

Creep and Physical Ageing of Injection Moulded, Fibre Reinforced Polypropylene

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ABSTRACT

Tensile creep data have been obtained at 23°C as a function of physical age from testpieces of glass fibre reinforced polypropylene cut from injection moulded square plaques in directions parallel and transverse to the flow direction. Smaller compliances were measured for loading parallel to the flow than for loading in the perpendicular direction, reflecting the preferential alignment of the fibres with the flow. Two creep functions have been used to model the creep behaviour over both a limited timescale where the age of the testpiece remains effectively constant and a wider timescale where significant further ageing of the material occurs. The results of these analyses reveal significant differences between modelling injection moulded polypropylene and compression moulded material.

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CONTENTS

1	INTRODUCTION	1
2	BRIEF SURVEY OF ANALYSIS METHODS	1
2.1	ANALYSIS OF SHORT-TERM DATA	2
2.2	ANALYSIS OF LONG-TERM DATA	3
3	EXPERIMENTAL	4
4	RESULTS AND DISCUSSION	4
4.1	ANALYSIS OF CREEP DATA FROM SPECIMENS PARALLEL TO THE FLOW DIRECTION ..	5
4.1.1	<i>Analysis assuming a horizontal baseline</i>	5
4.1.2	<i>Analysis assuming an inclined baseline</i>	8
4.2	ANALYSIS OF CREEP DATA FROM SPECIMENS CUT PERPENDICULAR TO THE FLOW DIRECTION	10
5	CONCLUSIONS	10
	ACKNOWLEDGEMENTS	11
	REFERENCES	12
	FIGURE CAPTIONS	13

1 INTRODUCTION

A number of empirical functions are currently being developed to accommodate the influence of physical ageing on the creep rate of plastics^{1,2}, where physical ageing involves slow structural changes in both amorphous and semicrystalline polymers as a result of the material being quenched from the melt to form a solid which is not in structural equilibrium. This effect is seen as a progressive increase in density and a decrease in the rate of change of compliance with log time during creep tests of long duration.

The molecular origins of creep and physical ageing are not fully understood, although it has been suggested that for semicrystalline polymers, such as polypropylene at room temperature, changes in the mechanical properties are attributable to changes in the conformation of the tie molecules coupled with the motion of chains through the crystal lamellae^{3,4}. These molecular rearrangements manifest themselves in dynamic mechanical measurements as an α retardation process that can be characterized by a limiting compliance level at short times (D_0), a magnitude (ΔD_α), a mean retardation time (τ) and a parameter m which serves to define the width of the retardation time spectrum. This α retardation process is superimposed on a shorter β retardation associated with the glass-transition of the amorphous regions of the material.

Most previous studies of the effects of physical ageing on creep have been concerned with unreinforced materials using specimens cut from extruded or compression moulded sheets. These materials are typically of high molecular weight and are often essentially unoriented, or isotropic, owing to the small shear deformations produced in the melt during processing. By contrast, injection moulded plastics can have quite high degrees of local molecular or fibre orientation due to the high shear rates involved in the processing. Thus the resulting properties, including the creep behaviour, may exhibit a substantial anisotropy. Furthermore, the relatively low molecular weight grades of polymer employed in injection moulding could influence the degree of crystallinity and hence the shape of the creep curves through changes in the relative compliance contributions from overlapping relaxation processes.

In this paper we present an analysis of the influence of physical ageing on the short- and long-term tensile creep behaviour of injection moulded plates of glass-fibre reinforced polypropylene. The analysis includes a comparison of two commonly used functions for modelling physical ageing effects and forms part of a study of the range of applicability of such models.

An analysis of short-term creep data for unreinforced injection moulded polypropylene, and for other injection moulded plastics is described elsewhere².

2 BRIEF SURVEY OF ANALYSIS METHODS

Values for some of the parameters required by the empirical functions that are used to model

the influence of physical ageing on the creep behaviour of plastics can be obtained from tensile creep tests of limited duration. In these short-term tests the period of testing is kept below $0.3t_e$ where t_e is the period of elapsed time between quenching a sample from some elevated temperature T_α (at which the structure is at equilibrium with respect to the α - process) and the instant of load application. This procedure ensures that the age of the testpiece remains effectively constant during the test. A number of such tests can be performed on a given testpiece providing that enough time is allowed between successive loadings for the material to recover, which in practice needs to be at least $2t_e$. The parameters obtained from a short-term test series can be used to predict the creep behaviour over the limited timescale of $0.3t_e$ for elapsed times other than those for which data are available.

In long-term creep tests, loads are applied to testpieces for periods of time $>0.3t_e$ and hence the age of the sample progressively increases during the period of measurement. A consequence of this further ageing is that some of the parameters used in the functions which describe short-term creep become dependent on creep time as well as the initial age of the material. Having established appropriate time dependencies of these parameters creep behaviour can be predicted not only for material of different ages but also for creep times in excess of those for which data have been obtained.

2.1 ANALYSIS OF SHORT-TERM DATA

For several polymers the time dependent compliance $D(t)$ can be described over a limited timescale by

$$D(t) = D_0 \exp(t/\tau)^m \quad (1)$$

where D_0 is a limiting compliance at short times and τ is the mean retardation time of a spectrum of times characterised by the parameter m . The kernel of this function is consistent with the stress relaxation function $\exp(-t/\tau)^m$ proposed by Kohlrausch⁵ and extensively used by Struik and others^{6,7}.

An alternative function which has been successfully used to describe the creep of predominantly semicrystalline polymers⁴ is based on the Williams-Watts model for describing charge decay in dielectrics⁸ and is consistent with the creep recovery function $\exp - (t/\tau)^m$. This creep function is of the form

$$D(t) = D_0 + \Delta D_\alpha (1 - \exp-(t/\tau)^m) \quad (2)$$

The parameters D_0 , τ and m have a similar significance as in the Struik function (equation (1)) although it should be noted that the values of the parameters required to describe a given creep curve will be different. The quantity ΔD_α represents the magnitude of the relaxation process.

A value for this parameter can either be obtained by least-squares optimization of the function to a series of short-term creep curves or estimated from an analysis of dynamic mechanical data⁹. In (1) and (2) it is usually found that D_0 decreases slightly with increasing t_e whilst ΔD_α and m remain essentially constant and the predominant effect of ageing is through an increase in τ with t_e .

For many applications a simpler function can be derived from equation (2) based on the first term of the series expansion of the exponential term. This is written as a power law of the form

$$D(t) = D_0 + Kt^m \quad (3)$$

where $K = \Delta D_\alpha / \tau^m$. This representation of the power law is consistent with Findley's equation¹⁰ although the effects of physical ageing on the parameters in his original work were not explored.

2.2 ANALYSIS OF LONG-TERM DATA

The equations described in the previous section are only valid if there is no significant change in the effective age of a specimen during the test, if further ageing of the testpiece does occur as in a long-term test then one or more of the parameters will become time dependent. In general the decrease in creep rate which is attributable to further ageing during a long-term test can be modelled to a good approximation in terms of a progressive increase in τ . This can be achieved by replacing $(t/\tau)^m$ by the integral $(\int_0^t du/\tau(u))^m$ where u is a dummy time variable. It has been suggested¹¹ that $\tau(u)$ can be described by a hyperbolic function of the form

$$\tau(u) = (\tau^2 + C^2 u^{2\mu'})^{0.5} \quad (4)$$

where C and μ' are adjustable parameters. Substitution of the long-term integral into equations (1) and (3) gives

$$D(t) = D_0 \exp\left[\int_0^t \frac{du}{(\tau^2 + C^2 u^{2\mu'})^{0.5}}\right]^m \quad (5)$$

and

$$D(t) = D_0 + \Delta D_\alpha \left[\int_0^t \frac{du}{(\tau^2 + C^2 u^{2\mu'})^{0.5}}\right]^m \quad (6)$$

respectively.

3 EXPERIMENTAL

An injection moulding grade glass-fibre reinforced polypropylene (PC072/3NAT) containing 13.2 volume percent fibres was obtained from Himont (UK) Ltd. This material was injected into a coathanger-gated mould to produce square plaques of dimensions 150 × 150 × 2.66 mm, details of the mould and the conditions used have been described elsewhere^{12,13}. Rectangular testpieces of nominal dimensions 150 × 10 mm × the thickness of the plaque were cut parallel and perpendicular to the flow direction at the positions indicated in Figure 1.

The fibres were found from optical micrographs to have an average length/diameter ratio of ~39 and their distribution within the plaques was investigated using both optical microscopy and injection moulding simulation software (Moldflow). The results of these analyses showed the typical skin-core structure characteristic of injection mouldings. Although the mean fibre orientation was parallel to the direction of flow the alignment of the fibres varied from skin to core: fibres in the outer skins were aligned parallel with the flow direction and those in the core transverse to it^{12,13}.

Prior to creep testing the testpieces were heated to 100°C for a period of 30 minutes to erase any effects of previous thermal history. At the end of the annealing period the testpieces were quenched into water at 23±1°C and after a period of 3-5 minutes removed and dried. They were then mounted in tensile creep rigs which have been described elsewhere^{4,14} and stored at the test temperature (23±0.2°C) for various periods of time, t_e .

