



Generation of Creep Data for Injection-Moulded Plastics

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ABSTRACT

Tensile creep moduli $E_{\theta}(t)$ have been determined for thermoplastic strip specimens cut at different angles θ to the flow direction from injection-moulded, anisotropic plates. The materials studied were polypropylene (PP) and poly(butylene terephthalate) (PBT), both in the unreinforced state and reinforced with short glass fibres. The observed patterns of anisotropy are consistent with related studies of crystal lamellar orientation and fibre orientation resulting from the deformation (or flow) and subsequent crystallisation of polymer melts. Short-term creep curves for specimens of different age and for different stress levels have been successfully modelled with a stretched-exponential function. The specification of values of the parameters appearing in such functions can provide a convenient method for presenting creep data and incorporating the data into finite element programmes for the creep of components.

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Approved on behalf of Managing Director, NPL, by Dr M K Hossain,
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1 INTRODUCTION

There is now a recognised need for more relevant and user-friendly data on the creep and other properties of plastics for improved product design^{1,2}. Tensile creep data have traditionally been presented as plots of the time-dependent strain $\epsilon(t)$ versus $\log t$ for various values of the applied constant stress σ and different temperatures T , together with isochronous and/or isometric cross-sections of the curves at different σ . Alternative methods of graphical presentation have involved plots, against $\log t$, of the compliance function $D(t)=\epsilon(t)/\sigma$ or its reciprocal, the creep modulus $E(t)$. In order to harmonise the presentation of creep data for plastics, a standard has been issued (ISO 11403-1)³ that requires the tabulation of $\epsilon(t)$ values for specified values of creep time, stress and temperature. Moore et al^{1,2} have also proposed that a reference value for the creep modulus could be specified together with abbreviated arrays of factors, representing the values of modulus normalised with respect to the reference value, at selected times, strains and temperatures.

The acquisition and presentation of creep data is further complicated by their sensitivity to other variables not yet adequately addressed by existing standards. These variables include the process-induced structural orientation and also the physical age of the material (ie the storage time between processing and load application).

The structures of moulded plastics generally comprise regions of molecular or fibre orientation the direction of which varies from place to place in the material. Structural elements close to material surfaces usually exhibit a high orientation parallel to the flow direction in the mould whereas a transverse or random orientation may exist in the interior regions^{4,5}. This often gives rise to 'skin-core' morphologies, where the relative thickness of skin and core layers, and hence the effective material moduli, will depend on the processing conditions and overall material thickness.

Tensile creep data are usually obtained using standard tests (ISO 899-1)⁶ that employ end-gated, injection-moulded bars. In the surface layers of such specimens the molecules or fibres may be highly oriented in the flow direction along the length of the bar. Measured moduli of these specimens may thus be considerably higher, and creep rates lower, than values that would be obtained for directions transverse to the flow and are unlikely to be representative of the properties of moulded components. To explore the anisotropy of mechanical properties produced by injection-moulding, workers at the ICI^{1,2,7} developed a square plate specimen (150 x 150 mm) using a coathanger-gated mould to produce unidirectional flow parallel to one edge of the plate. Creep moduli could be determined for strips cut from the

plate at different angles to the flow direction and the ratio of the modulus at some angle θ (eg 90° or 45°) to the (reference) modulus at $\theta = 0^\circ$ used in design calculations of an effective component modulus^{1,2}. A proposal has since been accepted for a new work item in ISO relating to the preparation of a standard plate specimen for determining the anisotropic properties of injection moulded plastics⁸.

The effects of physical ageing on creep behaviour are now well-documented⁹⁻¹³. The ageing process involves slow molecular rearrangements in glassy amorphous polymers or the amorphous regions of semicrystalline polymers in the approach to an equilibrium structure after cooling from a high temperature. The structural changes give rise to a progressive decrease in molecular mobility with increasing elapsed time t_e between the cooling and the instant of load application. In short-term tests ($t < 0.2 t_e$), curves of $D(t)$ or $E(t)$ versus $\log t$ for specimens of different age t_e shift to longer times with increasing t_e . In a long-term test, the effective age of the material increases significantly during the test and the creep rate progressively decreases with increasing creep time t .

The effects of ageing on the short-term creep behaviour have been successfully modelled using various compliance functions¹³ including a stretched-exponential function of the form

$$D(t) = D(0) \exp \left[(t/t_0)^\gamma \right] \quad (1)$$

Here $D(0)$ is the compliance in the limit $t \rightarrow 0$, t_0 is a mean retardation time for the creep process and γ is a parameter ($0 < \gamma \leq 1$) that characterises the width of the retardation time distribution. Although $D(0)$ often decreases somewhat with increasing age t_e , and may vary slightly with stress and temperature, γ is usually constant within experimental error and the dominant effect of ageing is to increase the retardation time according to

$$t_0 = A t_e^\mu \quad (2)$$

where the parameter A decreases with increasing stress and temperature and the 'ageing rate' μ has typical values between 0.7 and unity. The long-term creep behaviour has also been successfully modelled using extensions to equations (1) and (2) that allow for the increase in t_0 with increasing creep time t ^{12,13}.

The work reported here is aimed at the provision of a method for generating creep data on plastics that allows, in particular, for process-induced orientation and for the influence of physical ageing during the subsequent storage period. The approach has involved the modelling of short-term data for strips of specified age cut at different angles to the flow

direction from square-plate mouldings. Results have so far been obtained at 23 °C and at different stress levels for polypropylene (PP) and poly(butylene terephthalate) (PBT) each moulded in the unreinforced state and reinforced with short glass fibres. Recognising that values of creep modulus may be directly substituted into engineering design formulae, the data are expressed and modelled in terms of the creep modulus $E_{\theta}(t)$, where θ is the angle between the applied stress and the flow direction, using an equation that is the reciprocal of a modified form of (1). The model has been successfully extended to the analysis of long-term data for the glass-reinforced PP¹⁴ and has been incorporated into finite element programmes for predicting the creep of plate-like components¹⁵.

2 EXPERIMENTAL

2.1 MATERIALS

The unreinforced PP (T30S) and the glass-fibre-reinforced PP (PC072/3NAT) were obtained from Himont (UK) Ltd. The reinforced material contained 13.2 volume percent fibres having an average length/diameter ratio, estimated from optical micrograph measurements, of 39. BASF plc supplied the PBT (Ultradur B4500) and reinforced PBT (Ultradur B4300 G4), the reinforced material containing 10.8 volume percent glass fibres with an average length/diameter ratio of 37.

Details have been reported of the coathanger-gated square mould and the injection moulding conditions.^{16,17} The moulded plates measured 150 x 150 mm and had a nominal thickness of 2.7 mm. Thermal reversion studies¹⁶ suggested that the unreinforced plastics each had 'skin-core' structures, the molecules exhibiting a significant in-plane orientation in layers close to the surface and having an essentially random state of orientation within the central planes. Using optical microscopy and process modelling calculations, it was found that the reinforced materials also have skin-core structures, with the fibres near the surface oriented toward the flow direction and those in the core having a transverse or near random orientation. Furthermore, the reinforced PP had a thicker core layer and hence a somewhat lower overall fibre orientation toward the flow direction than the reinforced PBT.

Strips were machined from the plates with a nominal length of 150 mm, width 10 mm and thickness (2.7 mm) equal to the plate thickness. To specify the strip locations within the plates they were numbered according to the scheme illustrated in Figure 1.

An initial series of tests was carried out to explore the patterns of anisotropy and heterogeneity using specimens that had been stored for about 6 months between processing and load application. The majority of these tests were made on specimens from location 1 for each of the angles 0° , 90° and 45° between the specimen length and the flow direction. For the reinforced materials, some measurements were made on strips from different locations within the plates in the 0° and 90° directions respectively.

To investigate the effects of age state, selected strips from the initial tests were first heated for 30 mins at 100°C (for PP and reinforced PP) or at 80°C (for PBT and reinforced PBT) in order to erase previous ageing effects. They were then quenched in water at 23°C and creep tests subsequently performed at different elapsed times t_e after quenching.

2.2 DETERMINATION OF CREEP MODULI

Creep moduli $E_\theta(t) = \sigma/\epsilon(t)$ were obtained for times $t \geq 1\text{s}$ from measurements of the time-dependent strain $\epsilon(t)$ for strips subjected to a constant stress σ .^{10,18} All measurements were made at $23.0 \pm 0.2^\circ\text{C}$ by locating the loading rigs in temperature controlled chambers. For the initial investigations of well-aged material, and in the studies of ageing effects, low stresses (3-10 MPa) were employed that produced strains between about 0.1% and 0.5% and were considered close to the levels required for the onset of non-linearity. Subsequent tests were carried out, for specimens of age $t_e = 24\text{h}$, at various stress levels within the non-linear range. In all tests the creep duration was less than t_e , to ensure that the effects of any further ageing during the creep were negligible.

3 RESULTS AND DISCUSSION

3.1 PATTERNS OF ANISOTROPY AND HETEROGENEITY

It is instructive to discuss first the results of the initial investigation of specimens that had been stored for about six months between processing and load application.

The variation of creep moduli with $\log t$ for unreinforced PP is shown in Figure 2. These results are ascribed to the α -relaxation process which involves coupled motions of molecular segments in the amorphous and crystalline regions.^{10,19} At short times the value of $E_0(t)$ is greater than that of $E_{90}(t)$ but the creep rate is larger for stresses in the 0° direction and the curves for $E_0(t)$ and $E_{90}(t)$ cross at a creep time around 2h. At all times $E_{45}(t)$ is less than

$E_0(t)$ and $E_{90}(t)$. This pattern of anisotropy is consistent with that reported in the α -relaxation region for crosslinked polyethylene crystallised after stretching at a temperature above the melting point (see Fig 10.38, ref 20). It has been ascribed to the orientation of crystalline *lamellae* perpendicular to the molecular orientation direction and hence perpendicular to the direction of stretching or flow. The rigid lamellae and interlamellar amorphous material tend to be coupled in series along the flow direction and the progressive softening of amorphous material due to the α -process produces a larger reduction in $E_0(t)$ than $E_{90}(t)$. The relatively low value of $E_{45}(t)$ would arise from the low resistance to interlamellar shear and the fact that the resolved shear stress is a maximum in the direction parallel to the lamellar planes.

