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Prediction of Mechanical Properties of Polymers. Tensile Strength of Several Thermoplastics

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Synopsis

Tensile strength data for five thermoplastics [polycarbonate, phenoxy, poly(methyl methacrylate), polyethylene, and ethyl cellulose] are analyzed according to a modified rate equation. The agreement of the test results with the behavior described by the equation is excellent. Treatment of this type may be used to predict behavior of polymers from limited test data.

Introduction

Wolstenholme and Stark[1] and Coleman and Knox[2] suggested that the lifetime (or time to failure) t_f of a material under mechanical restraint may follow a process proceeding according to a rate equation. They obtained the relation

$$\log t_f = \log C - \log T + (\Delta F\ddagger/2.3RT) + bS/T \quad (1)$$

where $\Delta F\ddagger$ is the apparent free energy of activation for failure, S is the stress, and C and b are constants. Wolstenholme and Stark[1] recommended plotting isothermal data according to

$$\log t_f = D + b\ S/T \quad (2)$$

The apparent activation energy $\Delta F\ddagger$ can then be evaluated by extrapolating the straight lines of $\log t_f$ versus S/T to $S/T = 0$ and making an Arrhenius plot according to eq. (1). Rearrangement of eq. (1) to

$$\log t_f\ T(\Delta F\ddagger/2.3RT) = b\ S/T$$

will now permit plotting of all the data as $\log (t_f\ T/C) - (\Delta F\ddagger/2.3RT)$ versus S/T. The resulting straight line should pass through the origin and have slope b. According to reaction rate concepts b is related to the average volume of the element that participates in the failure process.

McAbee and Levi[3] successfully applied a slightly modified version of the above method to solid rocket propellant data[4] at two rates of load application over a range of temperatures of -60 to $+80$°C. In view of these results it was decided to obtain systematic data on several polymers to determine whether this relationship was generally valid. If the validity