Tensile stresses of 9.3MPa and 5.6MPa were applied to specimens cut parallel and perpendicular to the flow direction respectively. This resulted in measured strains spanning the range 0.15 - 0.28% and ensured that the creep behaviour was essentially linear. Single specimens which remained mounted within the test rig were used to obtain short-term creep data at different t_e to minimize any variability due to material variations or sample misalignment. The long-term tests were conducted wherever possible on these same testpieces after a period of heating to 100°C to erase the influence of previous thermal history. The repeatability of the creep tests was typically within 2%.

4 RESULTS AND DISCUSSION

Figure 2 shows creep data obtained from a series of short-term tests from testpieces cut from injection moulded plaques both parallel and perpendicular to the flow direction. From this figure it is evident that at comparable ages a testpiece where the mean fibre orientation is perpendicular to the applied force creeps significantly more than one where the mean fibre orientation is aligned with it, despite it being subjected to a lower stress.

4.1 ANALYSIS OF CREEP DATA FROM SPECIMENS CUT PARALLEL TO THE FLOW DIRECTION

As mentioned in the Introduction, creep in polypropylene for times in excess of 1s is thought to be due to an α relaxation process, superimposed on the shorter- time, glass-rubber β process. Determinations of creep compliance over a very wide time range for unreinforced, compression moulded polypropylene revealed a substantial merging of the β and α processes⁴. Modelling of the β process in terms of a symmetrical Cole-Cole function further indicated that the compliance contribution from the β process reached an asymptotic limit at short creep times (~ 100 s)⁴. However, based on experimental evidence for wholly amorphous polymers Struik¹⁵ suggested that the compliance contribution for the glass-rubber β process may continue to increase linearly with $\log t$ in the long time region and to effectively produce an inclined baseline to the α -compliance contribution. This suggestion was consistent with the shape of the creep curves for compression moulded polypropylene at temperatures above about 50°C. For injection-moulded polypropylene there is evidence to suggest that this overlap effect could be significant at room temperature (see Ref. 16 and Section 4.1.2 below).

The analysis of data described in section 4.1.1 below assumes that the β relaxation is fully relaxed over the timescale of our creep measurements so that the β -compliance contribution (D_0) is constant and the creep may be described by equations (1) or (3) without modification. This is equivalent to assuming a horizontal baseline to the α -compliance contribution. In view of possible overlap effects from the β -process, we then present an analysis (Section 4.1.2) based on modifications to equations (1) and (3) that allow for a linear increase in the β -compliance contribution with $\log t$ (inclined baseline).

4.1.1 *Analysis assuming a horizontal baseline*

The short-term creep data have been modelled in terms of equations (1) and (3) using a least-squares optimization routine to derive values for the parameters. During the initial phase of fitting the functions to the data, all the parameters were allowed to vary. Figure 3 shows a comparison of the fits of the equations with short-term test data covering a range of elapsed times from 3 - 200h. From this figure it is apparent that both functions are able to accurately describe the data.

As both m and D_0 showed a tendency to decrease with increasing elapsed time the data were analysed using mathematical descriptions of the elapsed time dependence of these parameters (Case 1) although the potential for simplifying the modelling by ignoring this apparent dependence was also explored and is described in Case 2.

Case 1: elapsed time dependent D_0 and m

The elapsed time dependence of the shape parameter m can be described by

$$m = m_0 t_e^{-\epsilon}$$

for both the Struik and power law functions⁴, where m_0 is the value of m at an elapsed time of 1s and ϵ represents the rate at which it decreases with elapsed time. This reduction in m represents a slight broadening of the distribution of retardation times with increasing age of the material. The parameters used to calculate m for each elapsed time are given in Table 1.

A plot of $\log D_0$ versus $\log t_e$ was found to be linear and of slope k following the relationship

$$D_0 = B t_e^{-k}$$

where B is the value of D_0 at an elapsed time of 1s. Values for B and k are given in Table 1.

The elapsed time dependence of the mean retardation time, τ in equation (1) can be described by

$$\tau = A t_e^{\mu} \quad (9)$$

where μ is the rate of ageing ($d \log \tau / d \log t_e$) and A is the value of τ at $t_e = 1$ s (Table 1). This equation can also be used to determine the ageing rate from the parameter K in the power law, since according to equation (3) $K = \Delta D_a / \tau^m$, where m is given by equation (7) thus

$$K^{-\frac{1}{m}} = A' t_e^{\mu}$$

where $A' = A \Delta D_a^{-1/m}$. A plot of $-1/m \log K$ versus $\log t_e$ yields a slope of μ and an intercept A' (Table 1). The predicted short-term behaviour based on equations (1) or (3) incorporating both the elapsed time dependent D_0 and m are now written as

$$D(t) = B t_e^{-k} \cdot \exp\left(\frac{t}{A t_e^{\mu}}\right)^{(m_0 t_e^{-\epsilon})}$$

and

$$D(t) = B t_e^{-k} + \left[\frac{t}{(A' t_e^{\mu})}\right]^{(m_0 t_e^{-\epsilon})}$$

respectively and are compared with short-term data in Figure 4. As with figure 3 both functions are able to accurately describe the short-term data but values of μ differ markedly from values usually obtained for other grades of polypropylene (Table 1).

Figure 5 shows creep data obtained over a relatively long period of time (~ 3 weeks) where significant further ageing of the material occurs during the test period. These data can be modelled using equations (5) or (6) which can be written as

$$D(t) = B t_e^{-k} \exp\left[\int_0^t \frac{du}{(A^2 t_e^{2\mu} + C^2 u^{2\mu'})^{0.5}}\right]^{(m_0 t_e^{-\epsilon})} \quad (13)$$

and

$$D(t) = B t_e^{-k} + \left[\int_0^t \frac{du}{(A'^2 t_e^{2\mu} + C'^2 u^{2\mu'})^{0.5}}\right]^{(m_0 t_e^{-\epsilon})} \quad (14)$$

to include the elapsed time dependence of τ , m and D_0 (equations (7), (8) and (9), noting that $C' = C \Delta D_a^{-1/m}$). For simplicity the short-term ageing rate μ was assumed to be equal to that (μ') in the long-term regions of the creep curves thus leaving only C or C' in the equations to be determined by least-squares optimization. The integrals were solved numerically during the optimization process using a commercial software package¹⁷.

Figure 5 shows a comparison of the calculated creep curves with experimental data for both the Struik equation and the power law. From this figure it is apparent that neither function is able to accurately describe the long-term creep of the material. Predicted curves based on the Struik equation tend to diverge at long times (low μ value) whereas the experimental curves converge over the same timescale. In contrast predicted curves based on a power law show pronounced downward curvature and cross-over at longer times, over-predicting the influence of further ageing during the test period arises from a very high apparent μ value calculated from short-term data. Attempts to improve the quality of the fits, (particularly those obtained with the power law function) by relaxing the assumption that $\mu = \mu'$ were generally unsuccessful.

Case 2: Constant D_0 and m

Given the unsatisfactory long-term behaviour of the functions containing elapsed time dependent parameters m and D_0 an alternative simpler approach was used to model the long-term data by assuming the parameters to be constant. The values of m chosen for each function, 0.10 for the Struik function and 0.15 for the power law, respectively, were based on average values obtained by fitting the equations to the short-term data. Plots of either $\log \tau$ or $-1/m \log K$ versus $\log t_e$ were found to be linear following equations (9) and (10) respectively, yielding the values of μ and A or A' listed in Table 2.

Figure 6 shows a comparison of short-term data with predictions based on the two functions using constant values for m and D_0 and calculated values for K and τ . Although both functions accurately describe the creep behaviour for short elapsed times there is a notable difference between the predictions and the data obtained at $t_e = 200h$. It should also be noted that m and μ values for both functions are significantly lower than previously reported values for other grades of (unreinforced) polypropylene^{2,18}.

Equations (5) and (6) with τ or K given by (9) or (10) respectively can be used without modification to describe long-term data as shown in Figure 7. Whilst there is a significant improvement in the quality of the fits to the data when compared with those obtained with a variable m and D_0 (figure 6) there is a tendency with both functions for the calculated curves to converge too rapidly at very long times. It should be noted that unlike the predictions based on Case 1 there is little difference in the behaviour of the two functions.

Analysis assuming an inclined baseline

Struik has extensively used superposition of short-term creep curves^{7,15} to derive values for the ageing rate μ . This involves a combination of vertical and horizontal shifts of curves obtained at different elapsed times on to a creep curve arbitrarily chosen as a reference. The procedure relies on the shape of the creep curves being constant and implies that m is independent of elapsed time. Figure 8 shows superposition of the short-term creep curves onto data obtained for an elapsed time of 24h and the shift directions required for the superposition are seen to be consistent with an inclined baseline of positive slope (see Fig. 8).

Equations (1) and (3) which describe short-term creep can be modified to accommodate an inclined baseline by substituting the constant D_0 by a function of the form $r + s \log(t)$ where s represents the slope and r is the limiting compliance at a creep time of 1s to give

$$D(t) = (r + s \log(t)) \exp(t/\tau)^m \quad (15)$$

$$D(t) = (r + s \log(t)) + Kt^m \quad (16)$$

respectively. It should be noted that whilst the value of s is common to both functions, r is not. The parameter s was obtained by plotting the vertical component of the shift required to superimpose short-term data obtained for different elapsed times onto a reference creep curve ($t_e = 24h$) against log time and found to be $6 \cdot 10^{-3}$ noting that this procedure assumes that r is constant. During the initial phase of fitting equations (15) and (16) to the data all the parameters

were allowed to vary despite the assumption being made in superimposing the creep curves that m is constant. The results of this analysis revealed a tendency for m to decrease with t_e despite superposition thus situations were explored where m was either allowed to depend on elapsed time (Case 1) or be a constant (Case 2).