The results for glass-reinforced PP in Figure 3 show that $E_0(t) > E_{45}(t) > E_{90}(t)$ at all times, and thus the pattern of anisotropy is simpler than that for the unreinforced polymer. The anisotropy ratio $E_0(t)/E_{90}(t)$ is also higher than that for the unfilled material, reflecting the net orientation of fibres toward the flow direction. From the results in Figure 3, the value of $E_0(t)/E_{90}(t)$ is found to increase from 1.54 to 1.73 as t increases from 10s to 10^5 s. The values of $E_{45}(t)$ are much closer to those of $E_{90}(t)$ than to those of $E_0(t)$, indicating a low resistance to shear along or perpendicular to the fibres. This result may partly relate to the low values of $E_{45}(t)$ for the matrix polymer.

Figure 4 reveals for glass-fibre-reinforced PP an increase in $E_0(t)$ with increasing distance from the centre of the plate, the value for specimen 3 being about 20% higher than that for specimen 1. However the transverse modulus $E_{90}(t)$ is little affected by the location of the strip within the plate. The variations in $E_0(t)$ should largely reflect an in-plane heterogeneity in the fibre orientation distribution and such variations are assumed to be much smaller for the unfilled materials.

For unreinforced PBT (Fig 5) the creep modulus plots exhibit a plateau for times below 100s and a downward curvature at longer times. This behaviour characterises the onset of the glass-rubber relaxation in the amorphous regions of the semicrystalline polymer. The values of $E_{90}(t)$ are about 3% lower than the values of $E_0(t)$ and $E_{45}(t)$. These differences are, however, only slightly in excess of the experimental reproducibility and the unreinforced PBT plates may thus be regarded as essentially isotropic with respect to the in-plane modulus.

The creep modulus curves for the glass-fibre-reinforced PBT were found to have a pattern of anisotropy ($E_0(t) > E_{45}(t) > E_{90}(t)$) similar to that for the reinforced PP. However, as shown in Fig 6 the $E_0(t)$ value decreases with increasing distance from the centre of the plate. The latter effect is opposite to that observed for the reinforced PP but the variation of $E_0(t)$ values

with location is relatively small. From the data in Figure 6 for the specimens at position 1, the anisotropy ratio $E_0(t)/E_{90}(t)$ is found to increase from a value of 1.86 at $t = 10$ s to a value of 2.12 at $t = 10^5$ s. These values are larger than those given above for the glass-reinforced PP, a result that is consistent with a somewhat higher net orientation of fibres toward the flow direction in the reinforced PBT (less extensive core region).

3.2 MODELLING OF DATA

In this section consideration will be given to the modelling of data obtained for reheated and quenched specimens as a function of the elapsed time t_e after quenching and of the stress level σ .

Using a least-squares optimisation procedure,²¹ it was found that equations (1) and (2) could only provide an accurate description of the compliance curves for PP and reinforced PP if the apparent values of γ and μ varied with t_e and were considerably smaller than the values obtained for compression moulded PP^{10,13}. This result was considered to reflect a merging of the glass-rubber (β) relaxation with the short-time tail of the α -relaxation,¹⁰ the relative contribution of the β -process being larger for the injection moulding grade of PP and for long t_e . As illustrated in Figure 7, the compliance curves for PP at different t_e (which predominantly characterise the α -process) tend to diverge at long times and can be superposed by a combination of upward vertical and forward horizontal shifts. This indicates that overlap from the β -process may be regarded as effectively producing an inclined baseline to the compliance curve in the α -region, a similar assumption having been made by Struik²² in analysing the physical ageing of semicrystalline polymers in his so-called region 3. To allow for the overlap effects, the compliance curves for PP and reinforced PP were thus reanalysed using the equation

$$D_\theta(t) = (D_1 + D_2 \log t) \exp \left[(t/t_0)^\gamma \right] \quad (3)$$

where the slope D_2 of the baseline was estimated as the tangent to the compliance curve for the longest t_e at $\log t = 0$ (see Fig 7). Assuming that D_2 and γ are constant, equation (3) gave a reasonable fit to the data with values of γ and μ (Table 1) close to those usually reported for PP.

Noting that $E_\theta(t) = 1/D_\theta(t)$, the required expression for the creep modulus is obtained from (3) as

$$E_{\theta}(t) = \left[(1/E_1) + (1/E_2) \log t \right]^{-1} \exp \left[-(t/t_0)^{\gamma} \right] \quad (4)$$

where $E_1 = D_1^{-1}$ and $E_2 = D_2^{-1}$. With the aid of the analyses of compliance curves, values of E_1 and t_0 were thus obtained for different t_e and σ (with E_2 and γ constant) and from these results the following relationships were subsequently derived,

$$E_1 = E_{\text{ref}} (1 - B\sigma) t_e^{\nu} \quad (5)$$

and

$$t_0 = A_0 \exp (-A_1\sigma) t_e^{\mu} \quad (6)$$

where E_{ref} and A_0 are reference values for E_1 and t_0 , respectively, defined for $t_e = 1\text{s}$ and $\sigma = 0$, and B , ν , A_1 and μ are constants.

Figures 8 and 9 exemplify the optimised fits of equations (4)-(6) to creep modulus curves for PP and the fits obtained for the fibre-filled PP are illustrated in Figures 10 and 11. Values of the derived parameters for each material are included in Table 1 for $\theta = 0^\circ$ and $\theta = 90^\circ$ respectively. The effects of fibre orientation are reflected by the higher value of $E_{\text{ref},0^\circ}/E_{\text{ref},90^\circ}$ for the filled material (1.46) compared with that for the unreinforced polymer (0.92). In this context note that the anisotropy ratio $E_0(t)/E_{90}(t)$ can be calculated using equation (4) with the parameters in Table 1, and varies for each material with t_e , σ and t . Such calculations show that for unreinforced PP, $E_0(t)/E_{90}(t)$ can have values either less than or greater than unity.

In the case of PBT and fibre-filled PBT any effects of overlap between the glass-rubber (α) process and the secondary (β) process are negligible¹¹ so that the baseline to the α -relaxation is assumed to be horizontal. It follows that $1/E_2 = 0$ so that equation (4) becomes

$$E_{\theta}(t) = E_1 \exp \left[-(t/t_0)^{\gamma} \right] \quad (7)$$

Note that E_1 now equals $E_{\theta}(0)$, the creep modulus in the limit $t = 0$. Hence equation (7) is the reciprocal of equation (1) and E_{ref} in (5) is now the reference modulus for $t_e = 1\text{s}$, $\sigma = 0$ and $t = 0$.

Since the unreinforced PBT is essentially isotropic, equation (7) with (5) and (6) has been fitted to the creep modulus curves for $\theta = 0^\circ$ only (see Fig 12), whereas for the fibre-filled

PBT fits have been obtained to the data for $\theta = 0^\circ$ and 90° , as shown in Figures 13 and 14. From the parameters required to optimise these fits (Table 1), a value of $E_{\text{ref},0^\circ}/E_{\text{ref},90^\circ} = 1.78$ is obtained for the fibre-filled PBT. This is larger than the corresponding value (1.46) for reinforced PP and consistent with the higher overall fibre orientation in the PBT material. It should be added that the dependence of $E_0(t)/E_{90}(t)$ on t_e, σ and t can again be calculated with the aid of equations (5)-(7), the time-dependence having been noted in section 3.1 above.

Equations (4)-(6) or (5)-(7) could, in principle, be used to interpolate or extrapolate creep modulus data over continuous ranges of t , t_e and σ . Some caution is, however, required in the use of such equations for data extrapolation. For creep times longer than t_e it is known, for example, that further ageing during the creep will substantially reduce the creep rate. This effect has been successfully accounted for by a modification to equation (4) or (7) which allows for the progressive increase in t_0 through an additional parameter that can be determined from long-term data.^{13,14}

Some discrepancies have also been found between the predicted creep moduli for materials with long t_e and the results for the non-reheated, well-aged specimens. As shown in Figure 15, the predicted curves for PBT for $t_e = 29$ weeks and 81 weeks are located at longer times than the experimental curves for non-reheated specimens with storage times equal to the respective t_e values. Similar discrepancies have been found for the other materials, and are considered to arise from the reheating of specimens to 80°C or 100°C prior to studying the effects of varying t_e and σ . Noting that the injection moulding process involves a rapid quenching of the material from the melt temperature ($250\text{--}270^\circ\text{C}$) to the mould temperature ($58\text{--}60^\circ\text{C}$), the subsequent reheating and quenching could, in addition to deaging the structure with respect to the short retardation time processes, effectively enhance the ageing of the longer retardation time processes and possibly produce some changes in crystal morphology. To obtain parameters more accurately representative of the initial moulded (deaged) material, a method should be employed for studying the effects of ageing that avoids the reheating stage. This might involve creep studies on unheated specimens covering longer ranges of t_e or delaying the onset of ageing by storing the original mouldings at very low temperatures prior to testing.²³

With the above precautions, it is evident from Table 1 that, for a given angle θ , creep moduli over wide and continuous ranges of t , t_e and σ can be specified by the values of between about five and eight different parameters. Although additional parameters would be required for accurate predictions of long-term creep¹⁴, and the effects of temperature,²⁴ some simplifications might be achieved by assuming that the values of certain parameters (eg B

and/or v) were generally negligible. The use of analytical functions in the generation and presentation of creep data can thus greatly reduce the problems of handling large quantities of numerical data. It can also provide an understanding of the interdependence of the effects of different variables on the creep data and a convenient means of incorporating the data into finite element programmes of component deformation.¹⁵

4 CONCLUSIONS

- (a) Anisotropic creep moduli $E_{\theta}(t)$, relevant to the design of plastic components, can be obtained from tensile measurements on strips of specified age cut at different angles θ to the flow direction from injection-moulded square plates.
- (b) A complex pattern of anisotropy for PP is ascribed to the orientation of crystal lamellae perpendicular to the flow direction. For glass-reinforced PP, $E_0(t) > E_{45}(t) > E_{90}(t)$ at all creep times t and the value of $E_0(t)$ increases with increasing distance from the centre of the plate.
- (c) For unreinforced PBT, the creep modulus is essentially isotropic, but after reinforcement with glass fibres the anisotropy is larger than that for reinforced PP, consistent with a higher overall level of fibre orientation (less extensive core region).
- (d) Creep modulus curves for different angles θ , age states and stress levels can be modelled with a stretched-exponential function suitably modified (in the case of PP and reinforced PP) to allow for the overlap of the short-time β -process. To obtain parameters accurately representative of the original mouldings, studies of ageing effects should employ a method that avoids reheating of the material.
- (e) The use of analytical functions can greatly simplify the generation and presentation of data and provides a convenient method for incorporating the data into finite element programmes for component design.