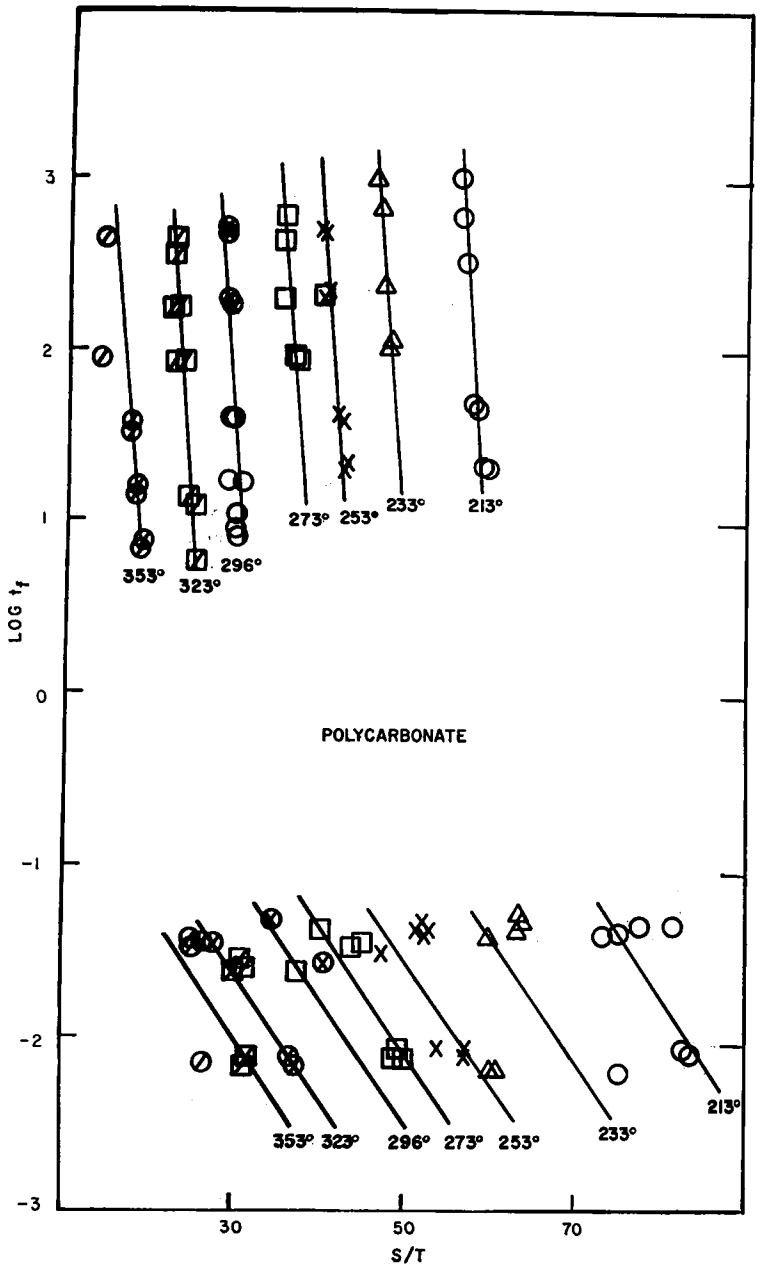
