

## **Modelling of Creep Data for Plastics**

**B E Read, G D Dean and P E Tomlins**

**March 1993**



# **Modelling of Creep Data for Plastics**

B E Read, G D Dean and P E Tomlins  
Division of Materials Metrology  
National Physical Laboratory  
Teddington  
Middlesex TW11 OLW

## **ABSTRACT**

A summary is presented of analytical functions capable of describing the creep behaviour of plastics over wide time ranges, accounting for the effects of physical ageing, stress level and temperature. The availability of such functions and associated parameters should provide an improved basis for the prediction of creep properties and facilitate the handling of data in computerised databases.

© Crown copyright 1993

National Physical Laboratory  
Teddington, Middlesex, United Kingdom, TW11 OLW

Approved on behalf of Chief Executive, NPL,  
by Dr M K Hossain, Head, Division of Materials Metrology

## CONTENTS

|                                                           |   |
|-----------------------------------------------------------|---|
| INTRODUCTION .....                                        | 1 |
| SHORT-TERM CREEP AND THE EFFECTS OF PHYSICAL AGEING ..... | 1 |
| LONG-TERM CREEP .....                                     | 2 |
| REFERENCES .....                                          | 3 |



## INTRODUCTION

In contrast to ceramics and metals, plastics materials exhibit viscoelastic properties and the time-dependence of their stress-strain relationships must be allowed for in the design of engineering components. Of fundamental importance in these design calculations are data obtained from tensile creep tests in which the strain  $\epsilon(t)$  is determined as a function of time  $t$  for specimens subjected to a constant stress  $\sigma$ . In accordance with available standards<sup>1-3</sup>, creep data are usually presented in the form of graphs of  $\epsilon(t)$  versus  $\log t$  for various stress levels and temperatures.

The creep behaviour may alternatively be specified by the creep compliance function  $D(t)$  defined by

$$D(t) = \epsilon(t)/\sigma \quad (1)$$

At low stress levels, for which  $\epsilon(t)$  is proportional to stress, a plot of  $D(t)$  versus  $\log t$  determined from a single creep test is sufficient to characterise the data. For such linear behaviour, the response of a viscoelastic material to any arbitrary time-dependent stress or strain input can be calculated accurately<sup>4</sup> from a knowledge of  $D(t)$ . The reciprocal of  $D(t)$ , known as the creep modulus, can often be used as a substitute for the elastic modulus in conventional design formulae to calculate approximately the time-dependent, load-deformation behaviour of plastics components<sup>4</sup>.

The creep function  $D(t)$  depends on a number of factors including the molecular structure (grade) of the polymer, process-related variables such as crystallinity and molecular orientation, the applied stress level (above the limit for linear behaviour) and temperature. The creep behaviour is also influenced by the physical age of the material, as determined by the duration and temperature of storage between processing and use<sup>5</sup>. An experimental determination of the creep properties of a polymer thus requires the acquisition of a large amount of data from time-consuming tests over ranges of stress and temperature on specimens subjected to various heat treatments and storage periods.

A substantial reduction in the duration and cost of the data collection would be possible if analytical expressions for  $D(t)$  were available that provided general descriptions of creep behaviour and enabled extrapolations and interpolations of the data to be performed. Furthermore, the handling of data in computerised databases would be facilitated by the need to store only the equations and associated parameters rather than tables of experimental values. In this context some proposed relationships are here discussed between the compliance function, age state, stress and temperature for various engineering thermoplastics.

## SHORT-TERM CREEP AND THE EFFECTS OF PHYSICAL AGEING

For a number of semicrystalline polymers, the variation of compliance with time during the early stages of a creep test is associated with the so-called  $\alpha$ -process and can be represented by the equation<sup>6,7</sup>

$$D(t) = D_U + (D_R - D_U) (1 - \exp - (t/\tau)^m) \quad (2)$$

Here  $D_U$  and  $D_R$  are the unrelaxed and relaxed compliances for the process in the short- and long-time limits, respectively,  $\tau$  is an effective retardation time and the parameter  $m$  is inversely proportional to the width of the process along the time axis (see Figure 1). Figure 2 shows the results of fitting equation (2) to creep curves obtained for polybutylene terephthalate (PBT) at a constant stress of 10 MPa. Each curve refers to a given elapsed time  $t_e$  between cooling the specimen from a temperature above the glass temperature  $T_g$  and the instant of load application. It will be evident that good fits are obtained only for short times



$t < t_e$  and that the predominant effect of physical ageing is to shift the curves horizontally to longer times with increasing age, or elapsed time  $t_e$ . These shifts correspond to an increase in the retardation time with age that relates to structural changes within the polymer and is accompanied by small but progressive increases in density.