In the analysis that follows we will mainly focus on the application of the Struik function noting that a similarity was again observed between the Struik and the power law functions in fitting the creep data, particularly in the short-term.

Case 1: elapsed time dependent r and m

Keeping s constant, initial values for the remaining variables in equation (15) were obtained by using a least-squares optimization routine. A plot of $\log m$ versus $\log t_e$ was found to be linear as was found in section 4.1.1 (equation (7)) where a horizontal baseline was assumed. The elapsed time dependence of the limiting compliance at short times, r can be described by

$$r = a_0 t_e^{-v} \quad (17)$$

where values for the parameters a_0 and v were obtained from a plot of $\log r$ versus $\log t_e$ (Table 3).

Very good fits to the short-term data were obtained using equation (15) with m and r calculated according to equations (7) and (17) respectively although the value of μ was significantly larger than has been previously found for polypropylene^{2,15} (Table 3). The long-term data was modelled using a revised form of equation (13) where the term $B t_e^{-k}$ was replaced by $(a_0 t_e^{-v} + s \log(t))$. Assuming that $\mu = \mu'$, the only variable in the modified form of equation (11) is C , which can be estimated by fitting this equation to the data using a least-squares optimization routine. Figure 9 shows a comparison of the 'best fit' with the data. From the figure it is apparent that the function overestimates the influence of physical ageing on the creep rate at creep times in excess of $10^{4.5}$ s. The resultant curvature in the predicted creep curve is due to the high value of μ used in the calculation. Attempts were made to improve the quality of the fit by reducing the size of μ' , the parameter controlling the ageing rate at long times, but these were unsuccessful.

Case 2: Constant r and m

Figure 10 shows a comparison of short-term creep data with predictions based on equations (15) and (16) with τ and K calculated according to equations (9) and (10). From this figure it is apparent that there is very little difference between the two functions over this limited timescale although it should be noted that the quality of the fits tends to decrease with increasing elapsed time. The values of μ and m although higher than those obtained for the inclined baseline are

now consistent with those typically found in the literature for other processing routes and grades of polypropylene^{2,15}.

Figure 11 shows fits of both the Struik and power law functions to long-term data. These fits were obtained by solving equations (13) and (14) for C and C' (Table 4) respectively after substitution of $(r + s \log(t))$ for the term $B t_e^{-k}$. It is apparent from figure 11 that there is very little to choose between the two functions over the timescale of the calculation. Furthermore the fit obtained for this set of conditions appears to be better than that shown in figure 7 where m and D_0 are independent of elapsed time and a level baseline is assumed.

4.2 ANALYSIS OF CREEP DATA FROM SPECIMENS CUT PERPENDICULAR TO THE FLOW DIRECTION

The creep data obtained from testpieces cut perpendicular to the flow direction were analysed following the procedures described in section 4.1 except that the analysis was confined to the Struik function due to the close similarities between it and the power law.

The parameters obtained for each of the conditions described in the analysis of data obtained from testpieces cut parallel to the flow direction are given in Tables 1 - 4 with the exception of the combination of an inclined baseline with an elapsed time dependent s and m which was not investigated.

As with the data obtained from testpieces cut parallel to the flow direction the most successful fit to long-term data was obtained assuming an inclined baseline with constant values of s and m (equation (15)) as shown in figure 12.

Thus the effects of overlap observed for unreinforced, compression moulded polypropylene at temperatures above 50°C are evident for the reinforced injection moulded material at room temperature. Similar effects have been observed for an unreinforced injection moulded polypropylene², which could be due to the lower molecular weight grades of polymer used in injection moulding. This could enhance the crystallinity or crystal lamellar thickness and reduce the relative compliance contribution from the α -process. In this context note that, in contrast to the results of Struik¹⁶, the short-time compliance levels for the unreinforced injection moulded material² were lower than those obtained for a compression moulded grade⁴.

5 CONCLUSIONS

Creep data obtained for specimens of glass-fibre reinforced polypropylene cut from injection moulded square plates exhibit a substantial anisotropy. The compliance values are smaller for loading parallel to the flow (along which fibres are, on average, preferentially oriented) than for loading in the perpendicular direction.

The Struik stretched exponential function (equation (1)) and a power law function (equation (3)) each provide a good description of short-term ($t \leq 0.3t_e$) creep compliance curves in the α -relaxation region. However, best fits to the data require values for the distribution parameter m that decrease with age t_e and values for the ageing rate $\mu = d \log \tau / d \log t_e$ that differ considerably from typical values reported for compression moulded grades of polypropylene at room temperature. Also the derived μ values do not provide acceptable fits to the long-term data.

The best overall description of both short- and long-term data (giving parameters consistent with those obtained for other grades of polypropylene) is obtained by fixing the values of m and D_0 and using modified forms of the creep functions which allow for a positive inclination of the baseline to the α -creep compliance curves. This is consistent with the directions of shift required to superpose the curves obtained for different t_e .

The successful use of an inclined baseline is ascribed to the effects of overlap of the short-time, glass-rubber (β) relaxation. Such effects could be larger for injection moulded grades of polymer owing to their relatively low molecular weights and consequent higher degrees of crystallinity which would serve to reduce the relative compliance contribution from the α -process.

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FIGURE CAPTIONS

Schematic diagrams of the injection moulded coathanger gated plaques showing the location of the testpieces. The arrows indicate the direction of flow.

The elapsed time dependence of short-term tensile creep curves at 23°C for testpieces cut parallel (○) and perpendicular to the flow direction (●). The stresses applied were 9.3 and 5.6MPa respectively.

A: Fits of the Struik function (equation (1)) (—) to short-term creep curves measured at different elapsed times for a testpiece cut parallel to the flow direction.

B: A comparison of the Struik (—) and power law functions (equation (3) (-----)). These calculations use optimum values for the parameters and assume a horizontal baseline.

Fig.4 A: Fits of the Struik function (equation (11)) (—) to short-term creep curves measured at different elapsed times for a testpiece cut parallel to the flow direction.

B: A comparison of the Struik (—) and power law functions (equation (12) (-----)). Values for the parameters required by these equations which assume a horizontal baseline and an elapsed time dependence for m and D_0 are given in Table 1.

A: Fits of the Struik function (equation (13)) (—) to long-term creep curves measured at different elapsed times for testpieces cut parallel to the flow direction.

B: A comparison of the Struik (—) and power law functions (equation (14) (-----)). Values for the parameters required by these equations are given in Table 1. The calculations assume a level baseline and use the elapsed time dependent values of τ , m and D_0 determined from short-term data.

A: Fits of the Struik function (equation (1)) (—) to short-term creep curves measured at different elapsed times for testpieces cut parallel to the flow direction using the parameters listed in Table 2.

B: A comparison of the Struik (—) and power law functions (equation (3) (-----)). Values for the parameters required by these equations are given in Table 2. The calculations assume a level baseline and that m and D_0 are constant.

A: Fits of the Struik function (equation (5)) (—) to long-term creep curves measured at different elapsed times for testpieces cut parallel to the flow direction using the parameters listed in Table 2.

B: A comparison of the Struik (—) and power law functions (equation (6) (-----)). Values for the parameters required by these equations are given in Table 2. The calculations assume a level baseline and that m and D_0 are constant.

- Fig.8 Short-term creep data obtained from a testpiece cut parallel to the flow direction can be superimposed onto an arbitrarily chosen reference set of data by applying a suitable combination of vertical and horizontal shifts. The vertical shift can be related to the slope of an inclined baseline.
- Fig.9 A fit of the Struik function to long-term data assuming an inclined baseline (as described in section 4.1.2, *case 1*) and elapsed time dependent values for m and r which were obtained using equations (7) and (17) respectively in conjunction with Table 3.
- Fig.10 A: Fits of the Struik function (equation (15)) (____) to short-term creep curves measured at different elapsed times for testpieces cut parallel to the flow direction using the parameters listed in Table 4.
 B: A comparison of the Struik (____) and power law functions (equation (16) (-----)). Values for the parameters required by these equations are given in Table 4. The calculations assume an inclined baseline and that m and D_0 are constant.
- Fig.11 A: Fits of the Struik functions to long-term data. These fits (Table 4) were obtained by solving equations (13) for C after substitution of $(r + s \log(t))$ for the term $B t_e^{-k}$.
 B: A comparison of the fits obtained using both the Struik (____) and power law (-----) functions to long-term data. The power law fits were obtained by solving equation (14) for C' (Table 4) respectively after substitution of $(r + s \log(t))$ for the term $B t_e^{-k}$.
- Fig.12 Fits of equation (15) using the parameters given in Table 4 to long-term data assuming an inclined baseline and elapsed time independent values for m and D_0 .