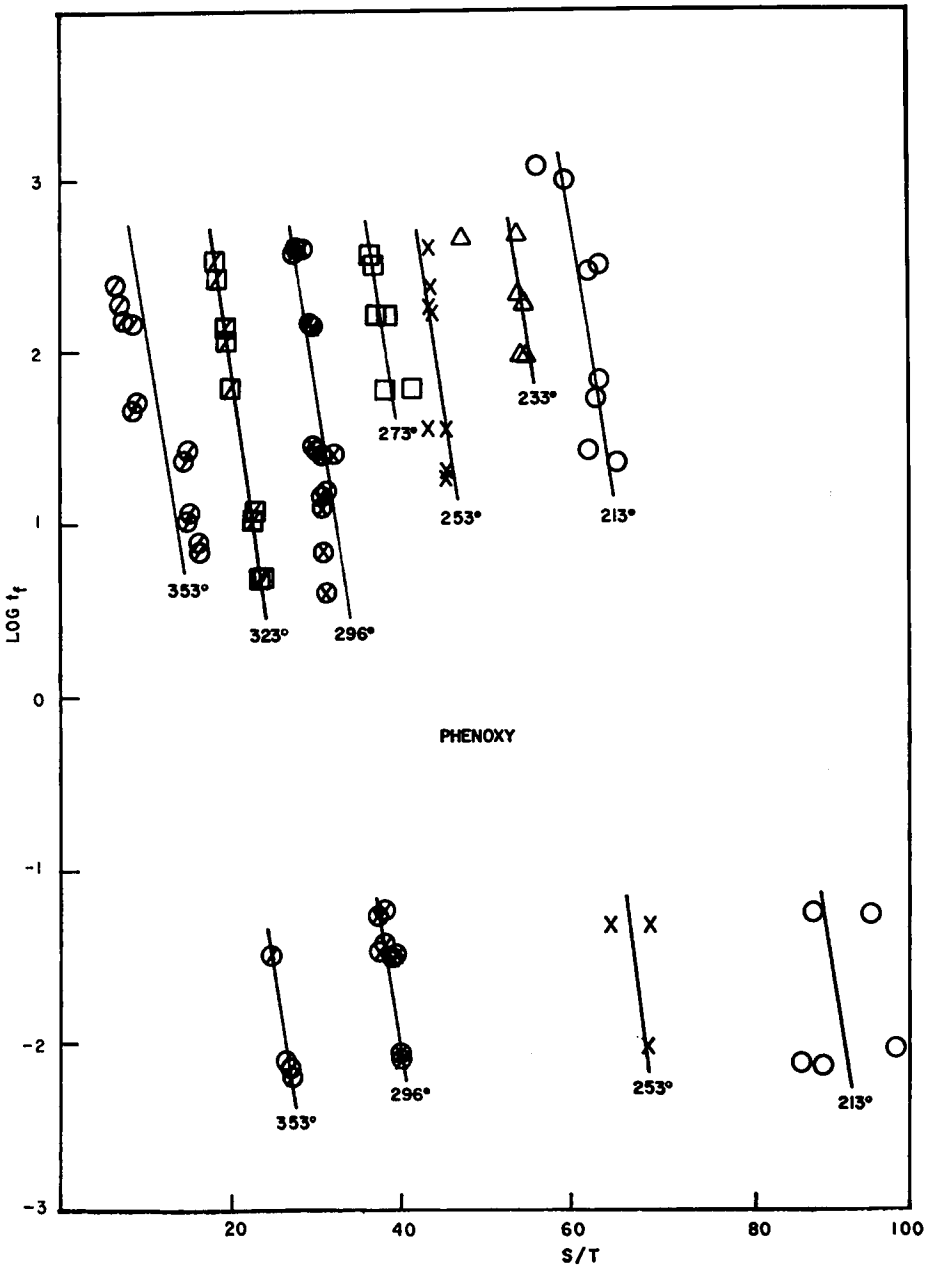