With increasing stress level, at a given age  $t_e$ , the short-term regions of the creep curves shift to shorter times (Figure 3). This effect is opposite to that produced by ageing and is attributed to a rapid reduction in  $\tau$  produced by a stress-induced deageing of the material<sup>8</sup>. Similar effects are observed when the temperature of a glassy polymer is suddenly increased and, from analyses of short-term data, it is found that  $\tau$  may be written

$$\tau = A t_e^\mu \quad (3)$$

where the parameter  $A(\sigma, T)$  decreases with stress and temperature and  $\mu$  is constant over wide ranges of these variables.

### LONG-TERM CREEP

In a long-term creep test the retardation time is no longer effectively constant but increases significantly with creep time owing to further ageing which occurs simultaneously with the creep. To allow for this effect it is necessary to replace equation (2) by

$$D(t) = D_U + (D_R - D_U) \left[ 1 - \exp - \left( \int_0^t \frac{du}{\tau(u)} \right)^m \right] \quad (4)$$

where the integral accounts for the time-dependence of  $\tau$  for all times  $u$  between 0 and  $t$ . Analyses of long-term data on the basis of this equation have shown that the variation of  $\tau(t)$  during the creep is generally given by

$$\tau(t) = (\tau^2 + C^2 t^{2\mu})^{1/2} \quad (5)$$

where  $\tau$  is the initial (short-term) retardation time given by equation (3) and  $C(\sigma, T)$  is a decreasing function of stress and temperature. Figures 2 and 3 illustrate the fits obtained to long-term creep data for PBT after substituting equations (5) and (3) into (4).

Various methods have been employed to determine  $D_U$ ,  $m$ ,  $A$   $\mu$  and  $C$  from experimental creep data<sup>6-8</sup>, and a method has also been reported for estimating  $D_R - D_U$  from dynamic loss modulus-temperature plots<sup>7</sup>. Values for these parameters could be determined by suppliers for specified grades of polymer on specimens that reflect structural features in moulded components. If these numerical values were stored in a database, together with a programme based on equations (3)-(5), compliance functions  $D(t)$  could subsequently be generated for different service conditions providing that the age of the material  $t_e$  were known at the time of loading. This would require a knowledge of the storage details subsequent to processing and thus involve collaboration between the processor and designer. Alternatively an estimate of the effective age  $t_e$  could readily be obtained using equation (3) from a short-term creep test on a specimen cut from the component prior to loading.



## REFERENCES

1. S. Turner, Mechanical Testing of Plastics, 2nd Ed, Godwin, London (1984).
2. BS 4618 (1970) Recommendations for the Presentation of Plastics Design Data; Part 1, Mechanical Properties. British Standards Institution, London.
3. ISO/DIS 11403-1 (1992) Plastics - Acquisition and Presentation of Comparable Multipoint Data - Part 1, Mechanical Properties.
4. F.J. Lockett, Engineering Design Basis for Plastics Products, HMSO, London (1982).
5. L.C.E. Struik, Physical Aging in Amorphous Polymers and Other Materials, Elsevier, Amsterdam (1978).
6. B.E. Read, G.D. Dean and P.E. Tomlins, Plastics and Rubber Materials and Applications 14, 153 (1990).
7. G.D. Dean, B.E. Read and P.E. Tomlins, Plastics and Rubber Materials and Applications 13, 37 (1990).
8. B.E. Read, J. Rheol. 36, 1719 (1992).



**Table 1. Parameters used to model the data  
for PBT in Figure 2**

| $t_e$<br>(h) | $D_u$<br>(GPa <sup>-1</sup> ) | $\tau$<br>(10 <sup>6</sup> s) | m     |
|--------------|-------------------------------|-------------------------------|-------|
| 24           | 0.355                         | 7.95                          | 0.378 |
| 72           | 0.344                         | 17.2                          | 0.378 |
| 240          | 0.338                         | 39.0                          | 0.378 |

