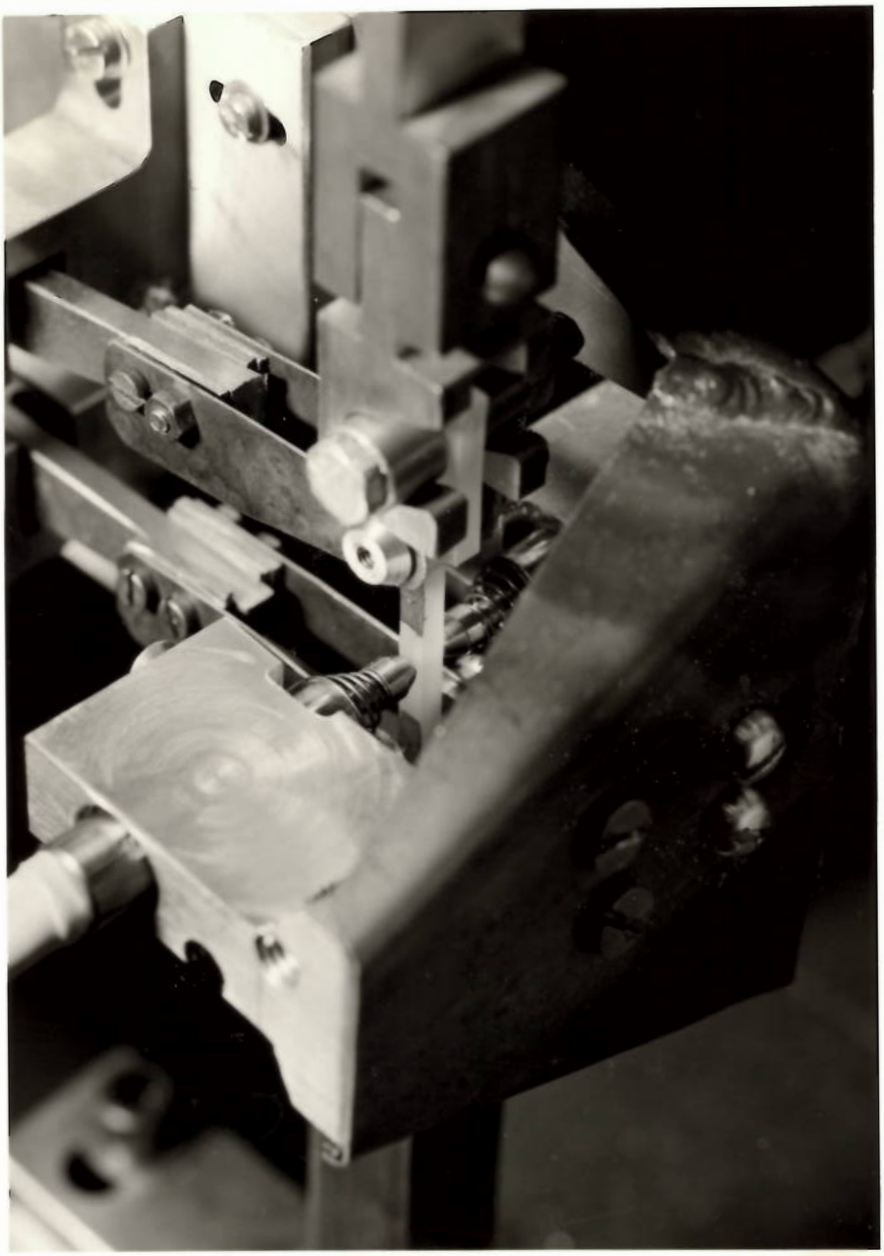

FIG. 2.5. Close-up of extensometers on 'heavy-duty' creep rig showing arrangement of the two-transducer extensometer and method of mounting the specimen.