Fig. 1. Stress rupture data at several temperatures for polycarbonate and phenoxy.

of this approach could be established, it would be possible to predict performance from a limited number of tests. Furthermore, the material parameters so obtained conceivably might be related to the molecular properties involved in the process of failure.



Experimental

Tensile strength data for five thermoplastics [phenoxy, polycarbonate, poly(methyl methacrylate), polyethylene, and ethyl cellulose] were analyzed by the procedure outlined above. The data for poly(methyl methacrylate), polyethylene, and ethyl cellulose were taken from the work of Ely.[5] The

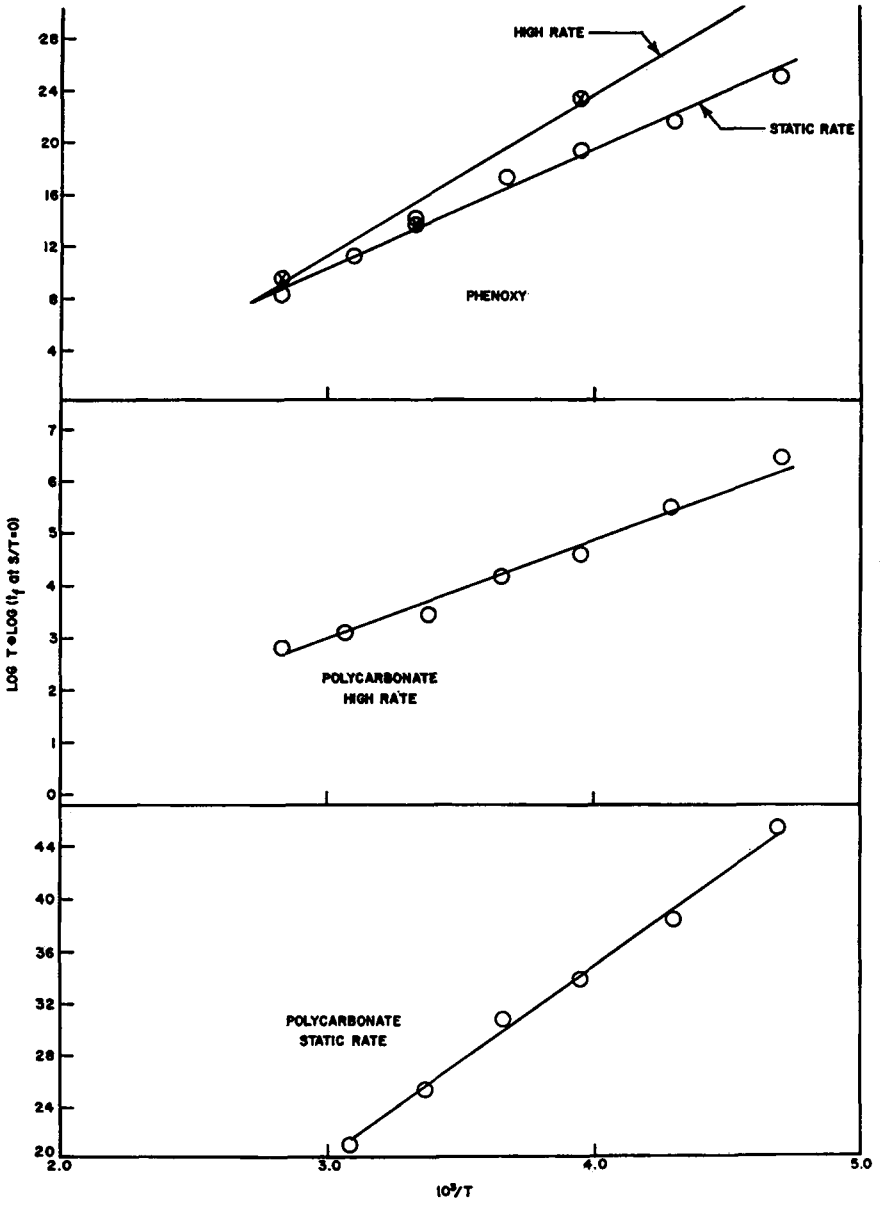


Fig. 2. Arrhenius plot for estimation of apparent activation energy of rupture of polycarbonate and phenoxy.

polycarbonate (Lexan, General Electric Co., Pittsfield, Mass.) and phenoxy (Union Carbide Corp., Bound Brook, N. J.) test specimens conformed to the requirements of ASTM D638, Type I, $^1/_8$ in. thick. A standard universal testing machine was utilized to obtain the static test data. The high-rate results were obtained with the equipment described previously.[6]

Results and Discussion

The stress rupture data for polycarbonate and phenoxy are shown in Figure 1. Reasonably parallel straight lines were obtained for the static data. Parallel lines are also drawn for the high-rate data, although in this case the scatter is troublesome in some cases. Figure 2 shows appropriate Arrhenius plots. It is to be noted that these are satisfactorily linear. According to eq. (1) a plot of $\log t_f - \log (t_f \text{ at } S/T = 0)$ versus S/T should be linear with slope b and should pass through the origin. Figure 3 shows such a plot for polycarbonate and phenoxy. These lines are quite satisfactorily linear and give some confidence in the validity of the treatment.

Literature data[5] were used to show the applicability of the method for several other polymers. Figures 4 and 5 show the $\log t_f - \log (t_f \text{ at } S/T = 0)$ versus S/T plots for poly(methyl methacrylate), ethyl cellulose,