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TABLE 1
VALUES OF PARAMETERS DERIVED FROM DATA MODELLING

Material	θ°	E_{ref} (GPa s ^{-v})	ν	B (MPa ⁻¹)	$(1/E_2)$ (GPa ⁻¹)	γ	A_0 (s ^{1-μ})	A_1 (MPa ⁻¹)	μ
PP	0	1.53	0.0184	0	0.058	0.17	634.7	0.454	0.75
PP	90	1.66	0.0089	0	0.042	0.17	425.7	0.497	0.85
PP/Glass	0	5.83	0	0.0016	0.006	0.16	5908	0.214	0.86
PP/Glass	90	4.00	0	0	0.009	0.16	1298	0.306	0.88
PBT	0	2.32	0.005	0.0022	0	0.32	69.5	0.081	0.82
PBT/Glass	0	6.87	0	0	0	0.25	1823	0.068	0.83
PBT/Glass	90	3.87	0	0	0	0.25	243.6	0.099	0.82

FIGURE CAPTIONS

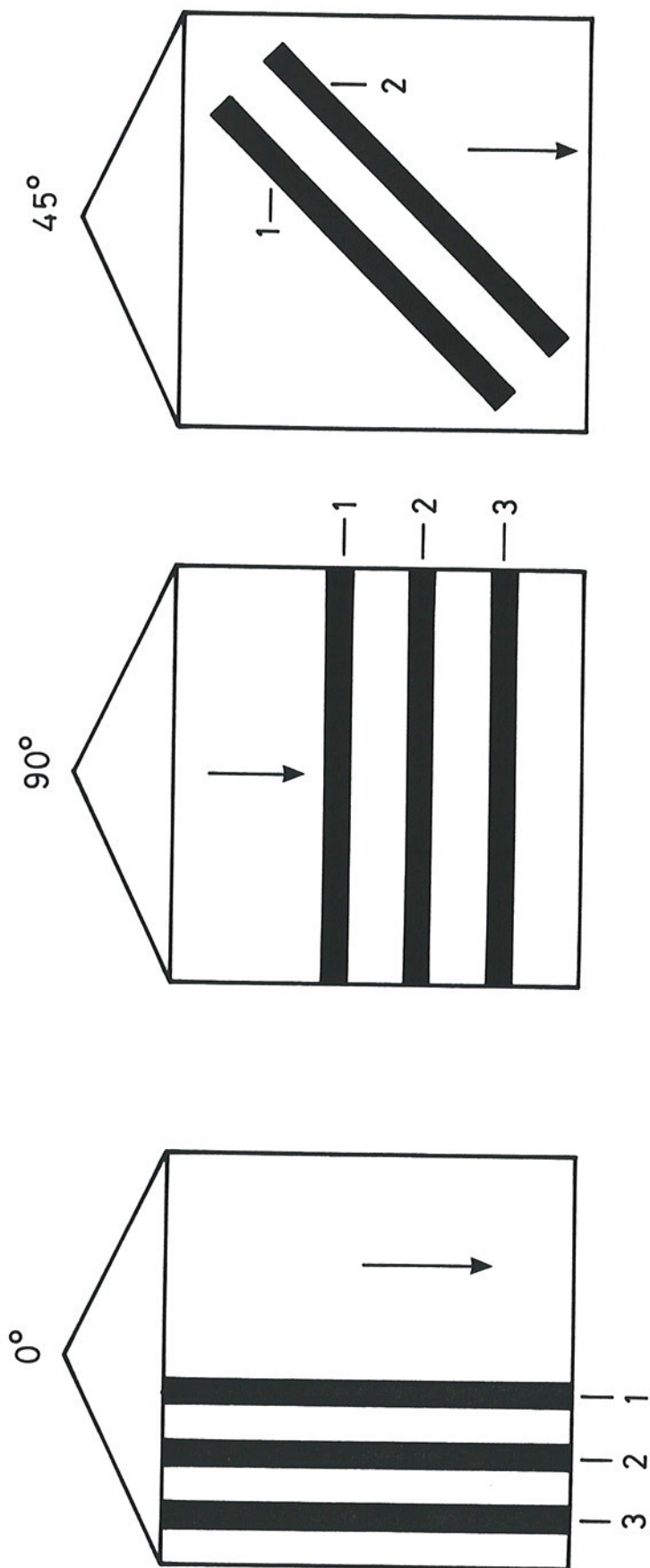
- Fig 1 Illustration of specimens employed in the creep tests.
- Fig 2 Creep modulus plots for unreinforced PP specimens 1 at different angles θ (see Fig 1). Storage period = 25 weeks. $\sigma = 3.6$ MPa.
- Fig 3 Creep modulus plots for glass fibre reinforced PP specimens 1 at different angles θ (see Fig 1). Storage period = 25 weeks. $\sigma = 9.3$ MPa.
- Fig 4 Creep modulus plots for glass fibre reinforced PP specimens at different locations within the plates (see Fig 1). Storage period = 32 weeks. $\sigma = 9.3$ MPa.
- Fig 5 Creep modulus plots for unreinforced PBT specimens 1 at different angles θ (see Fig 1). Storage period = 29 weeks. $\sigma = 3.6$ MPa.
- Fig 6 Creep modulus plots for glass fibre reinforced PBT specimens at different locations within the plate (see Fig 1). Storage period = 33 weeks. $\sigma = 10.5$ MPa.
- Fig 7 Compliance curves for PP for $\theta = 0^\circ$, $\sigma = 2.5$ MPa and different elapsed times t_e after quenching from the reheating temperature of 100°C . (—>—), illustration of direction of shift required to superpose curve at given t_e onto curve for higher t_e . (———), proposed baseline to curve for $t_e = 366\text{h}$. Since D_1 decreases with increasing t_e , the baseline will shift downward as t_e increases and its slope D_2 (assumed to be constant) will be somewhat larger than the slope of (—>—).
- Fig 8 (o), Experimental creep moduli for PP for $\theta = 0^\circ$. (a), $\sigma = 2.5$ MPa, varying t_e ; (b), $t_e = 24\text{h}$, varying σ . (———), optimised fits of equations (4)-(6) to the data giving values of parameters included in Table 1.
- Fig 9 As Fig 8 but for $\theta = 90^\circ$.
- Fig 10 (o), Experimental creep moduli for glass fibre reinforced PP for $\theta = 0^\circ$. (a), $\sigma = 9.3$ MPa, varying t_e ; (b), $t_e = 24\text{h}$, varying σ . (———), as in Fig 8.
- Fig 11 (o), Experimental creep moduli for glass fibre reinforced PP for $\theta = 90^\circ$. (a), $\sigma = 5.6$ MPa, varying t_e ; (b), $t_e = 24\text{h}$, varying σ . (———), as in Fig 8.

Fig 12 (o), Experimental creep moduli for PBT for $\theta = 0^\circ$. (a), $\sigma = 3.6$ MPa, varying t_e ; (b), $t_e = 24$ h, varying σ . (————), optimised fits of equation (7) with (5) and (6) to the data giving values of parameters included in Table 1.

Fig 13 (o), Experimental creep moduli for glass fibre reinforced PBT for $\theta = 0^\circ$. (a), $\sigma = 10.8$ MPa, varying t_e ; (b), $t_e = 24$ h, varying σ . (————) as in Fig 12.

Fig 14 (o), Experimental creep moduli for glass fibre reinforced PBT for $\theta = 90^\circ$. (a), $\sigma = 5.3$ MPa, varying t_e ; (b), $t_e = 24$ h, varying σ . (————), as in Fig 12.

Fig 15 Comparison of observed creep moduli (o) for non-reheated PBT specimens ($\sigma = 3.6$ MPa) at the specified storage times after processing with predicted curves (————) using equations (5)-(7) for specimens of corresponding t_e after reheating and quenching.