TABLES

Table 1: Case 1 -Variable m and D_0 with a level baseline

Orientation of testpiece with respect to flow direction	Function	m_0	ϵ	B (GPa ⁻¹)	k	A (s ^{1-μ})	A' (s ^{1-μ})	μ	C (s ^{1-μ})	C' (s ^{1-μ})	μ'
Parallel	Struik	0.297	0.10 2	0.21	0.034	1320	-	0.61	1000	-	0.61
	Power law	0.345	0.08 0	0.21	0.026	-	476	1.66	-	800	1.37
Perpendicular	Struik	0.527	0.14 2	0.42	0.060	8236	-	0.35	5519	-	0.39

Table 2: Case 2 - constant m and D_0 with a level baseline

Orientation of testpiece with respect to flow direction	Function	m	D_0 (GPa ⁻¹)	A (s ^{1-μ})	A' (s ^{1-μ})	μ	C (s ^{1-μ})	C' (s ^{1-μ})	μ'
Parallel	Struik	0.10	0.15	954	-	0.64	650	-	0.64
	Power law	0.15	0.16	-	1.88E7	0.64	-	95E6	0.64
Perpendicular	Struik	0.11	0.21	223	-	0.67	110	-	-

Table 3: Variable m and s with an inclined baseline

Orientation of testpiece with respect to flow direction	Function	m_0	ϵ	a_0 (GPa ⁻¹)	v	A (s ^{1-μ})	A' (s ^{1-μ})	μ	C (s ^{1-μ})	C' (s ^{1-μ})	μ'
Parallel	Struik	0.431	0.095	0.213	0.018	35.0	-	1.19	14	-	1.19

Table 4: Constant m and r with an inclined baseline

Orientation of testpiece with respect to flow direction	Function	m	r (GPa ⁻¹)	s	A (s ^{1-μ})	A' (s ^{1-μ})	μ	C (s ^{1-μ})	C' (s ^{1-μ})	μ'
Parallel	Struik	0.16	0.174	0.006	806	-	0.86	800	-	0.86
	Power law	0.22	0.179	0.006	-	2043 00	0.81	-	20000 0	0.81
Perpendicular	Struik	0.16	0.250	0.009	234	-	0.88	160	-	0.88

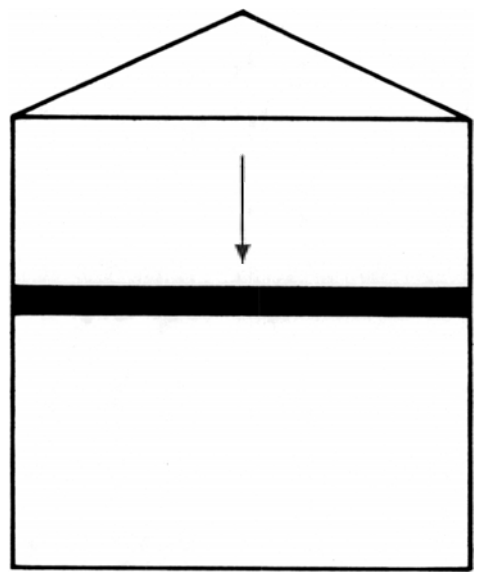
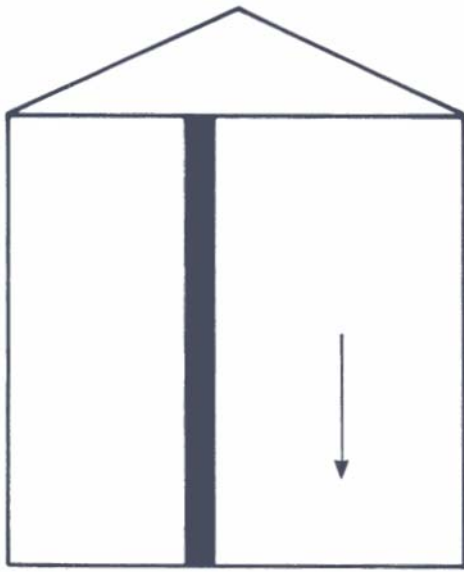