$$D_R - D_u = 1.5 \text{ GPa}^{-1}$$

$$A = 1652 \text{ s}^{1-\mu}$$

$$C = 1675 \text{ s}^{1-\mu}$$

$$\mu = 0.74$$

**Table 2. Parameters used to model the data  
for PBT in Figure 3**

| $\sigma$<br>(MPa) | $D_u$<br>(GPa <sup>-1</sup> ) | m     | A<br>(s <sup>1-<math>\mu</math></sup> ) | C<br>(s <sup>1-<math>\mu</math></sup> ) |
|-------------------|-------------------------------|-------|-----------------------------------------|-----------------------------------------|
| 10                | 0.355                         | 0.378 | 1652                                    | 1675                                    |
| 15                | 0.365                         | 0.416 | 555                                     | 900                                     |
| 20                | 0.370                         | 0.455 | 170                                     | 500                                     |
| 25                | 0.375                         | 0.484 | 43.8                                    | 275                                     |

$$D_R - D_u = 1.5 \text{ GPa}^{-1}$$

$$\mu = 0.74$$



## FIGURE CAPTIONS

- Fig 1            Schematic illustration of parameters used to specify the creep compliance function.
- Fig 2            Creep compliance curves for PBT at 23 °C for a stress level of 10 MPa and different ages  $t_e$ . Broken lines (- - -) are extrapolations of short-term data based on equation (2). Full lines (—) are predictions of long-term creep behaviour using equations (3), (4) and (5). Parameters employed are given in Table 1.
- Fig 3            Creep compliance curves for PBT at 23 °C and age  $t_e = 24\text{h}$  for the different stress levels indicated. Theoretical lines (—) are based on equations (3), (4) and (5) with parameters given in Table 2.