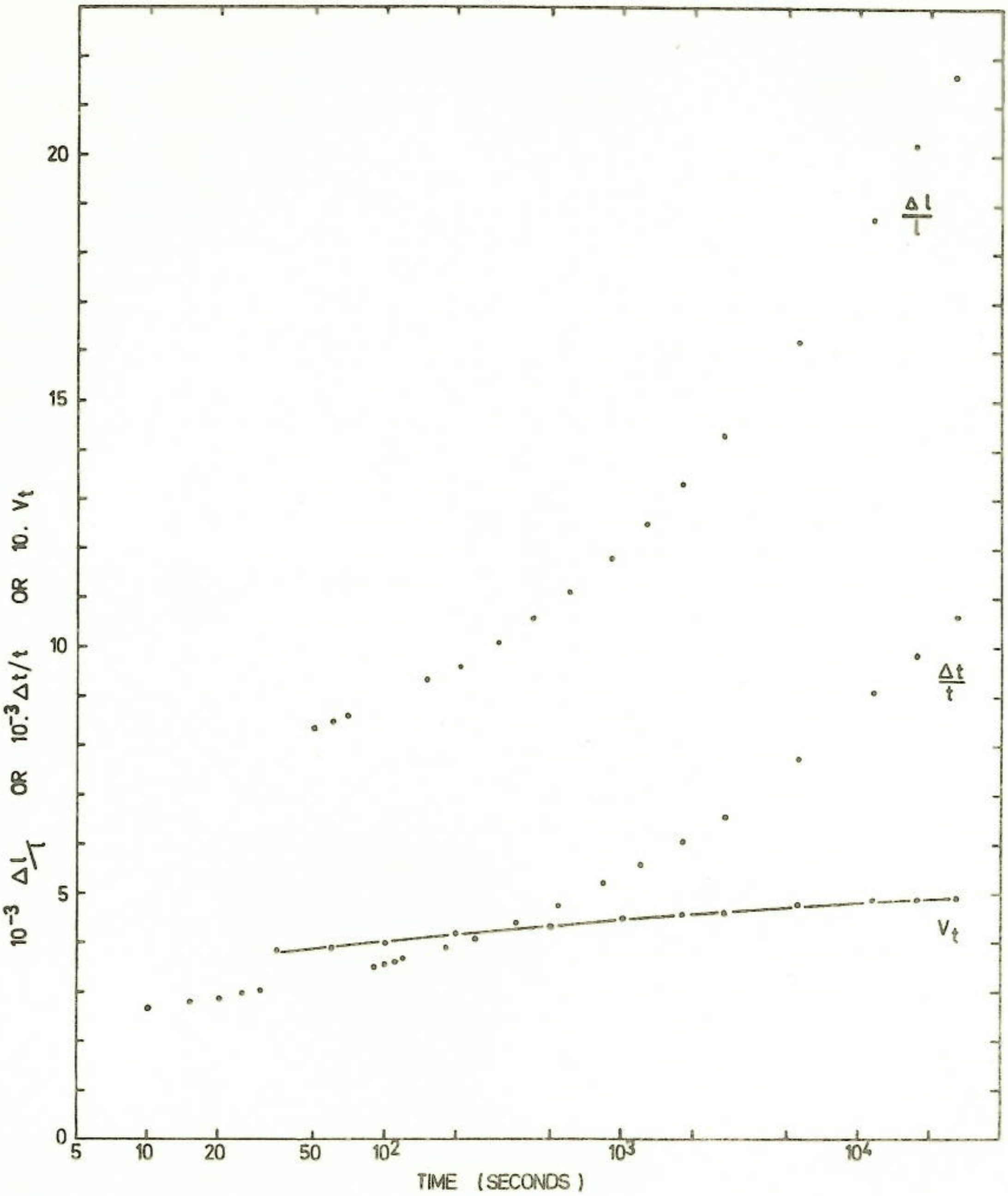

FIG. 2.6. VARIATION OF LONGITUDINAL STRAIN ($\Delta l / l$), THICKNESS CONTRACTION STRAIN ($\Delta t / t$) AND CREEP CONTRACTION RATIO FOR POLYPROPYLENE (STRESS = $1{\cdot}24 \times 10^8$ dynes/cm^2)