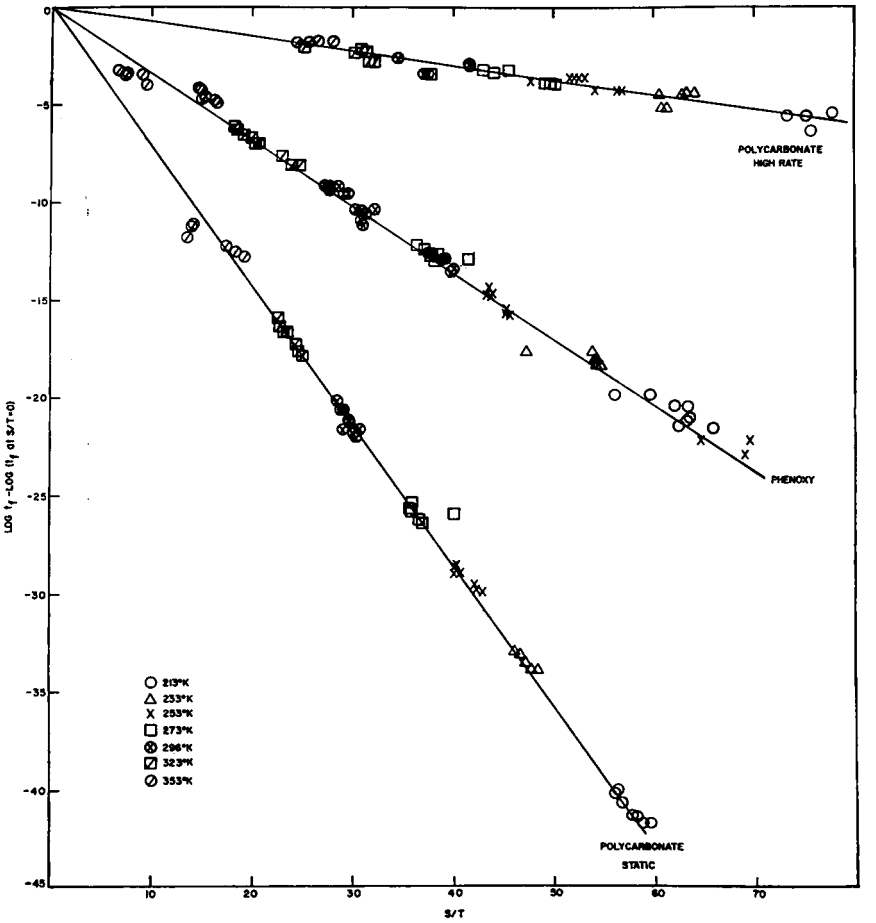
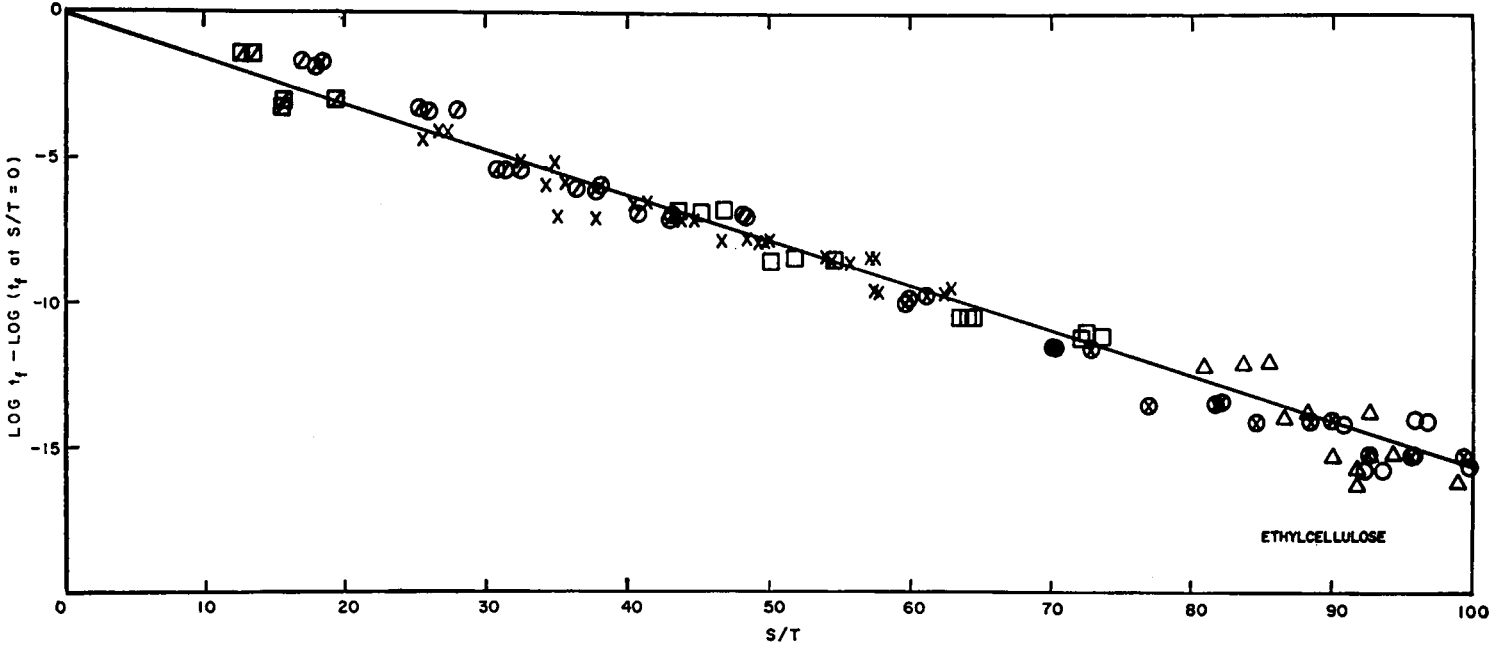


Fig. 3. Plots of $\log t_f - \log (t_f \text{ at } S/T = 0)$ vs. S/T for polycarbonate and phenoxy.