Fig. 1

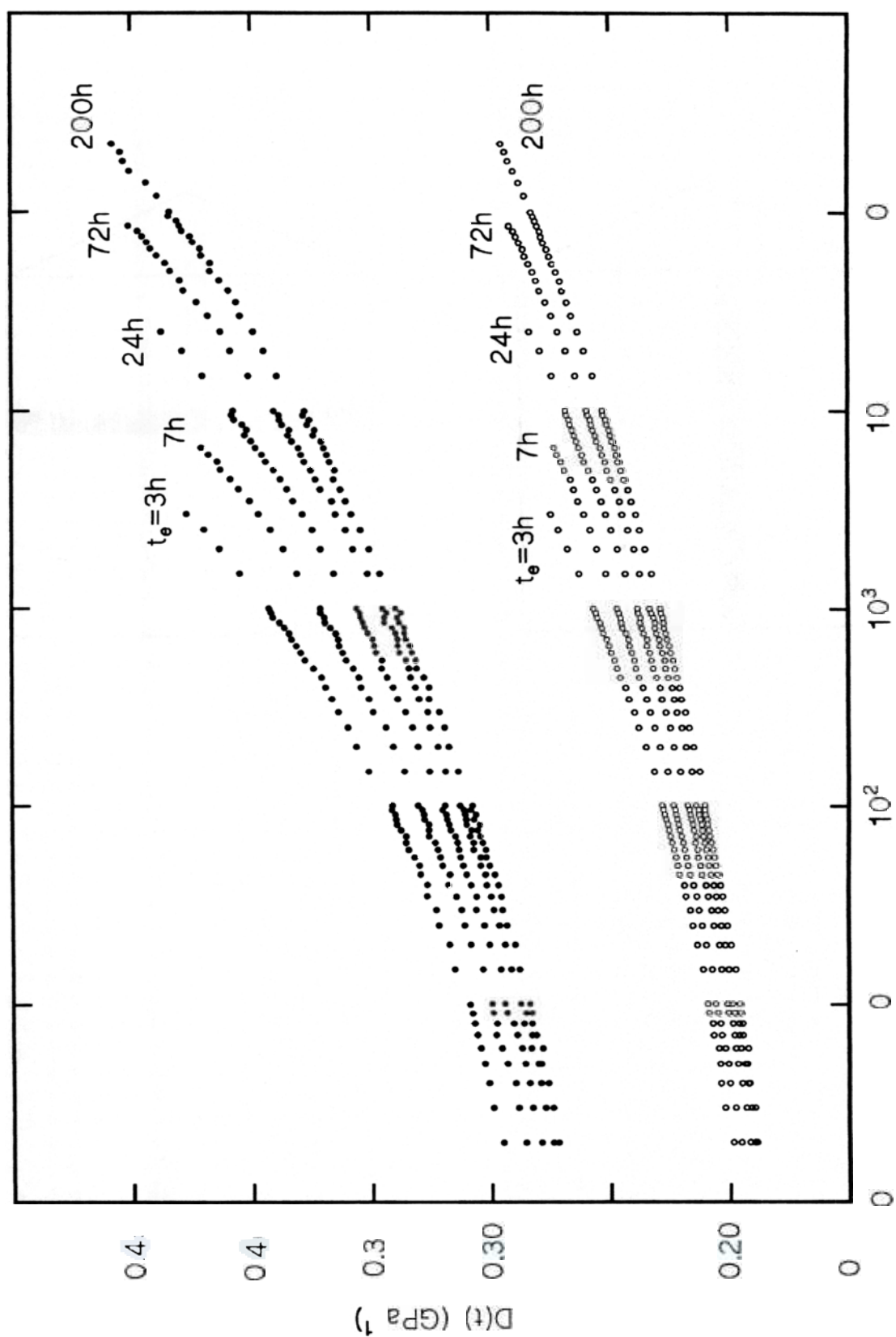


Fig. 2

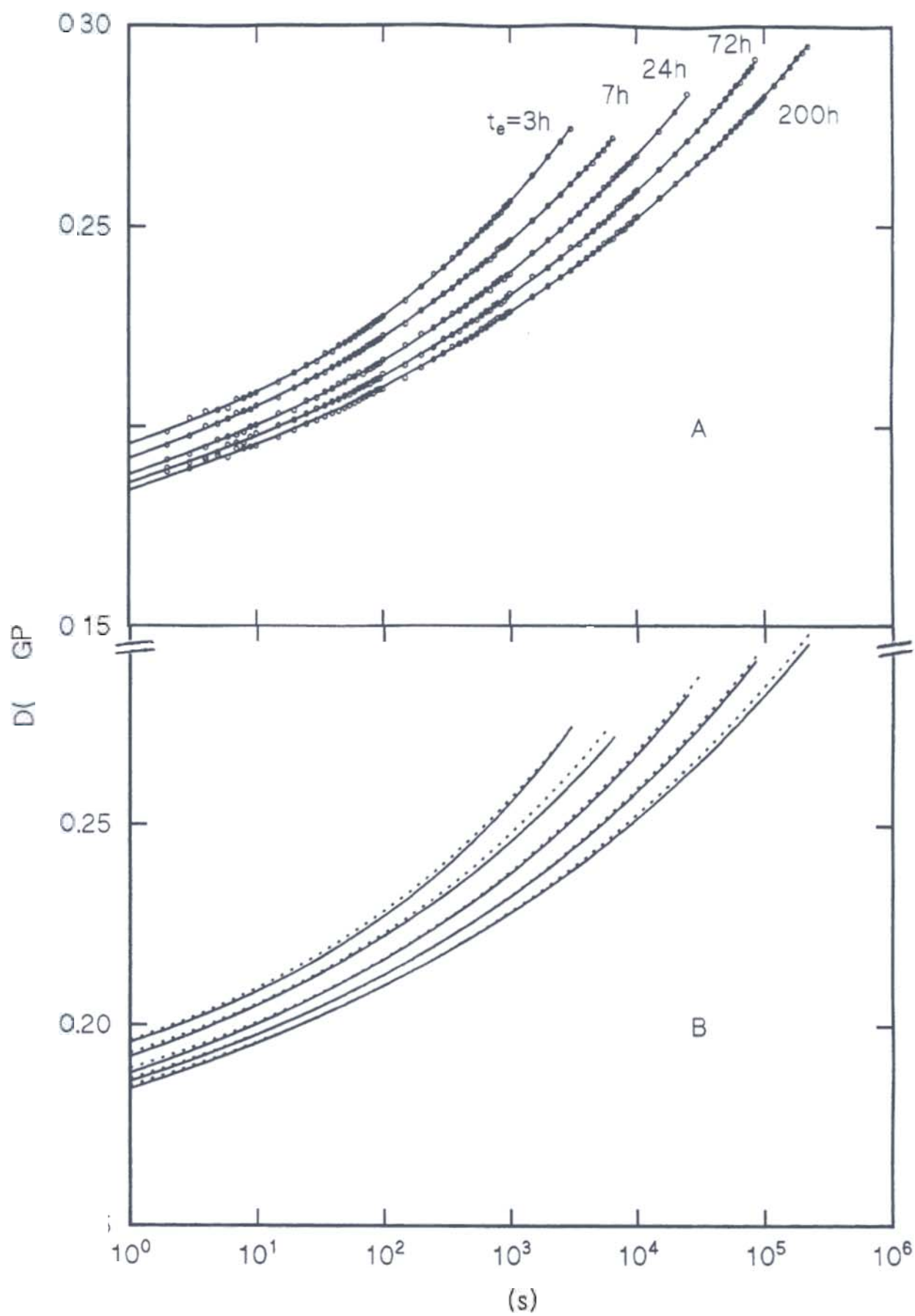


Fig. 3

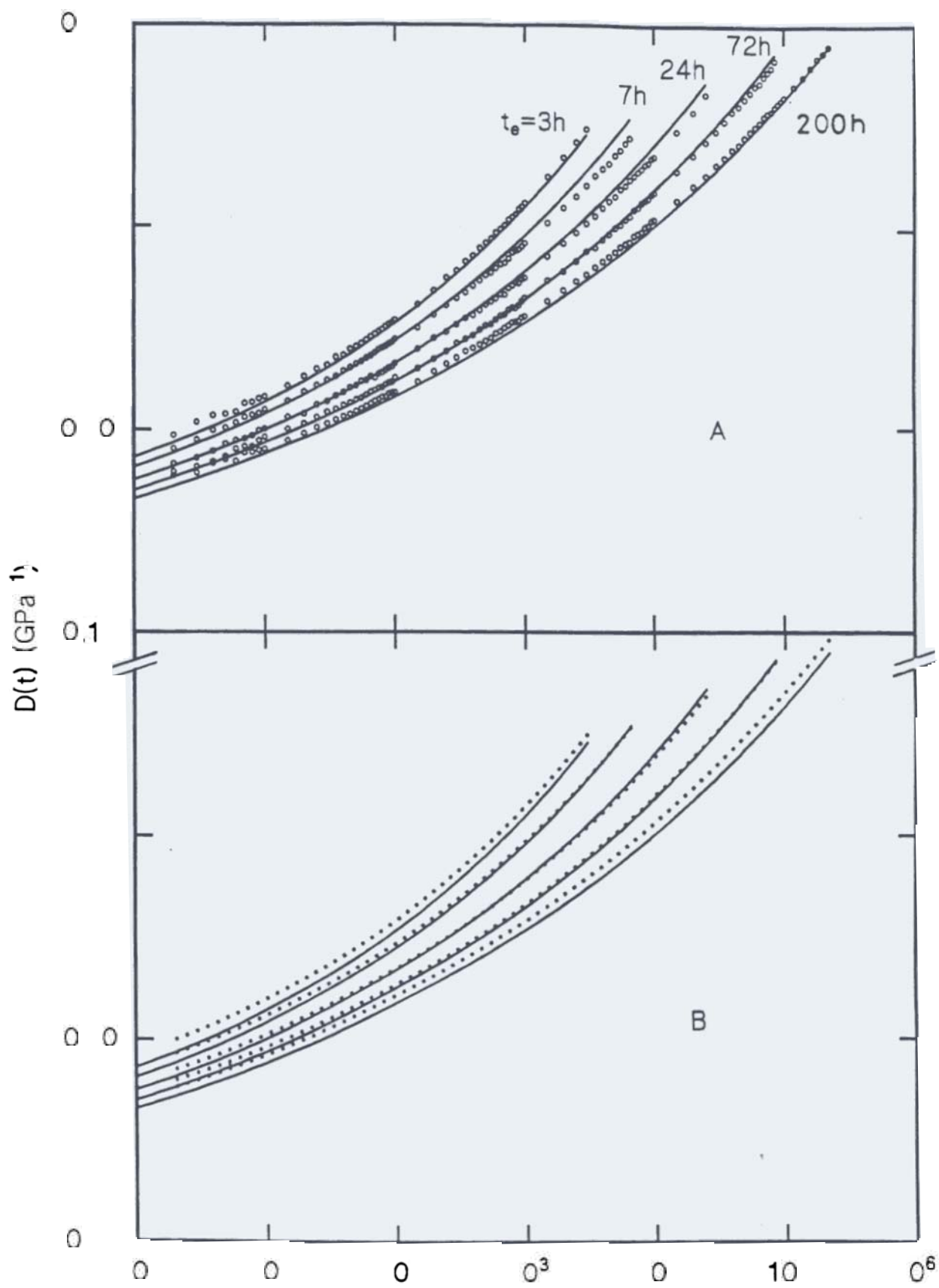