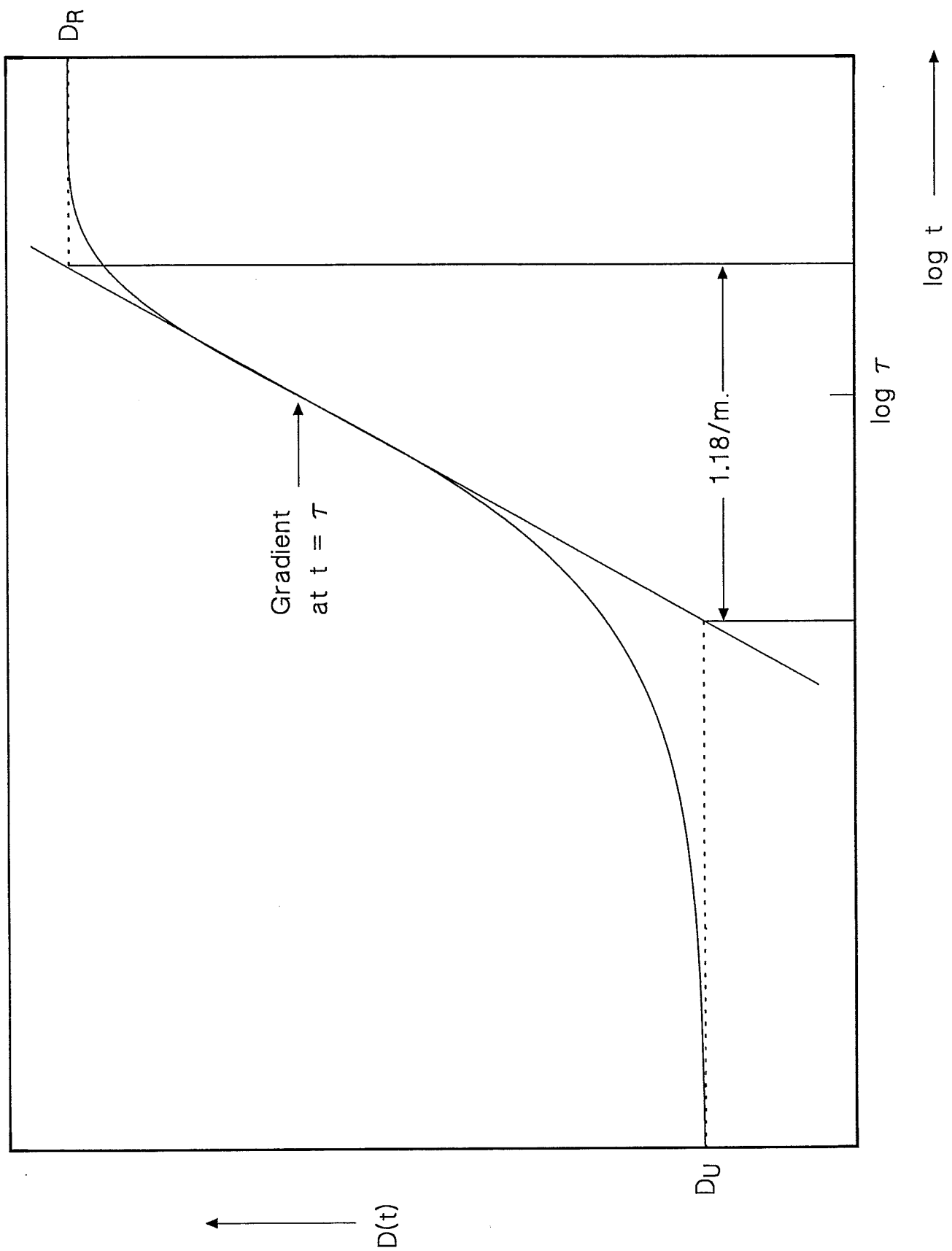


FIG.1



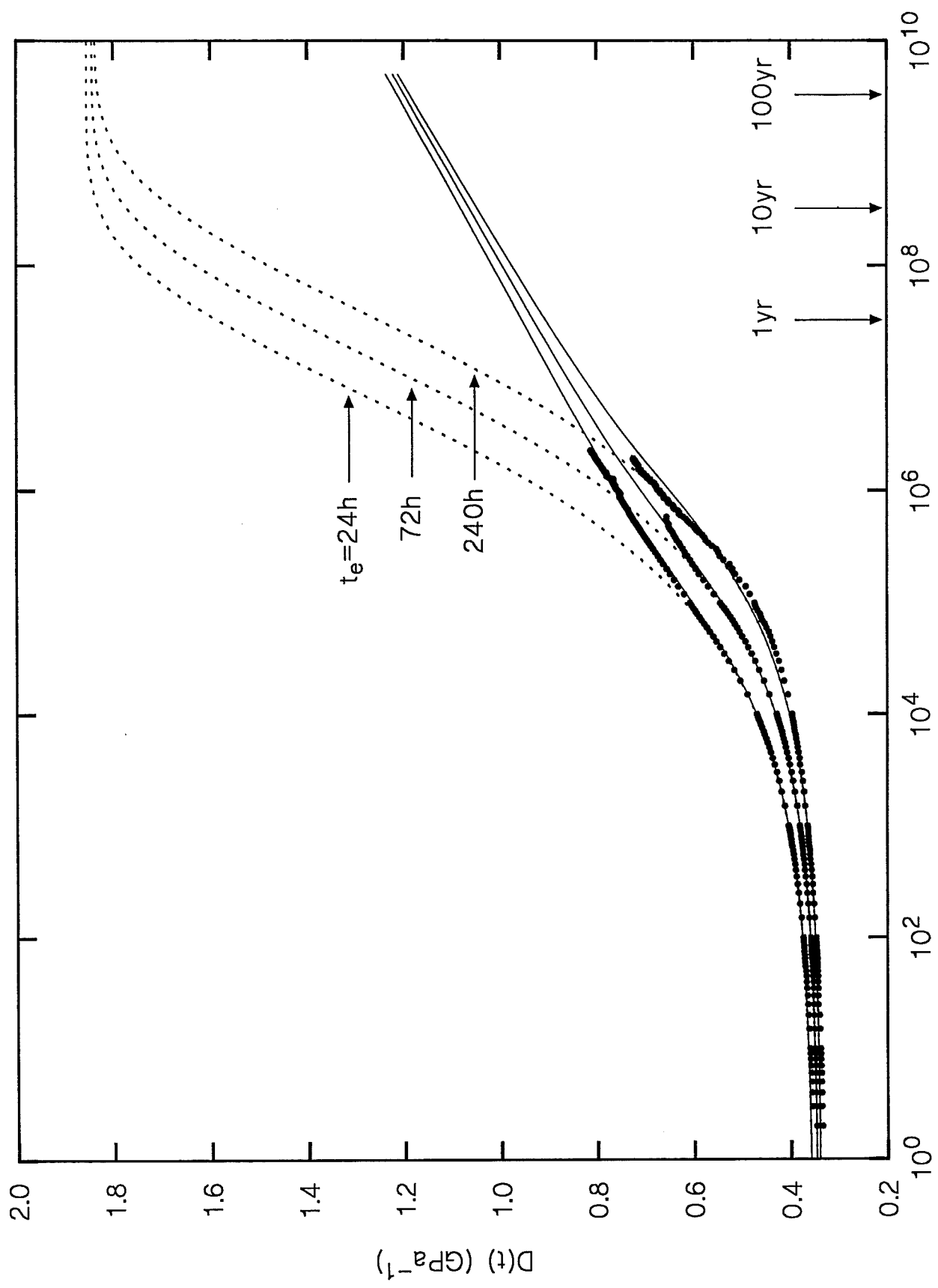