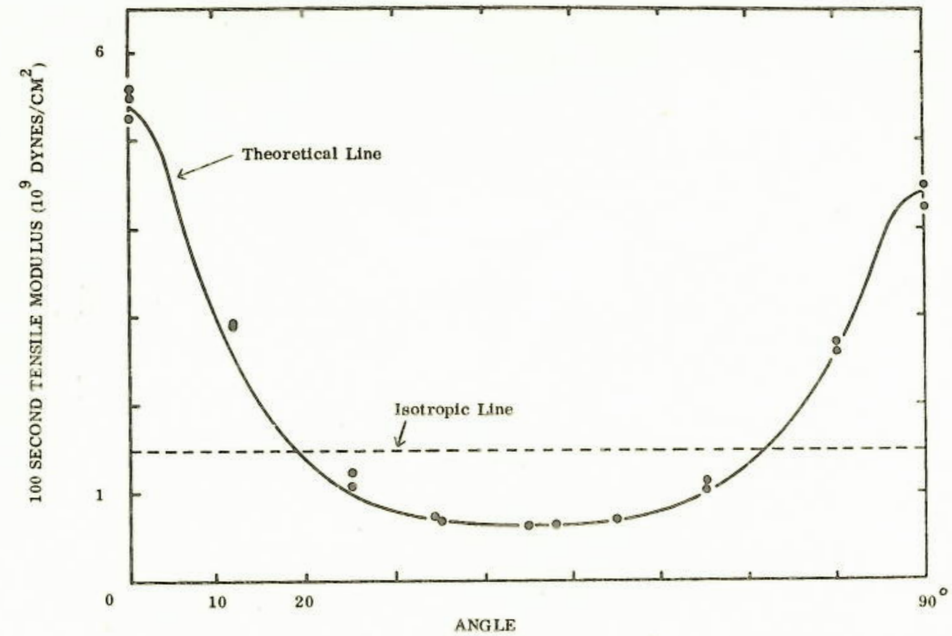

FIG. 3.1 VARIATION OF THE 100 SECOND TENSILE CREEP MODULUS WITH ANGLE. (MEASURED AT 0.2% STRAIN.)

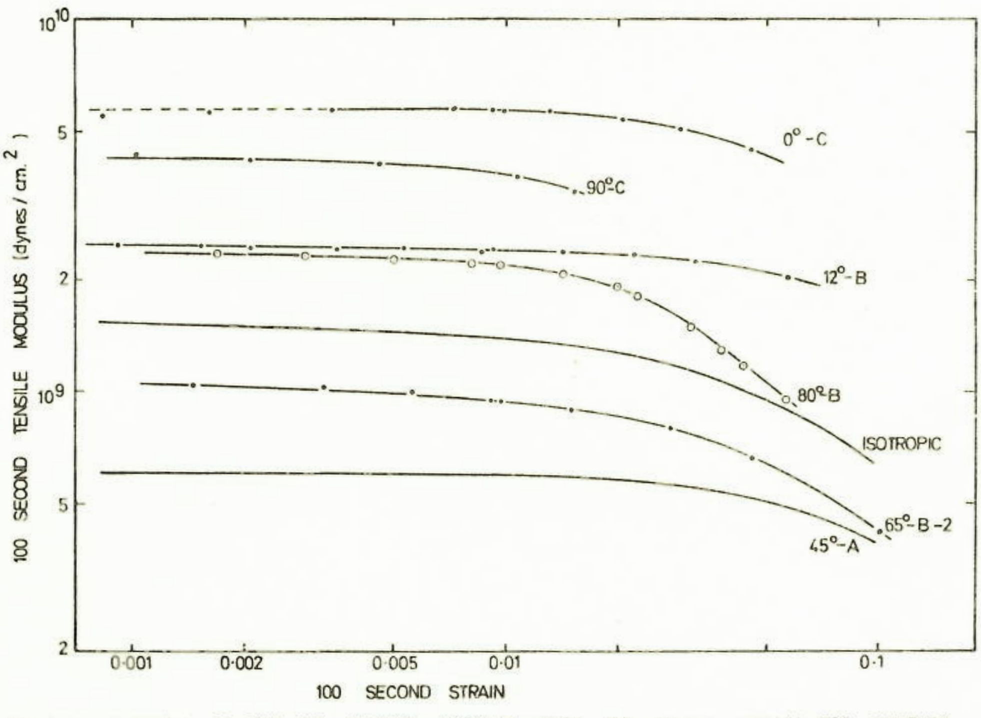

FIG. 3.2. VARIATION OF THE 100 SECOND MODULUS WITH 100 SECOND STRAIN FOR SAMPLES CUT AT VARIOUS ANGLES TO THE DRAW DIRECTION.