Arrows indicate flow direction

Fig. 1

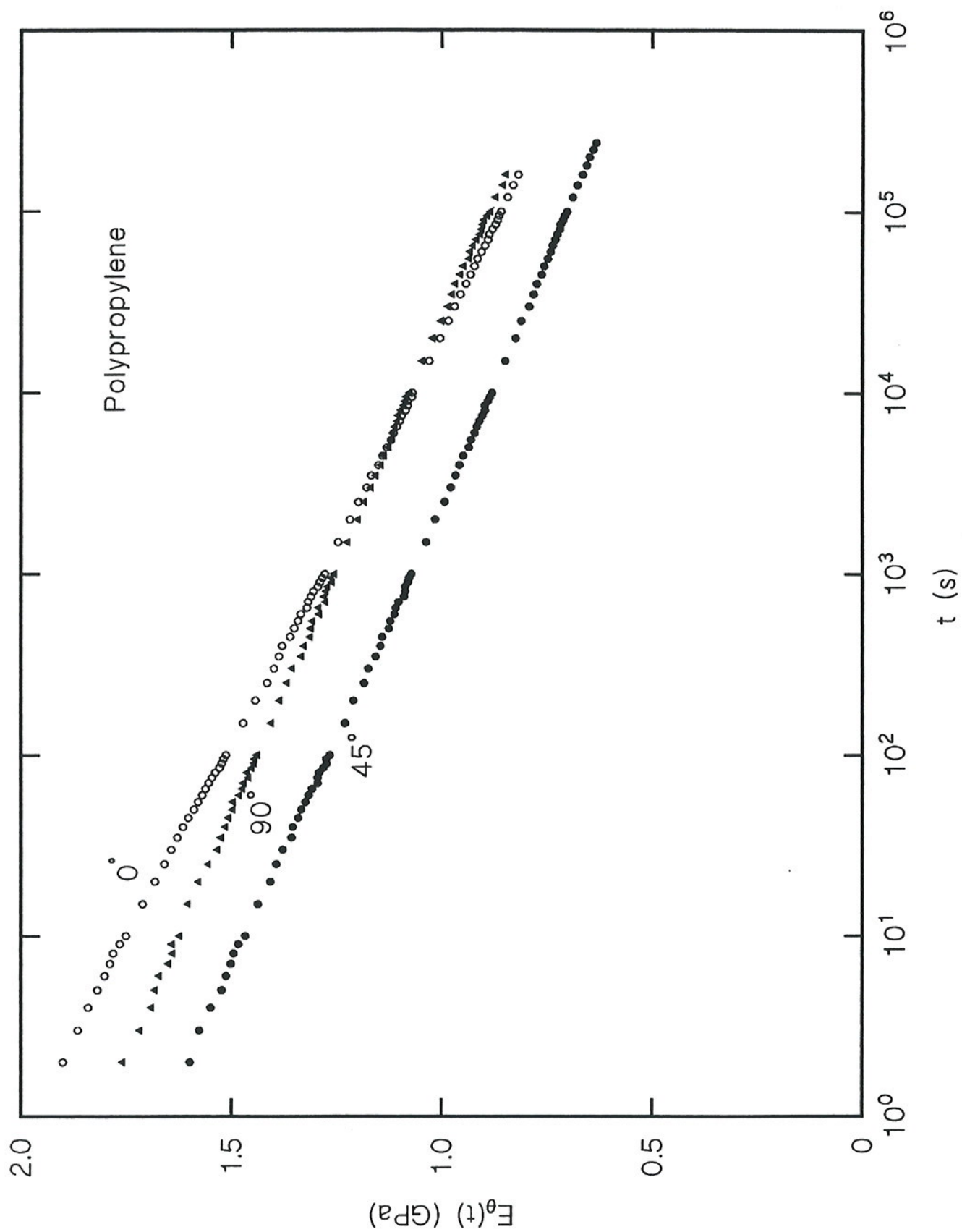


Fig. 2

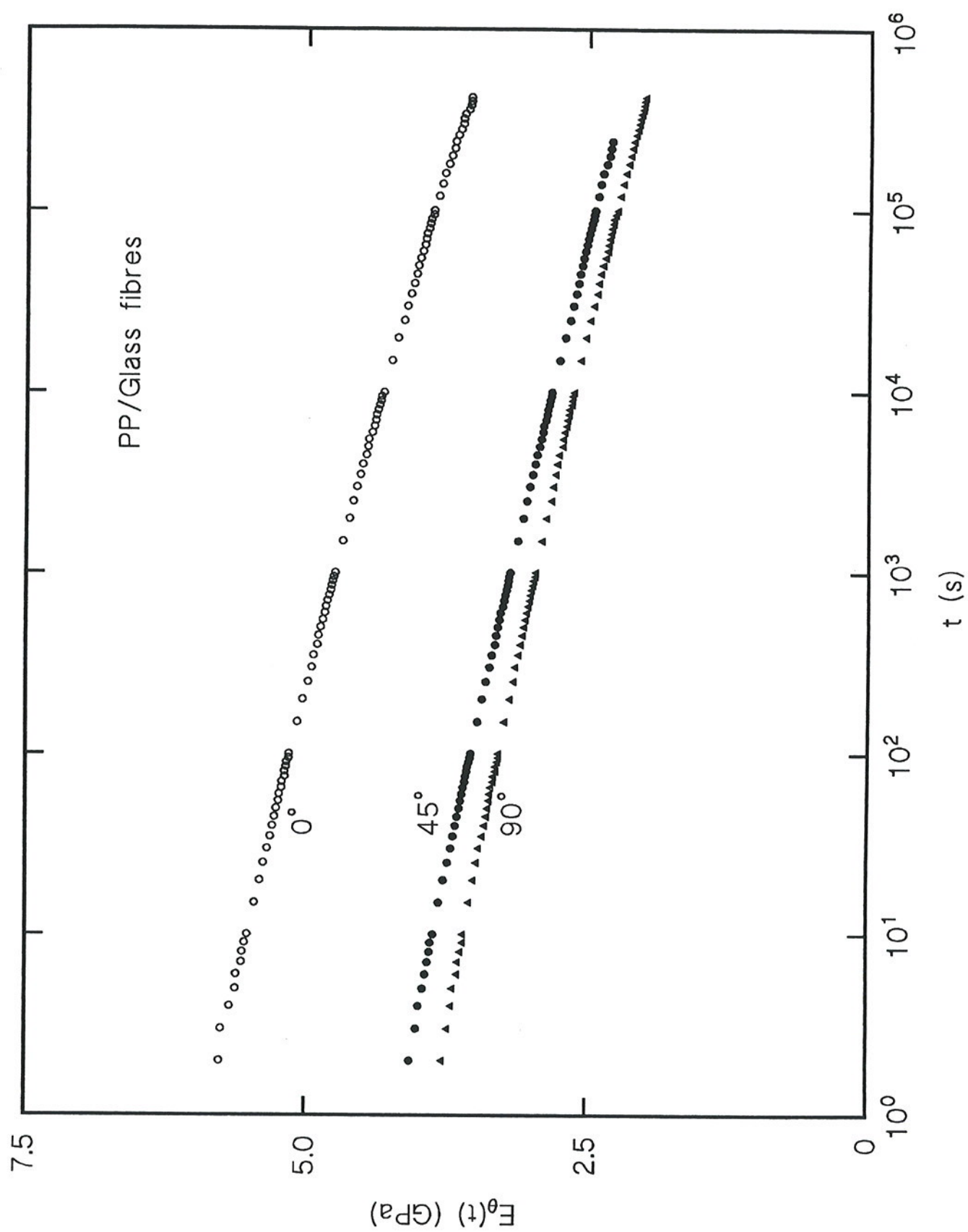


Fig. 3