Fig 4

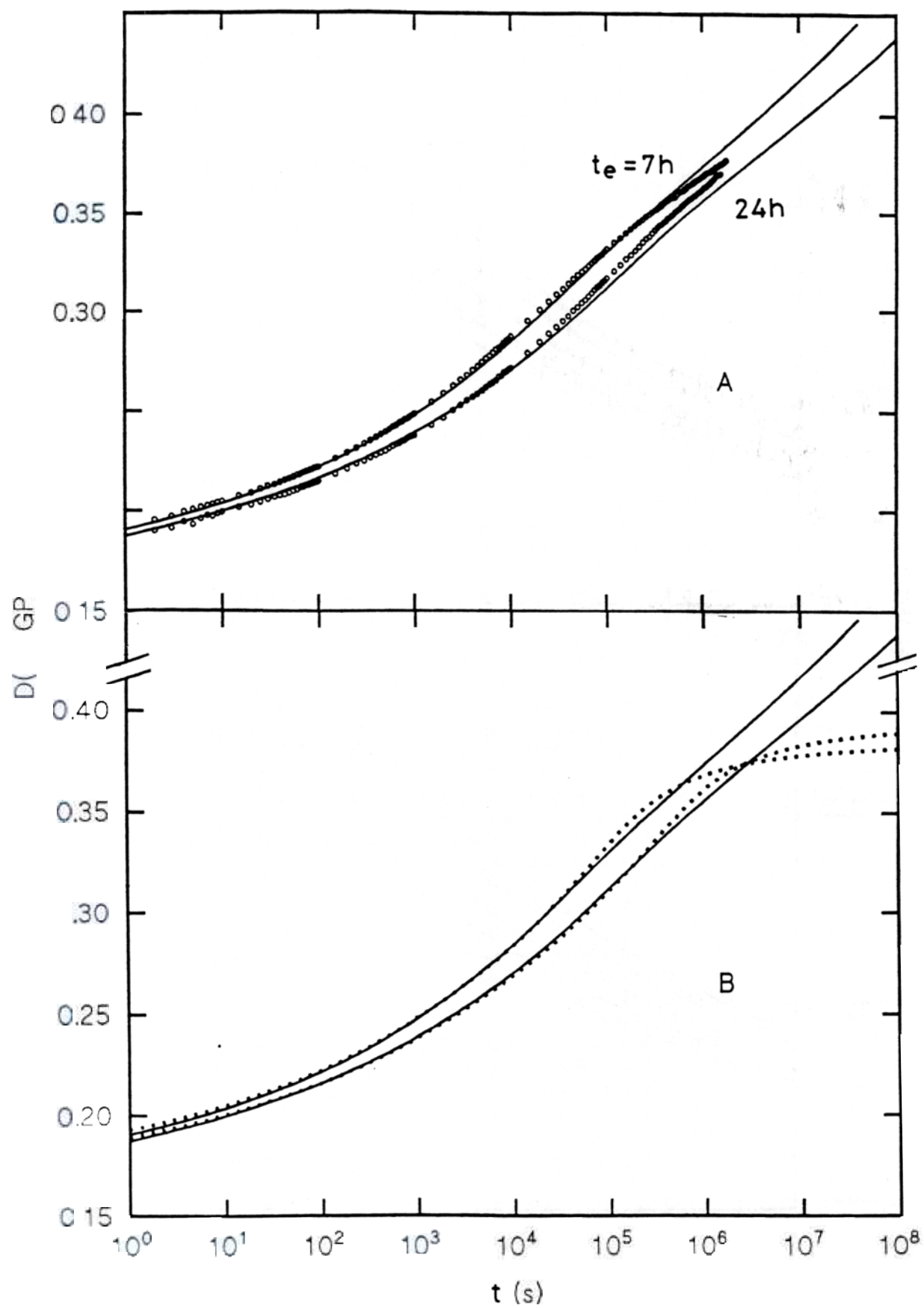


Fig 5

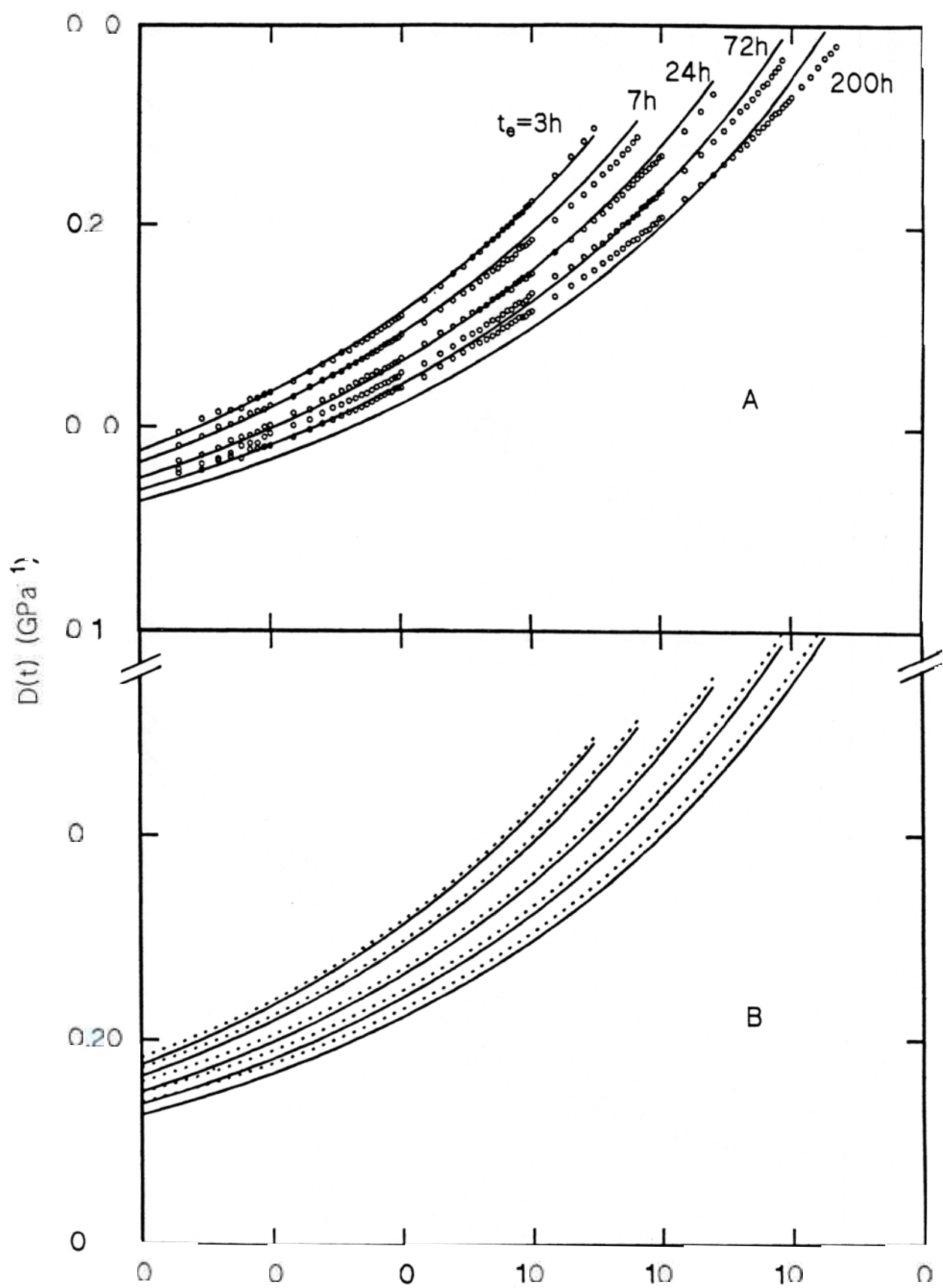


Fig 6

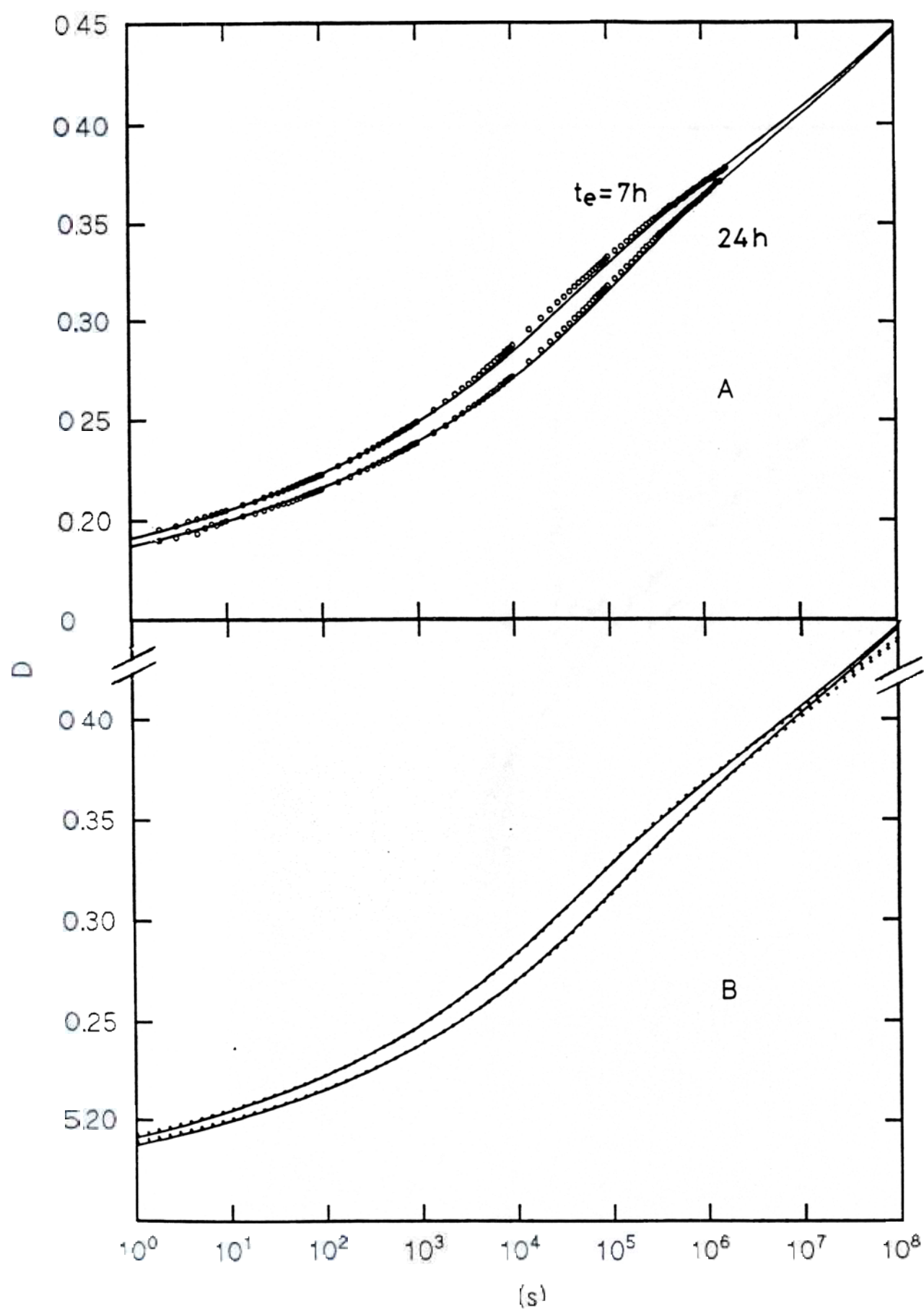