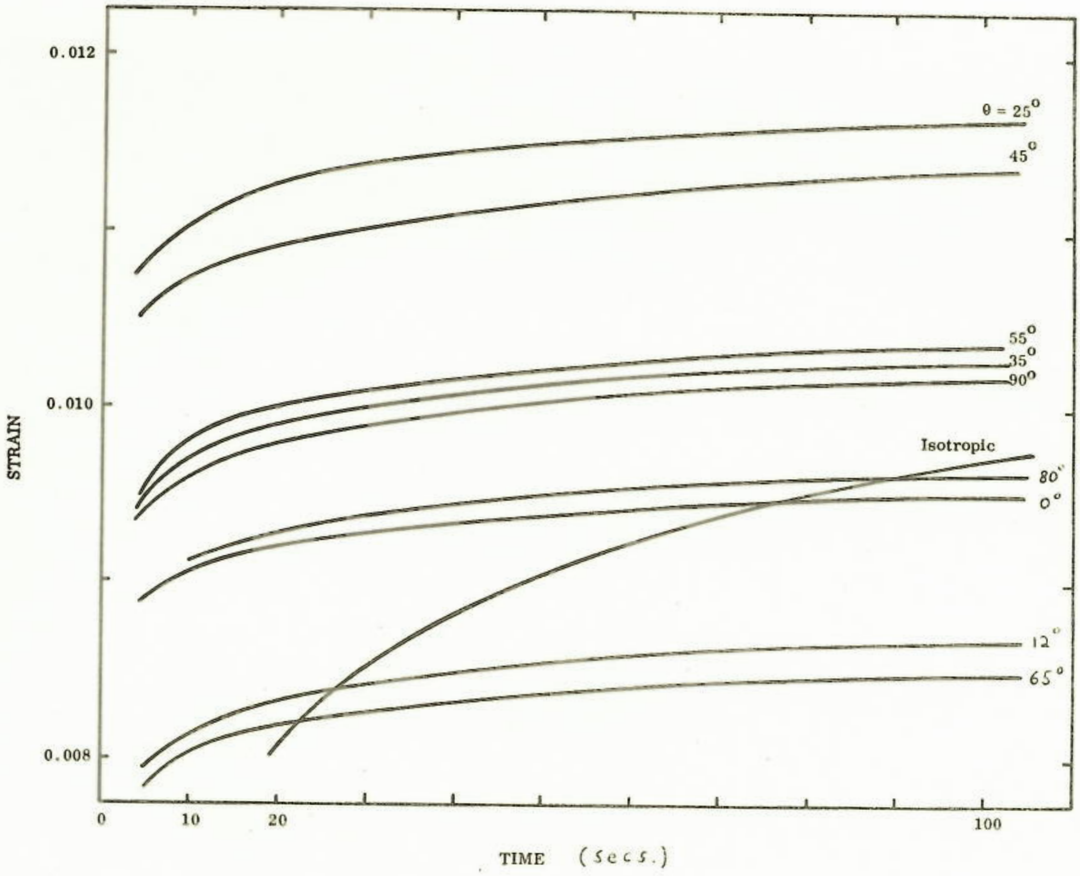

FIG. 3.3 CREEP CURVES FOR SPECIMENS CUT AT VARIOUS ANGLES, θ, TO THE DRAW DIRECTION. (100 SECOND STRAINS IN RANGE 0.85% TO 1.16%.)