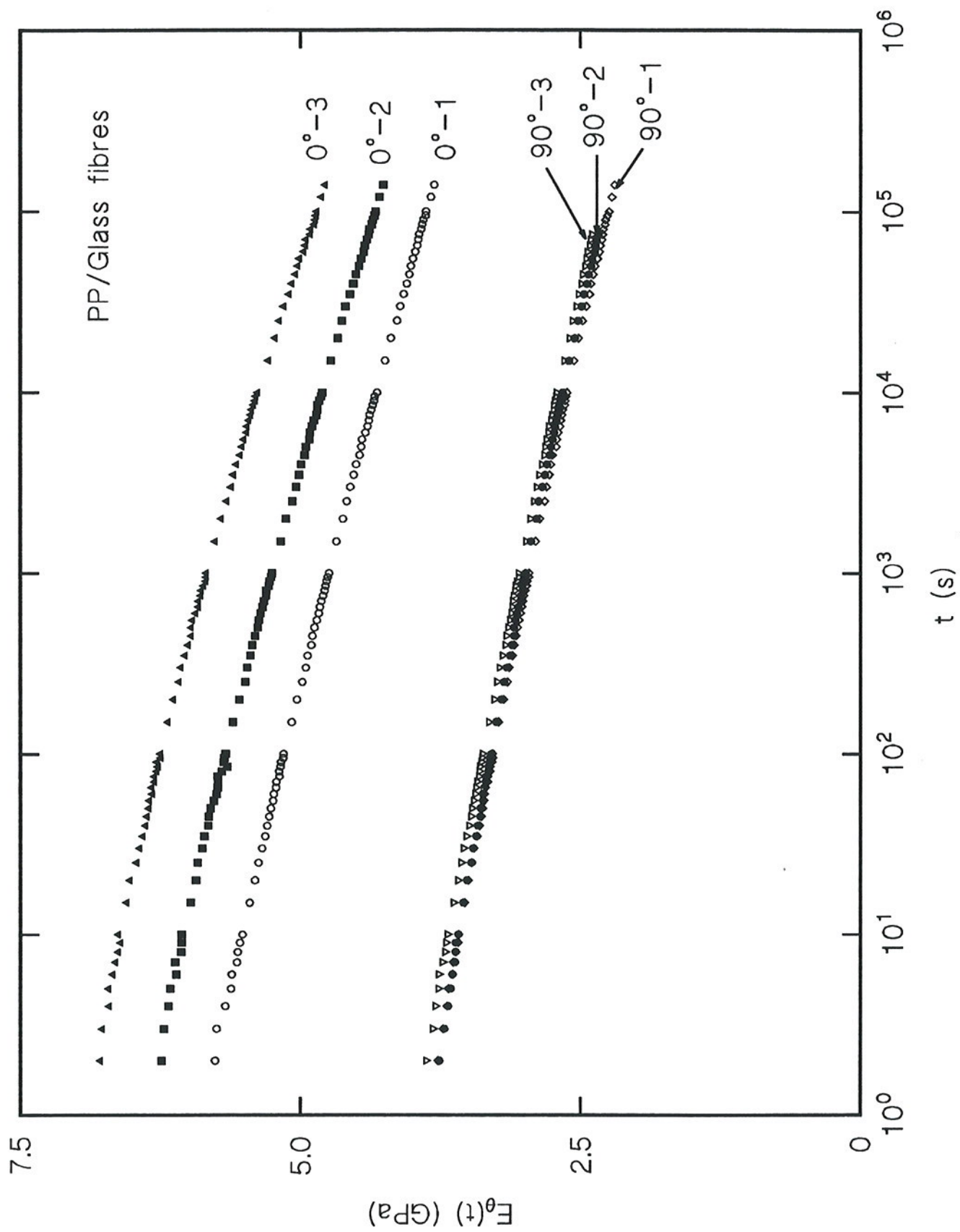


Fig. 4

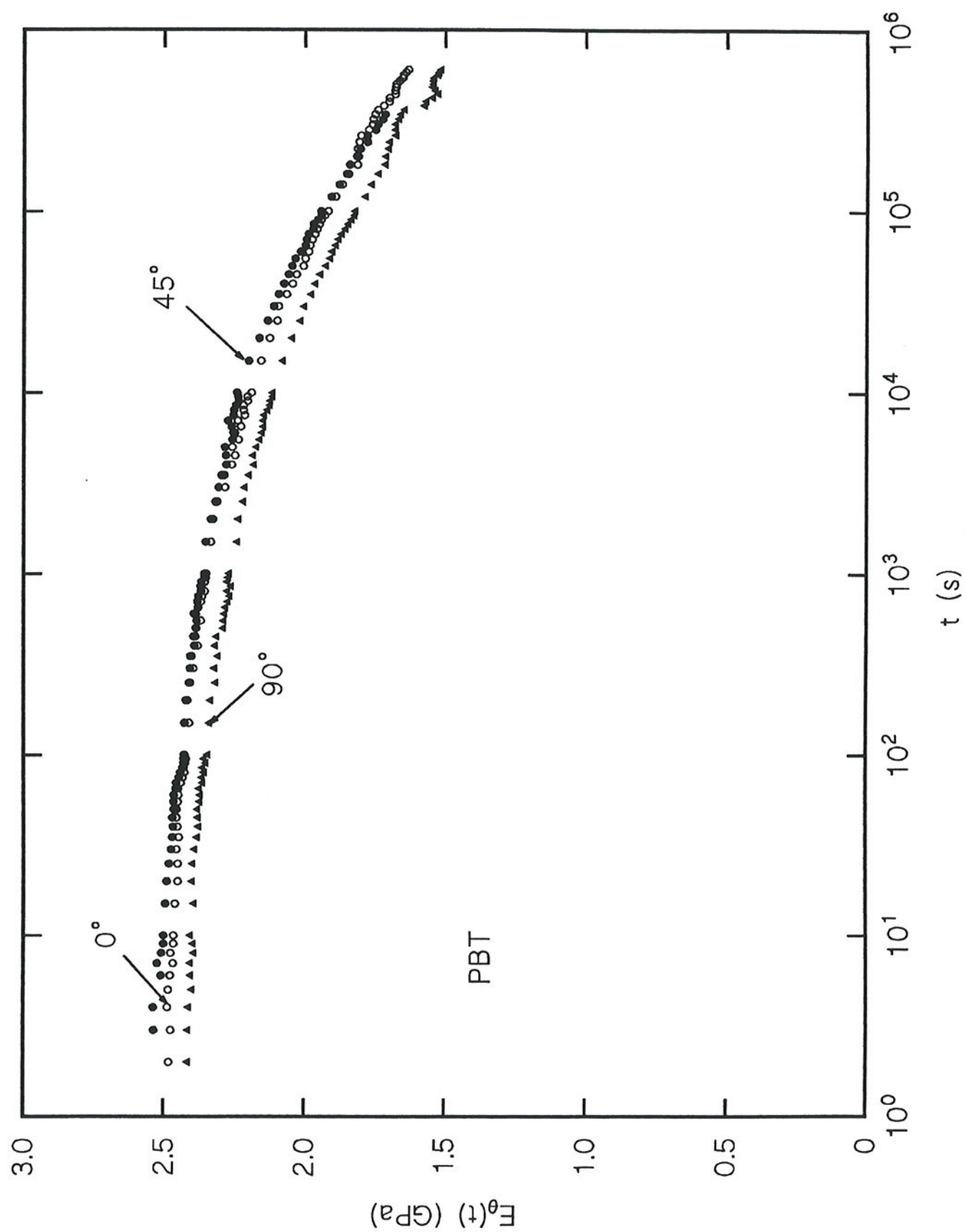


Fig. 5

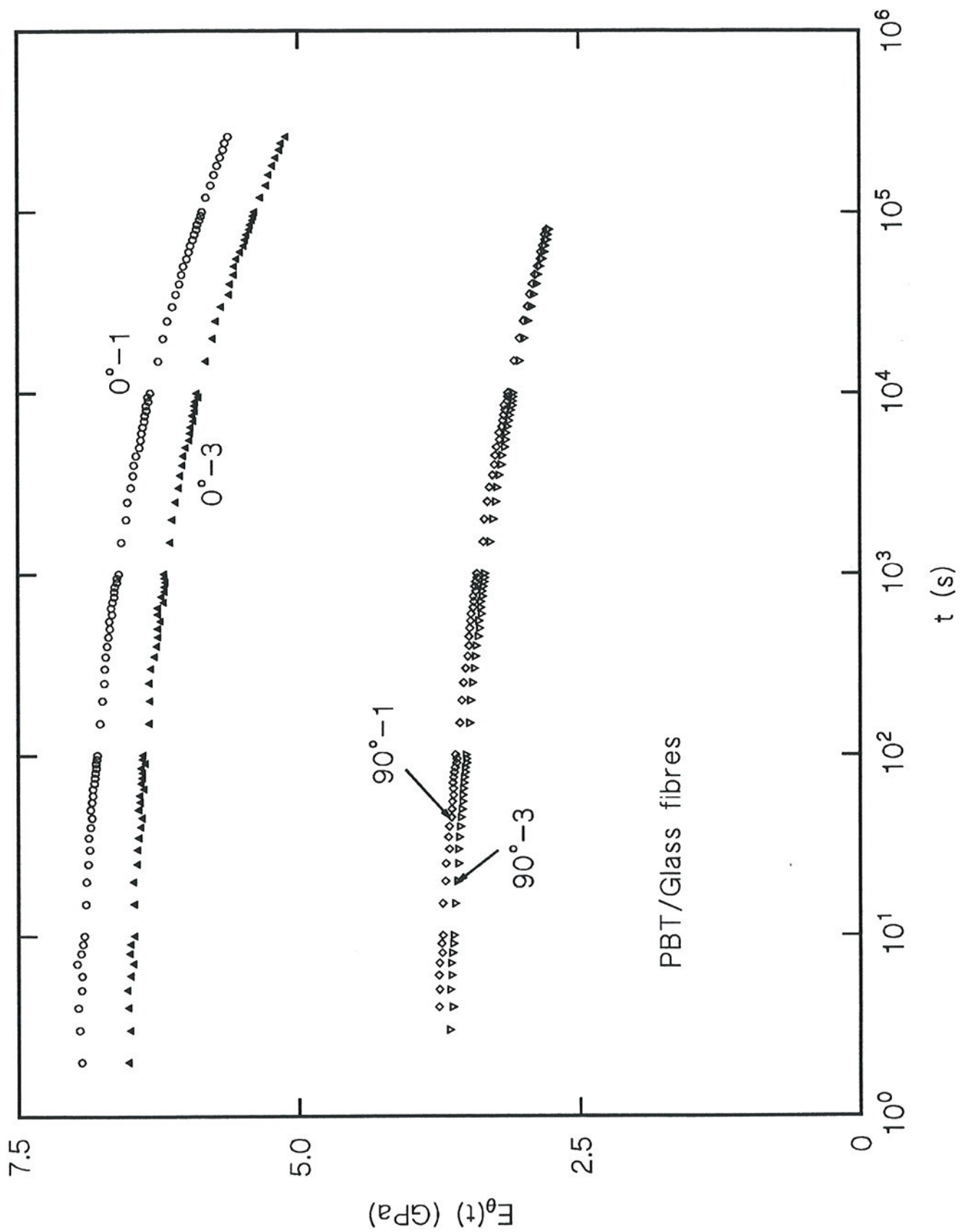


Fig. 6