Fig. 7

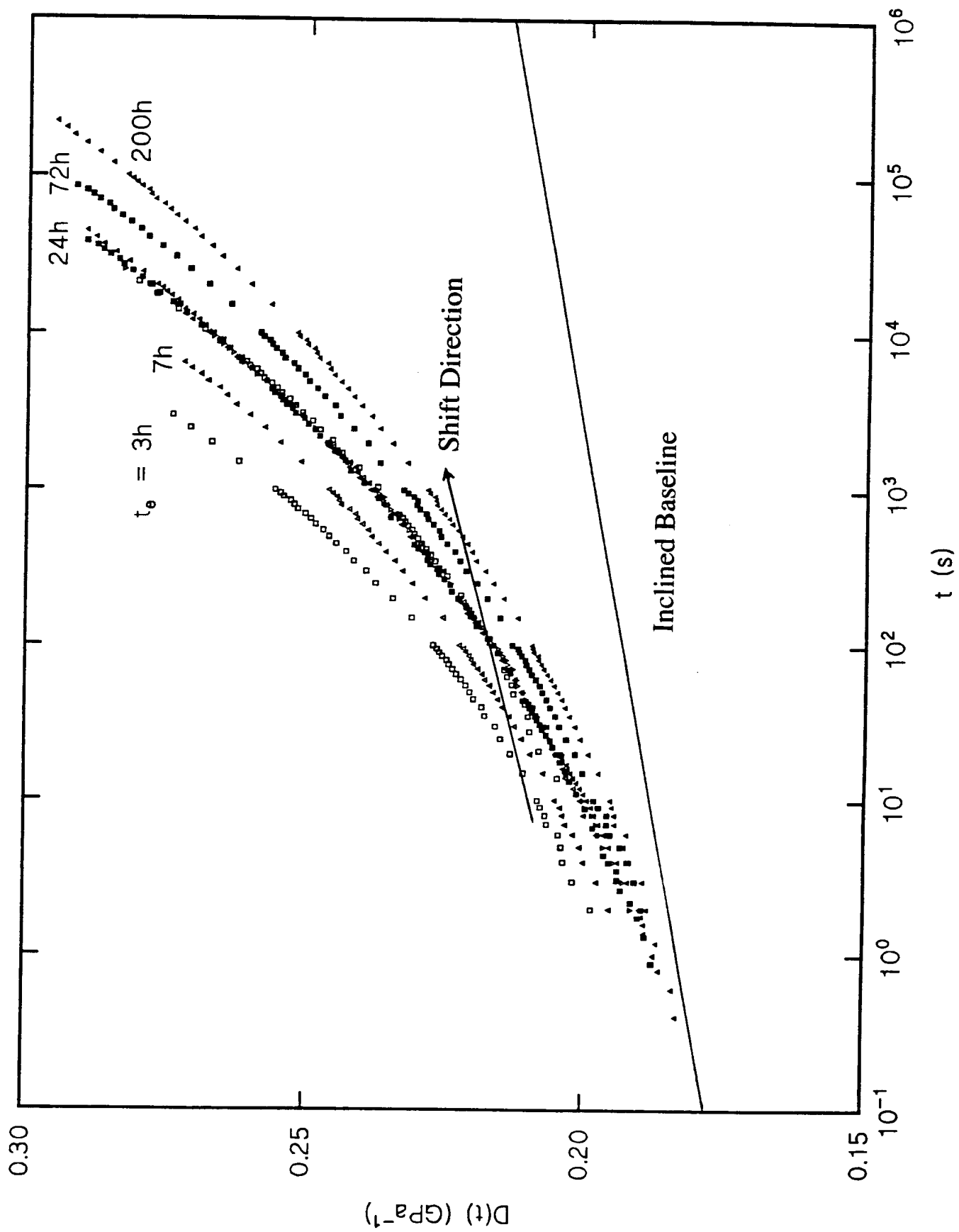


Fig. 8

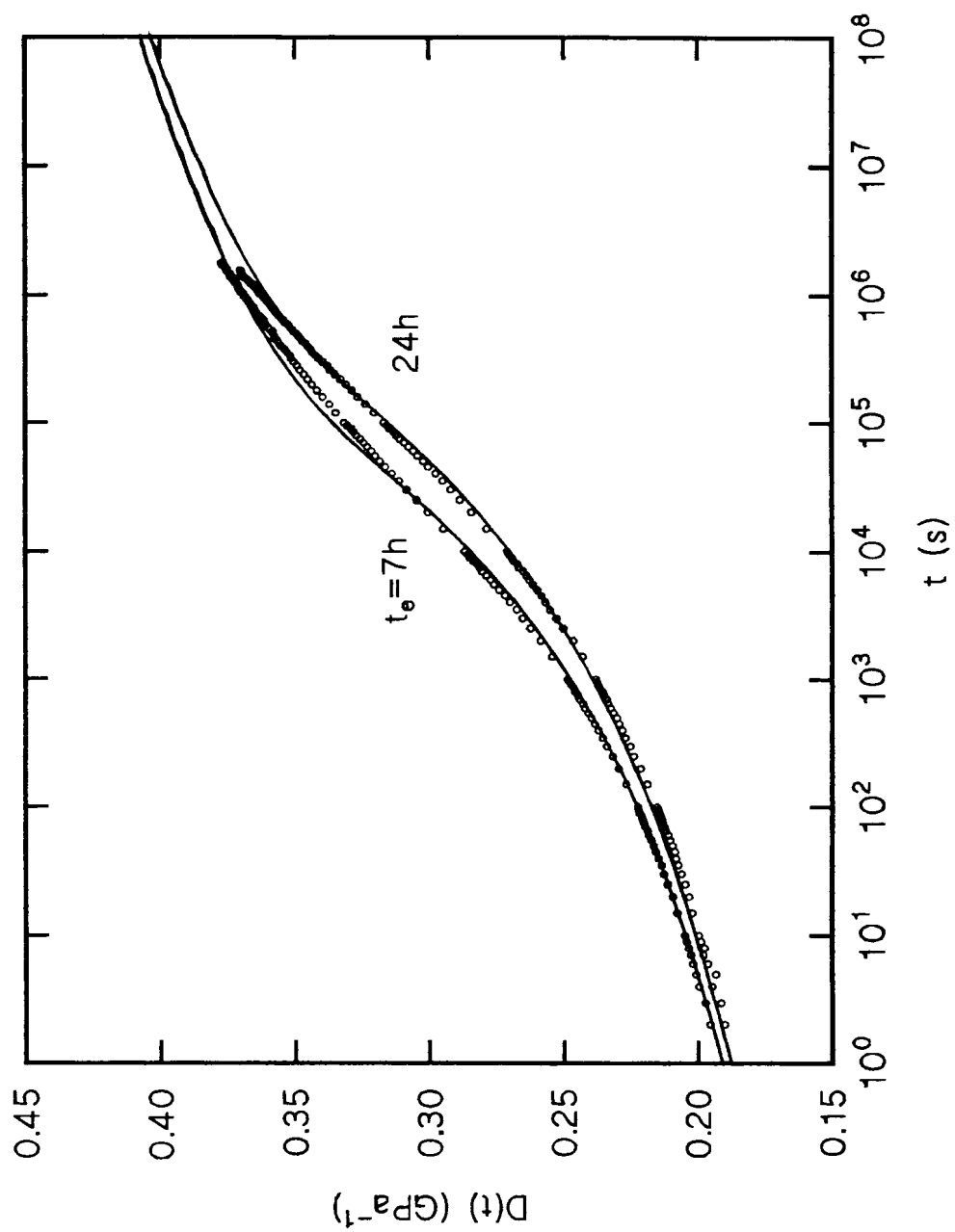


Fig. 9