FIG.2



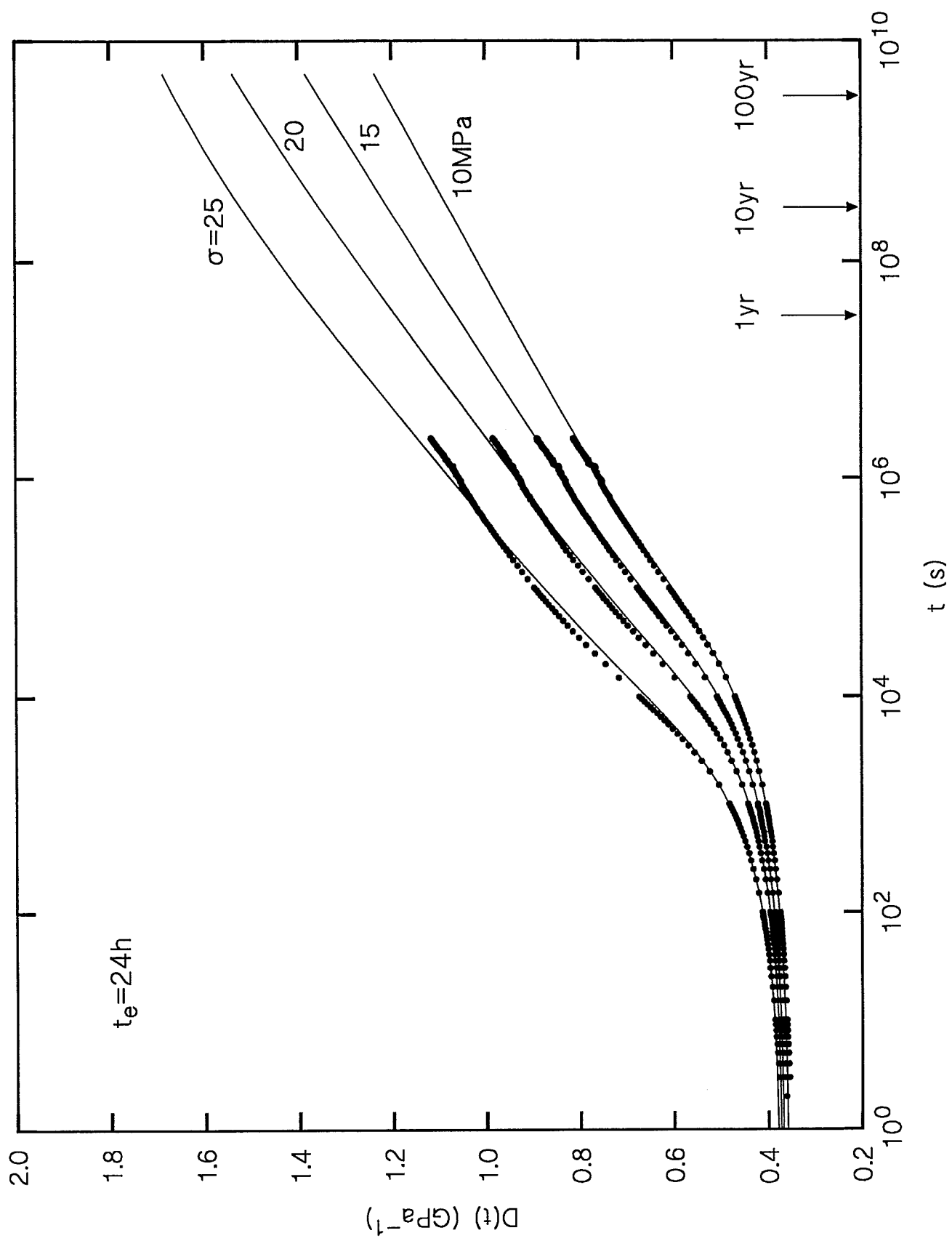


FIG.3