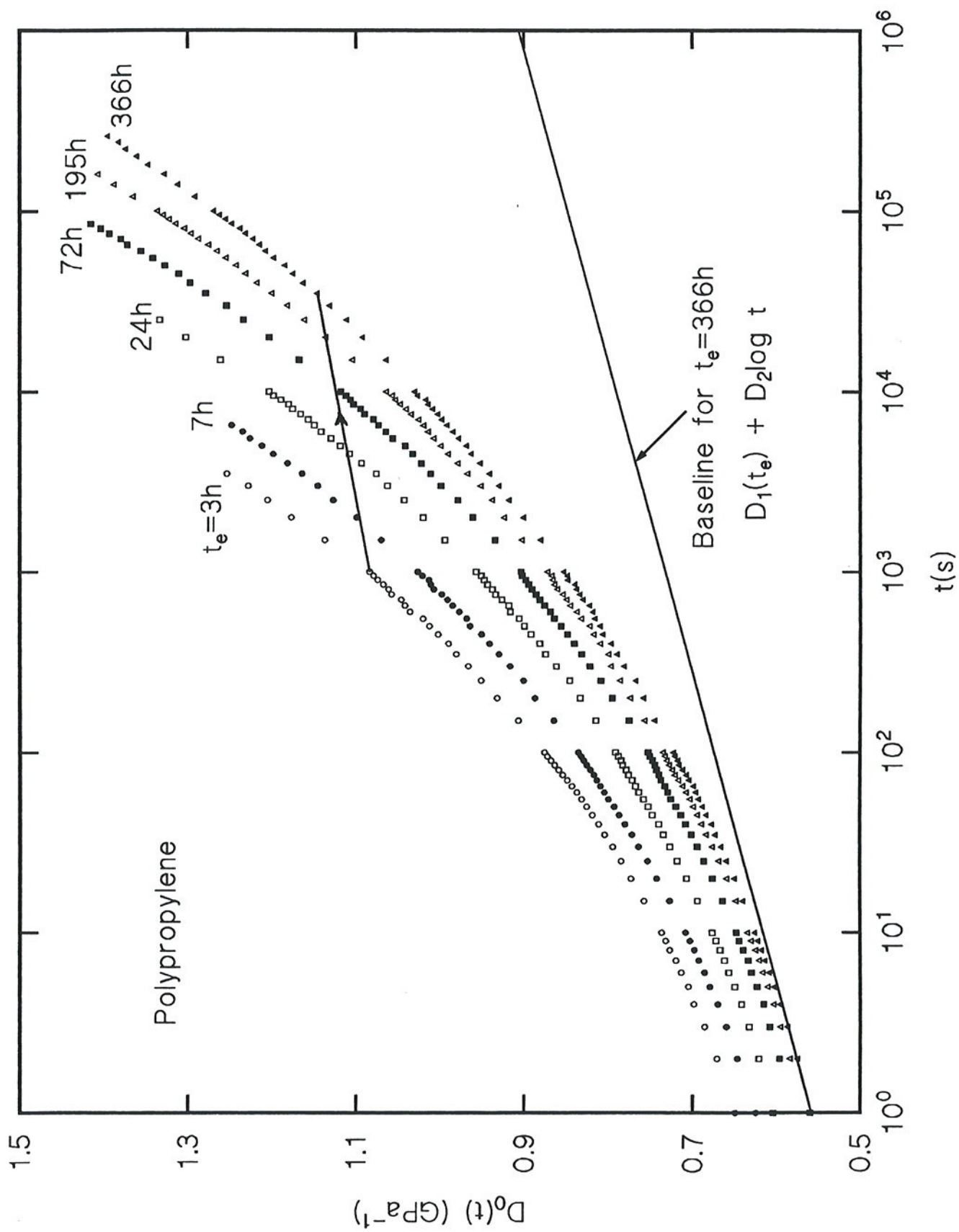


Fig. 7

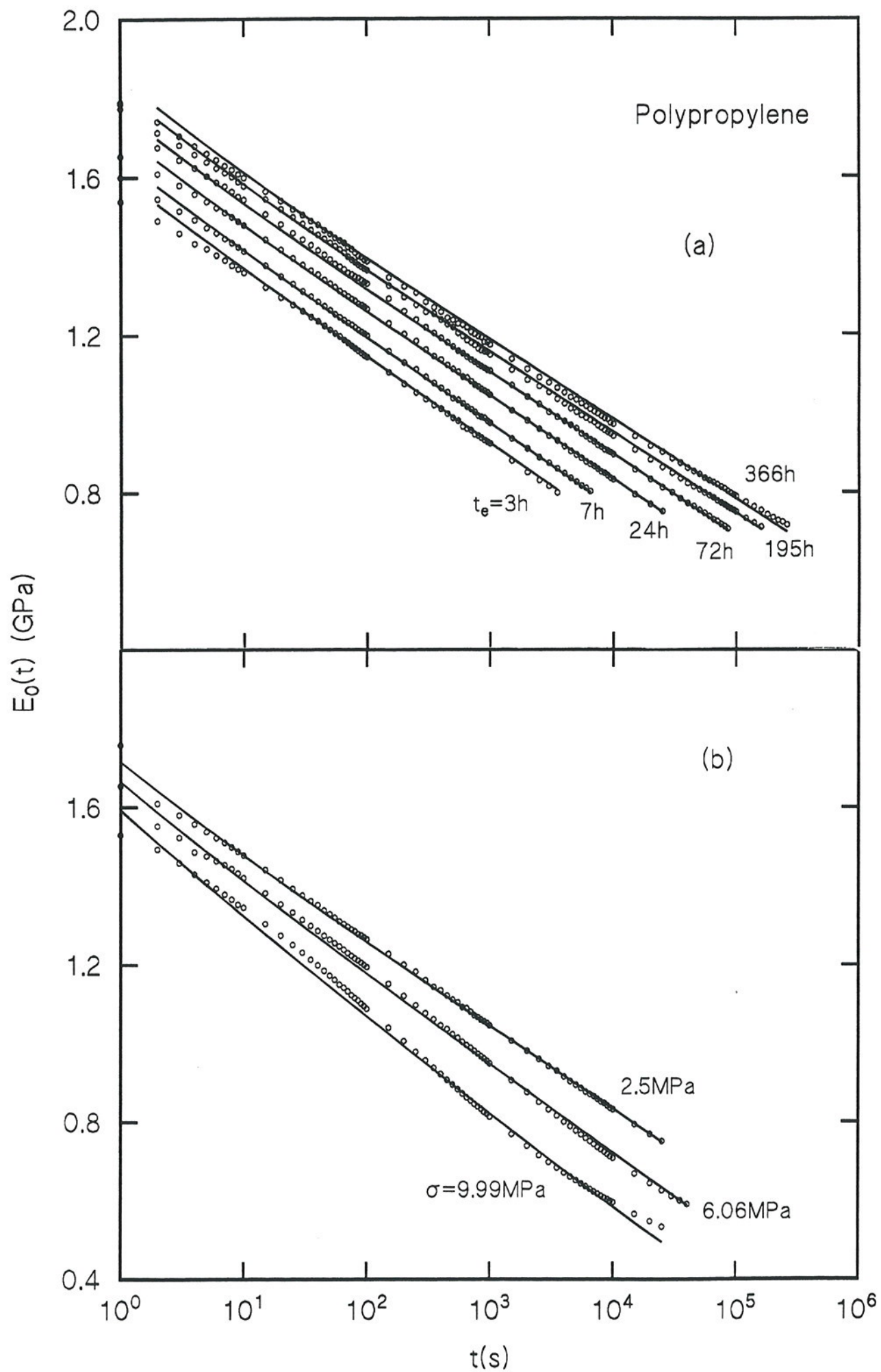


Fig. 8

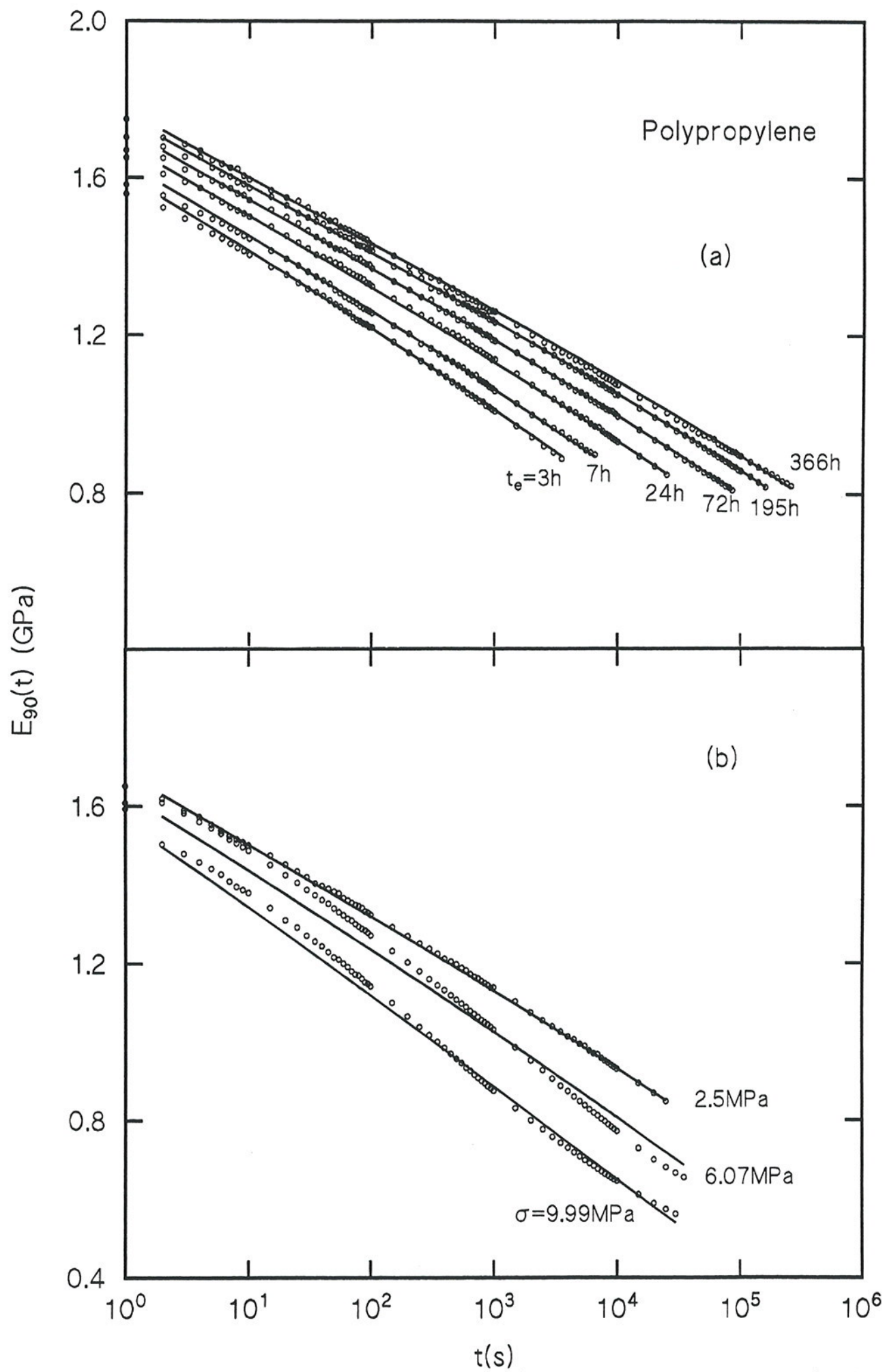


Fig. 9