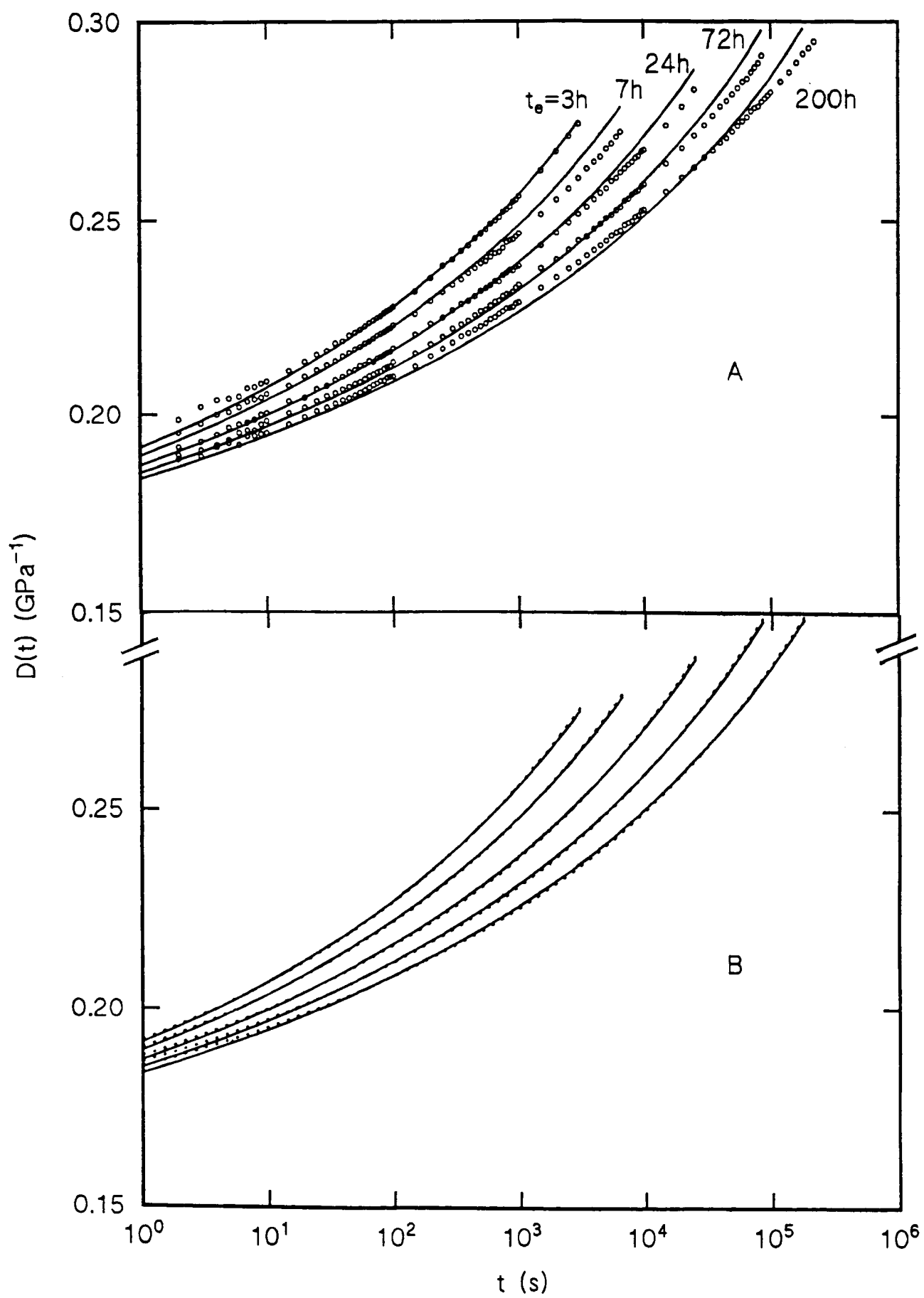


Fig. 10

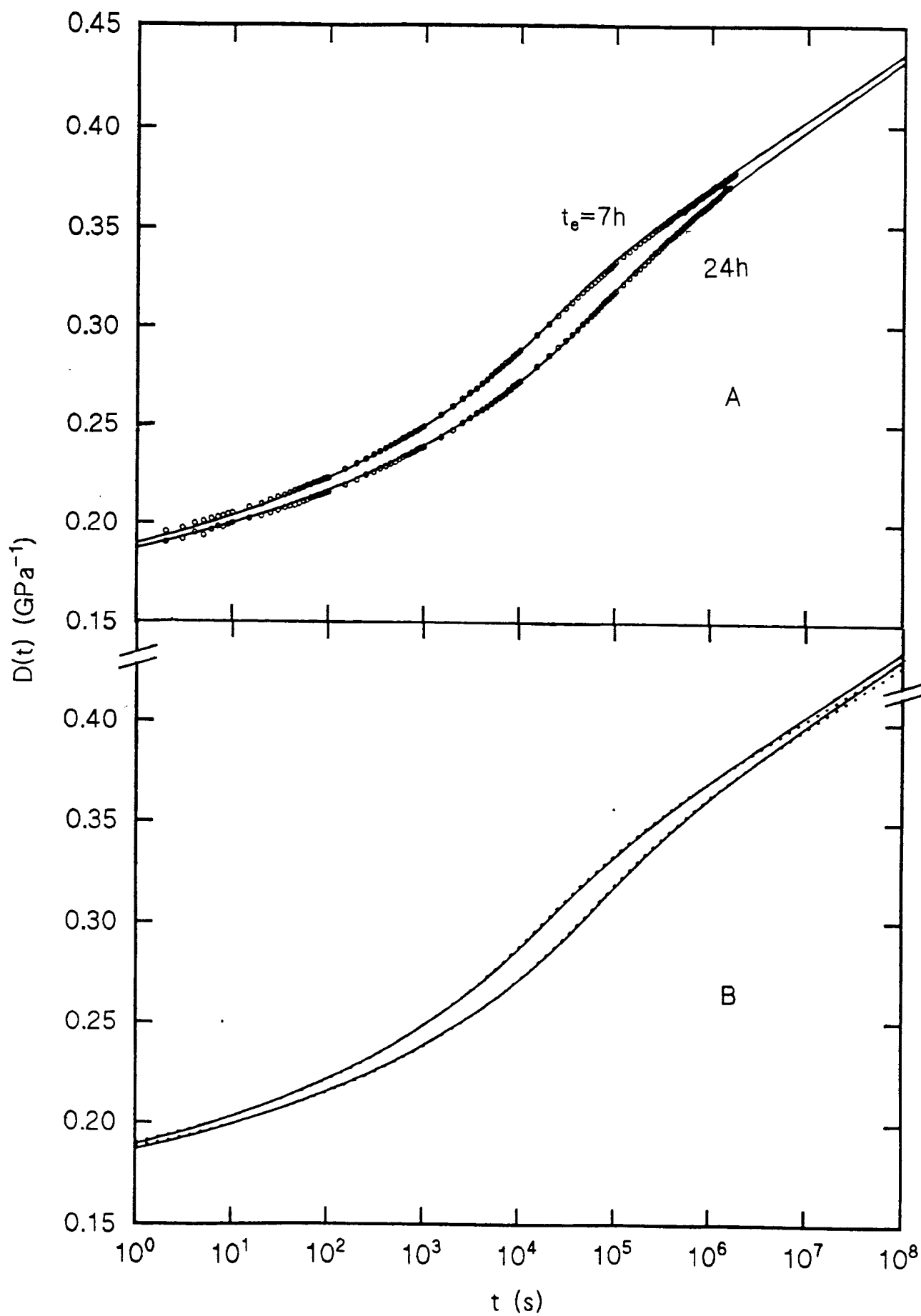


Fig. 11

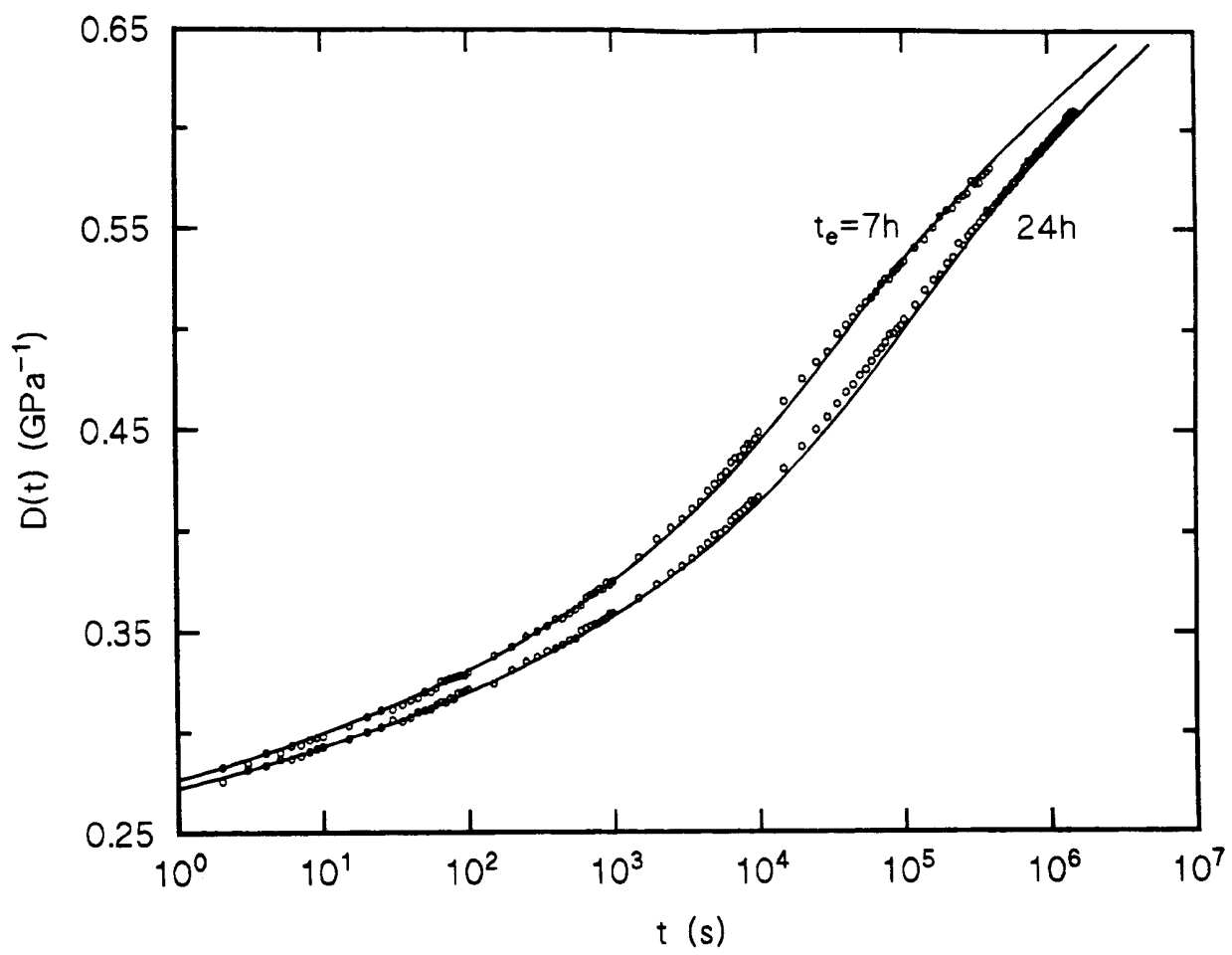


Fig. 12