0
-5
-10
-15
LOG t_f − LOG (t_f at S/T = 0)
0
10
20
30
40
50
60
70
80
90
100
S/T
ETHYLCELLULOSE

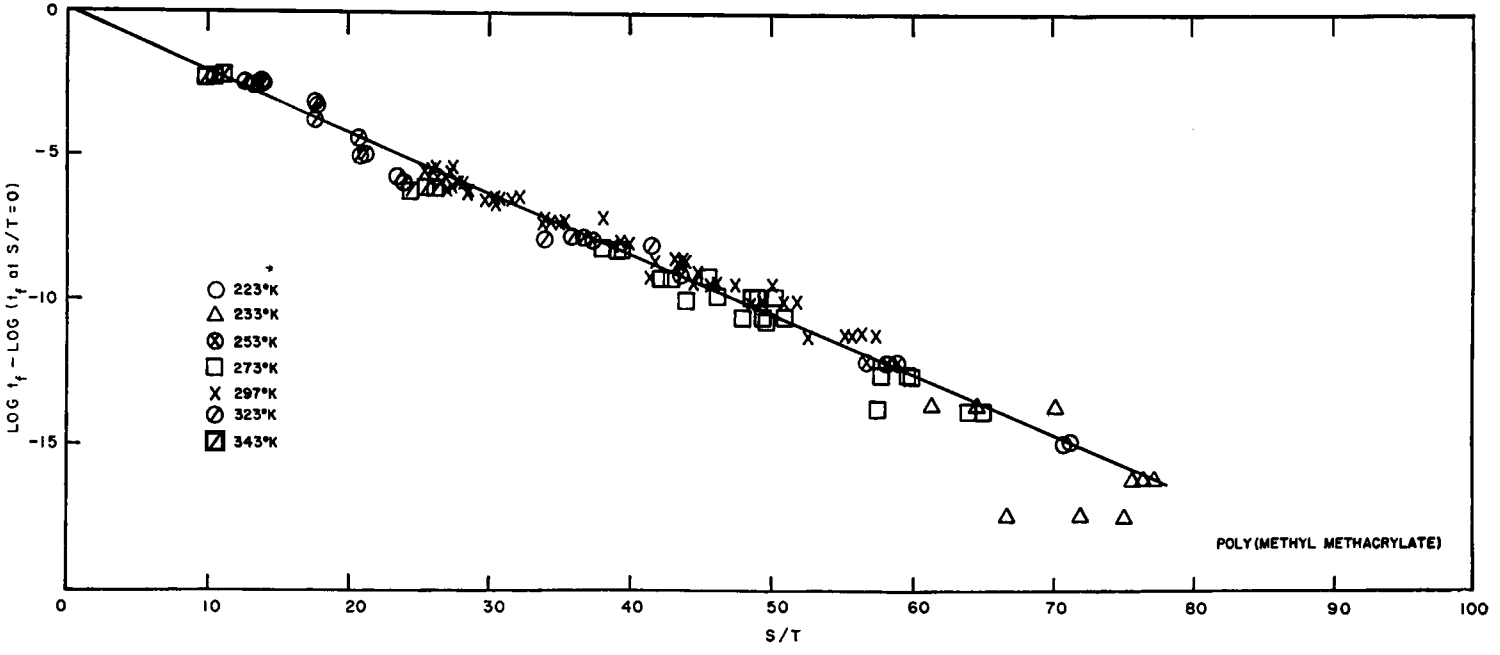


Fig. 4. Plots of $\log t_f - \log (t_f \text{ at } S/T = 0)$ vs. S/T for poly(methyl methacrylate) and ethyl cellulose.