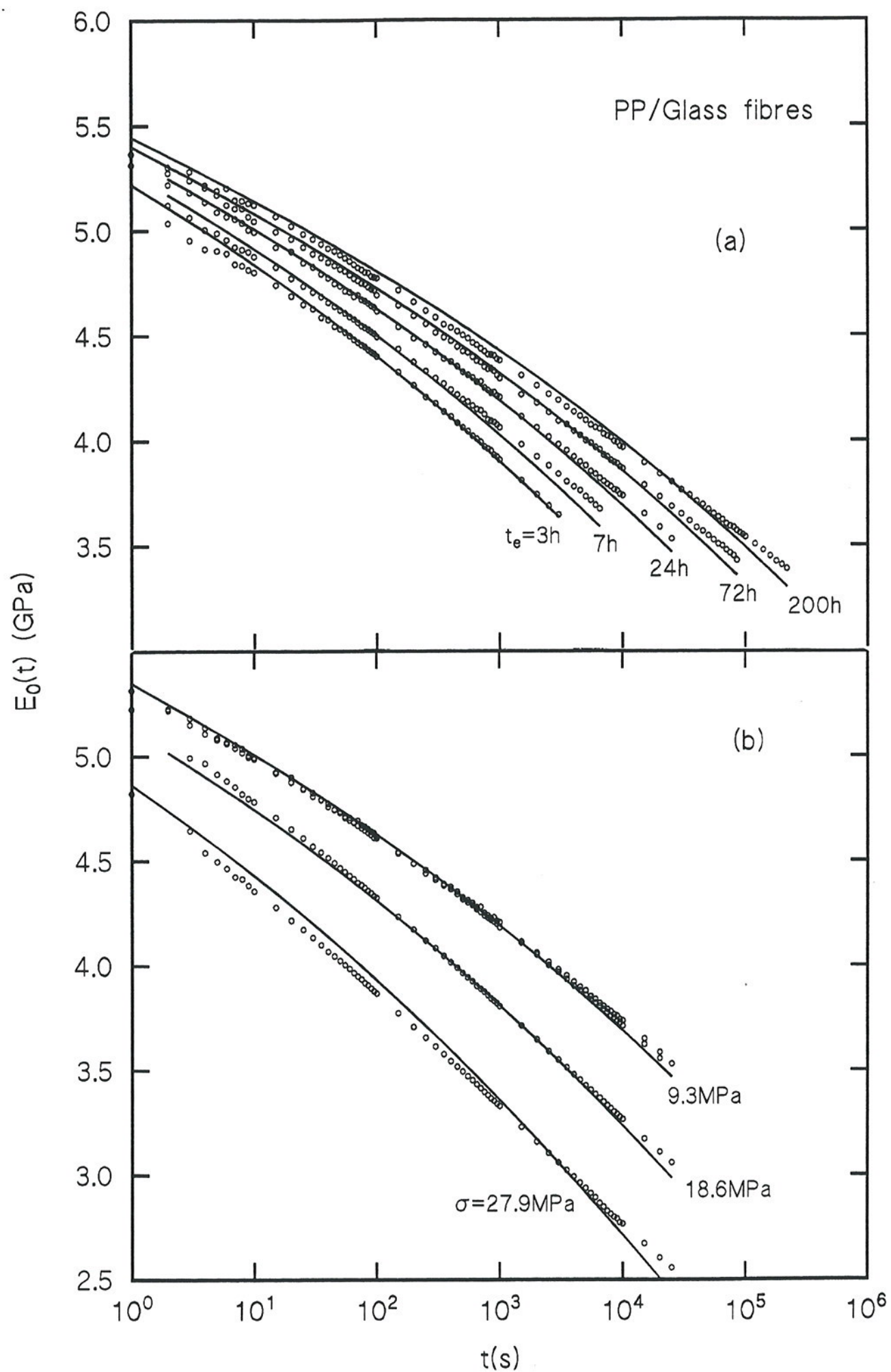


Fig. 10

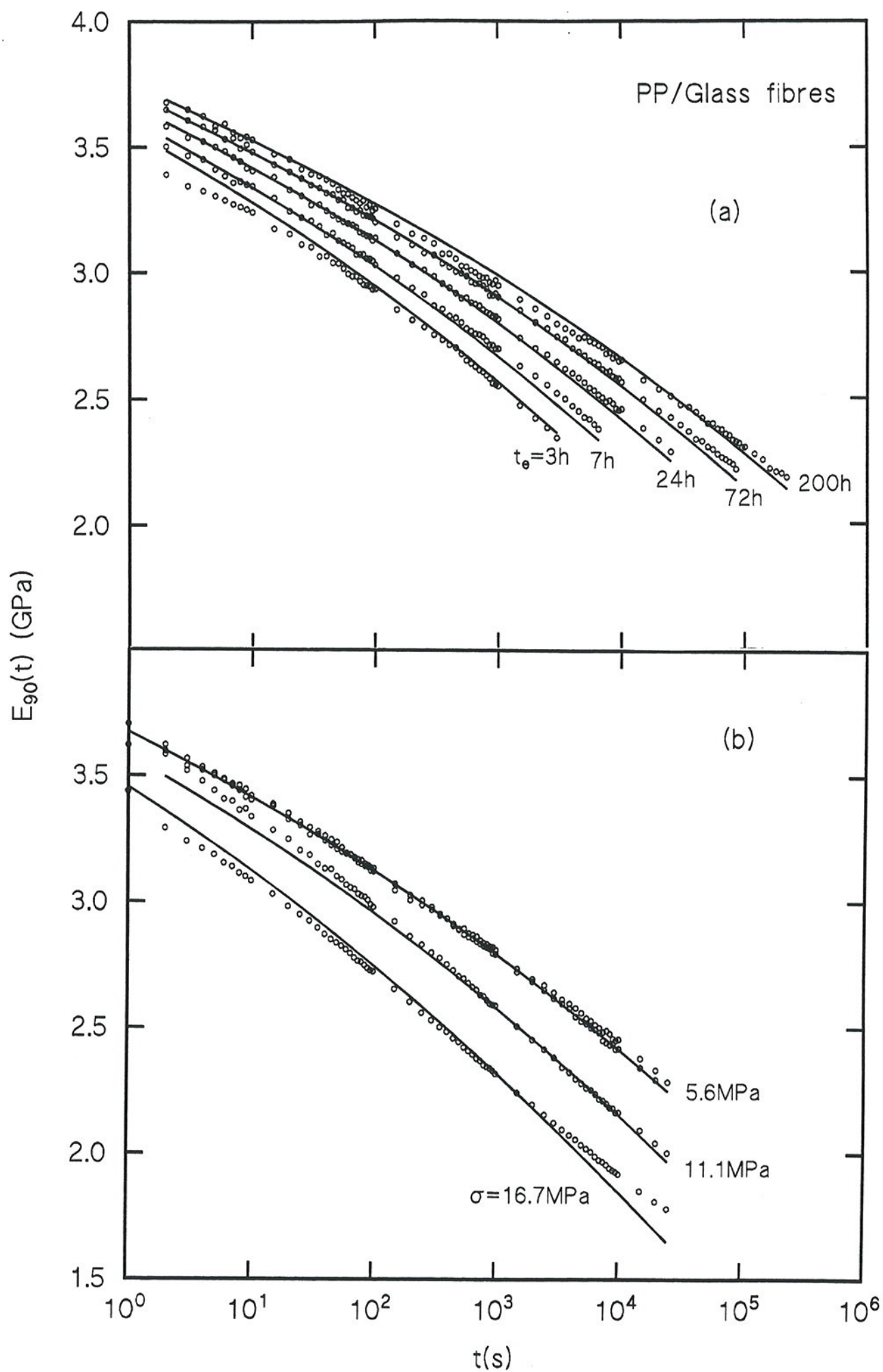


Fig. 11

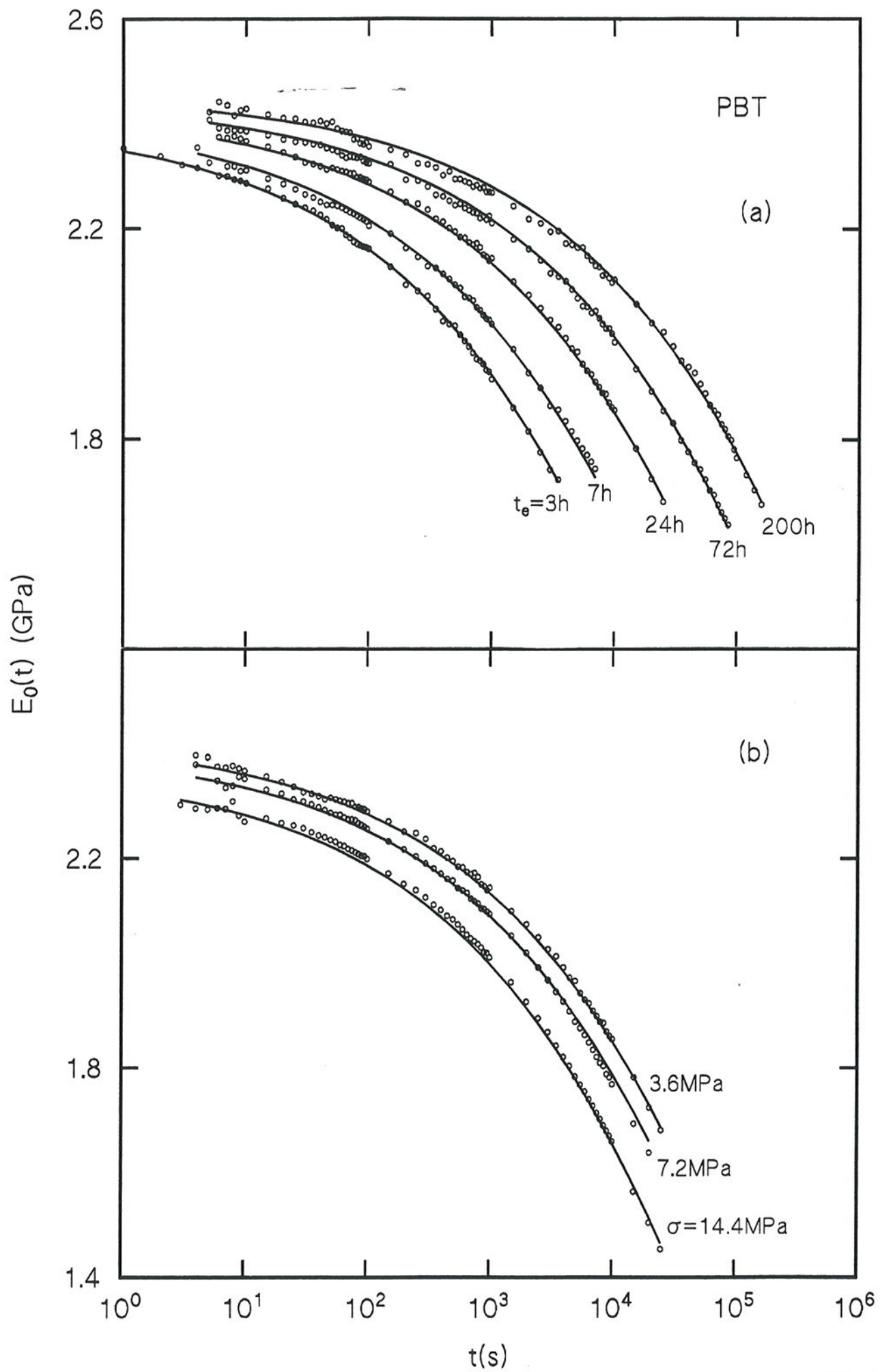


Fig. 12