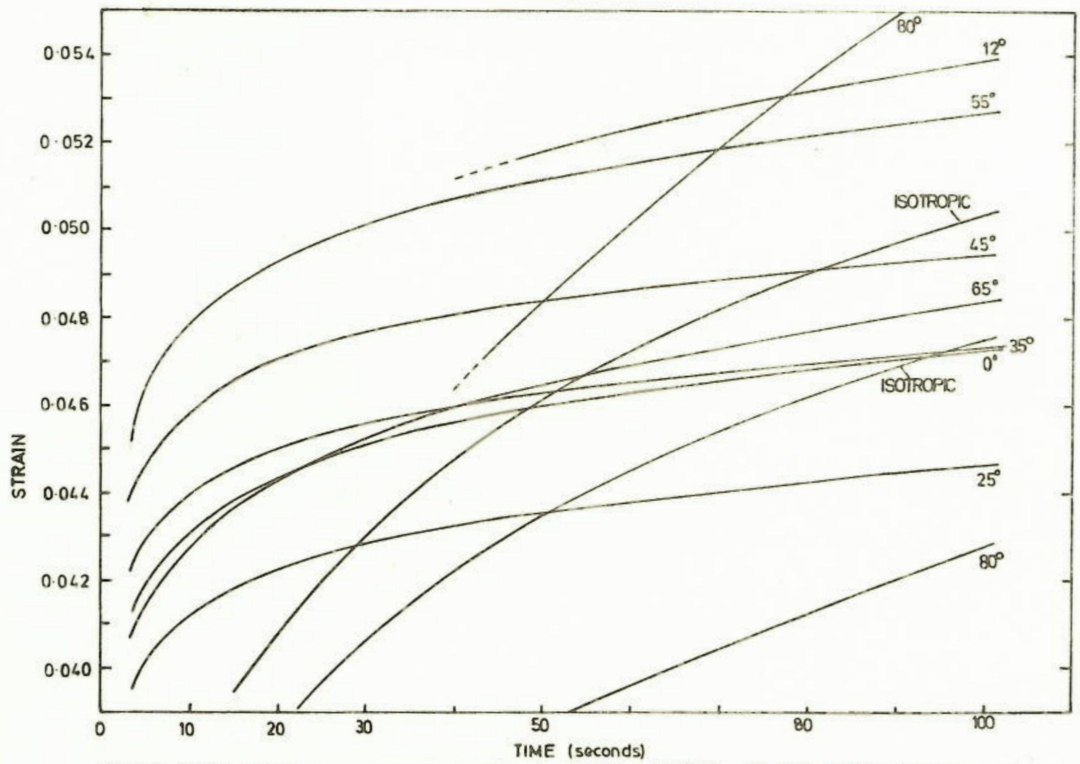

FIG. 3.4. CREEP CURVES FOR SPECIMENS CUT AT VARIOUS ANGLES TO THE DRAW DIRECTION OF AN ANISOTROPIC POLYTHENE SHEET. (100 SECOND STRAINS IN RANGE 4·5% TO 5·3%).

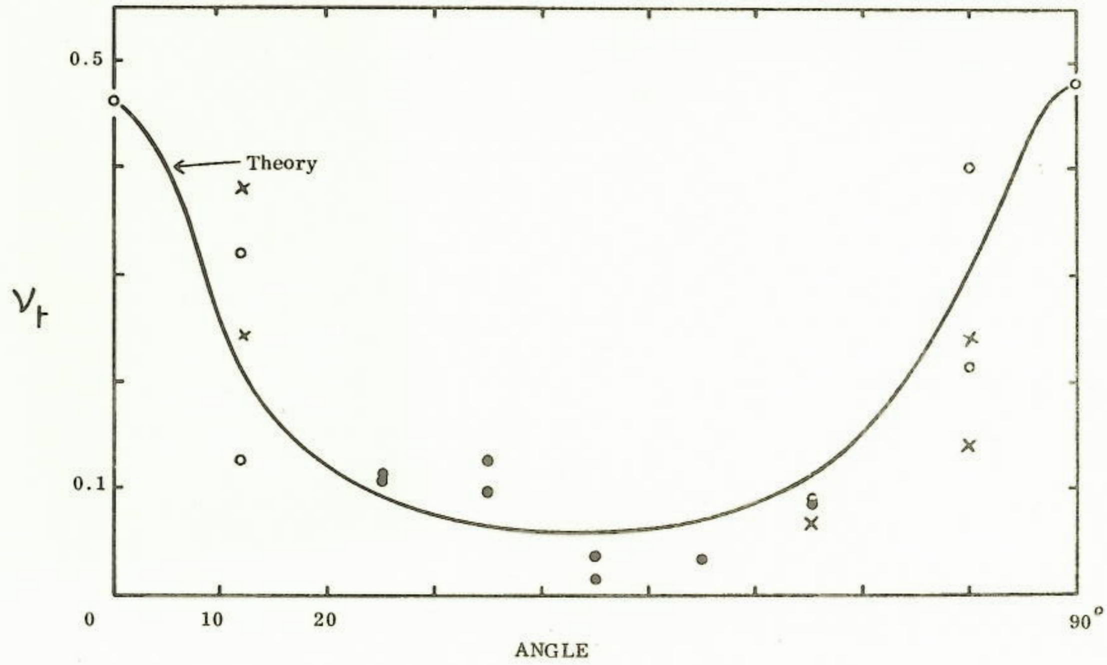

FIG. 3.5 VARIATION OF THE 100 SECOND THICKNESS CONTRACTION RATIO, ν_t, WITH ANGLE, θ.

- 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%.)