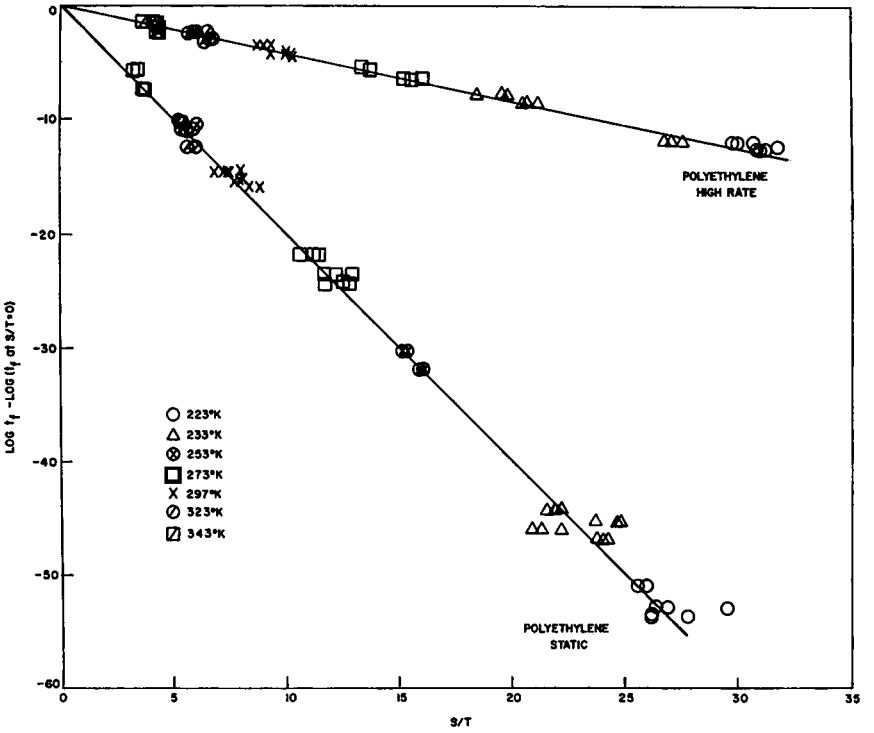


Fig. 5. Plots of log t_f − log (t_f at S/T = 0) for polyethylene.

TABLE I
Summary of Parameters

Polymer	$-b$	Apparent activation energy, kcal.
Polyethylene		
Static	2	123
High rate	0.4	23
Poly(methyl methacrylate)		
Static	0.21	37
High rate	0.21	37
Ethyl cellulose		
Static	0.16	39
High rate	0.16	39
Polycarbonate		
Static	0.71	65
High rate	0.07	9
Phenoxy		
Static	0.33	44
High rate	0.33	58

and polyethylene. Once more the linearity is quite satisfactory in all cases.

A summary of parameters is shown in Table I. The results obtained suggest that a method such as that described here may find use in predicting failure times or mechanical strength of polymers at various temperatures from the limited experimental data necessary to establish the appropriate parameters. Of course, such predictions would hold only for a temperature range in which the polymer shows no transitions.[3] Different parameters may be expected above and below the temperature of such transitions.

References

1. W. E. Wolstenholme and C. F. Stark, Report No. 1, Contract DA-18-035-AMC-139(A), October 10, 1964.
2. B. D. Coleman and A. G. Knox, *Textile Res. J.*, **27**, 393 (1957).
3. E. McAbee and D. W. Levi, Picatinny Arsenal Technical Report 3258, Aug. 1965.
4. E. McAbee and M. Chmura, *J. Appl. Polymer Sci.*, **8**, 3 (1964).
5. R. E. Ely, Ordnance Missile Laboratories Report No. 2R25F, October 1957.
6. E. McAbee and M. Chmura, *SPE J.*, **19**, 83 (1963).

Résumé

Des résultats de force de tension ont été analysés conformément à une équation de vitesse modifiée pour cinq thermoplastiques (le polycarbonate, le phénoxy, le polyméthacrylate de méthyle, le polyéthyléne et l'éthylcellulose). L'accord des résultats avec le comportement décrit par les équations est excellent. Le traitement de ce type peut être utilisé pour prédire le comportement des polymères au départ de résultats tests limités.

Zusammenfassung

Zugfestigkeitsdaten für fünf thermoplastische Massen (Polykarbonat, Phenoxy, Polymethylmethacrylat, Polyäthylen und Äthylcellulose) werden mit einer modifizierten Geschwindigkeitsgleichung analysiert. Die Übereinstimmung zwischen den Testergebnissen und dem durch die Gleichung geforderten Verhalten ist asigezeichnet. Eine solche Behandlung kann zur Voraussage des Verhaltens von Polymeren aus beschränkten Testdaten verwendet werden.

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