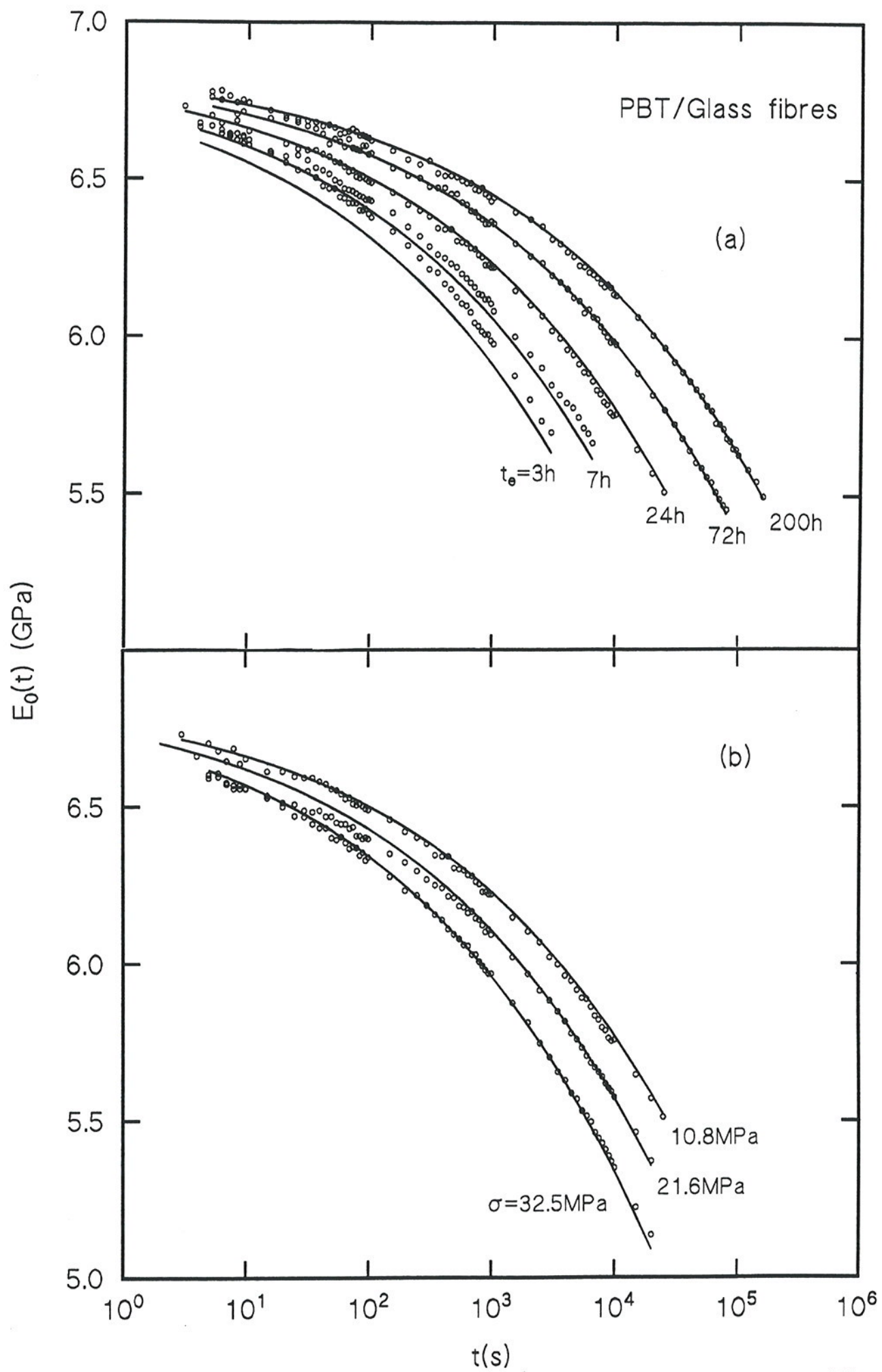


Fig. 13

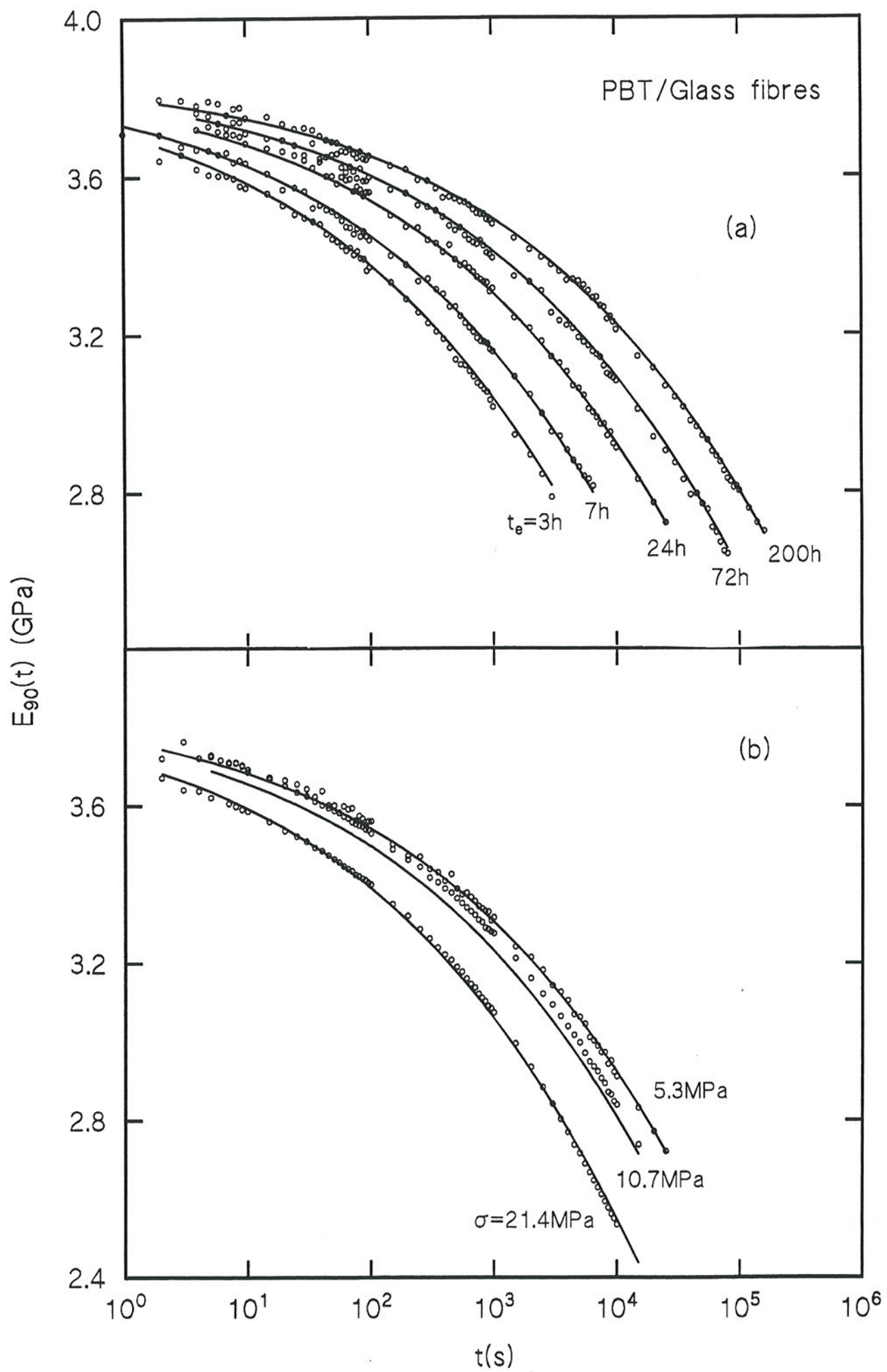


Fig. 14

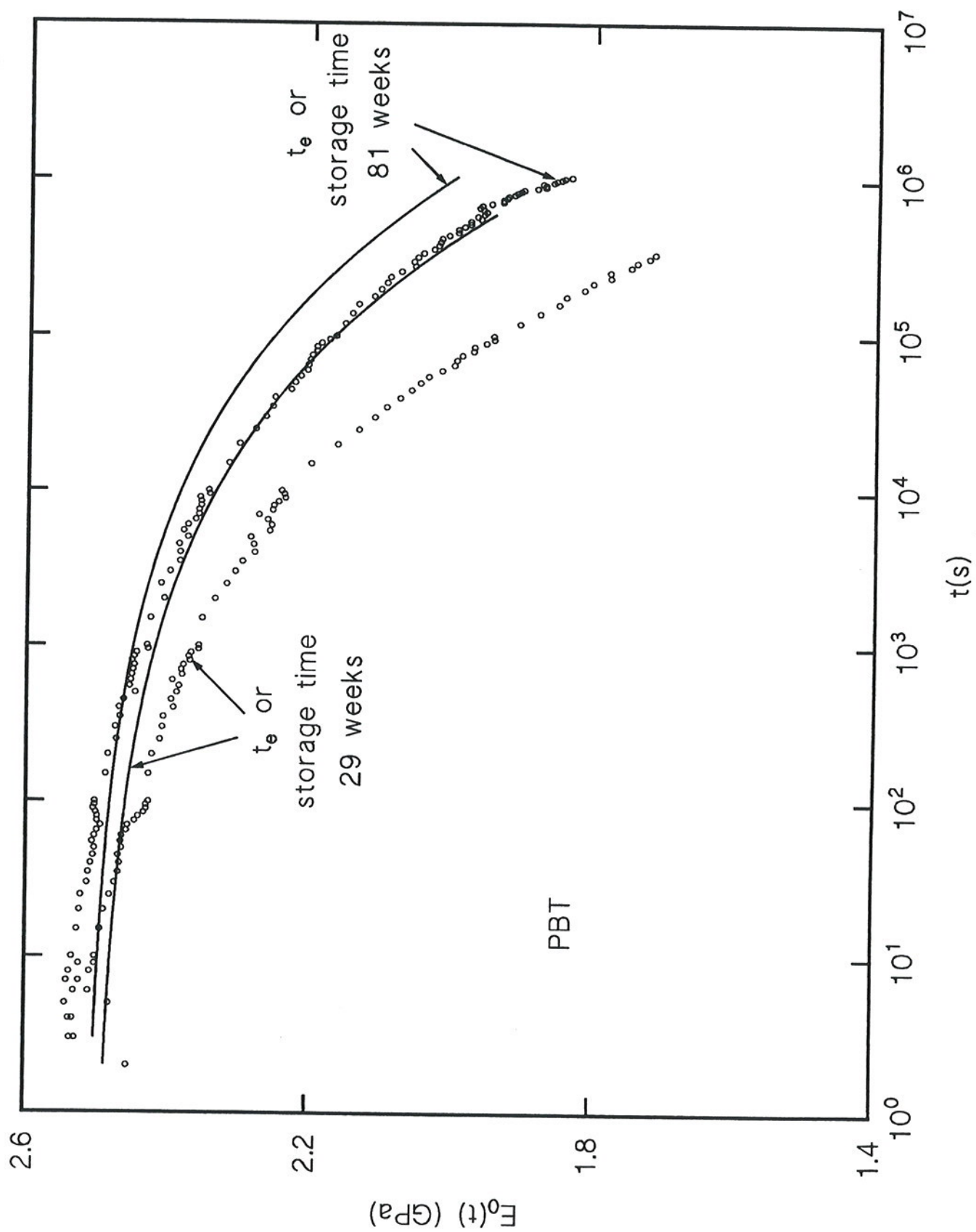


Fig. 15