JOURNAL OF APPLIED POLYMER SCIENCE VOL. 13, PP. 1899-1908 (1969)

Prediction of Mechanical Properties of Polymers. Tensile Strength of Glass-Reinforced Plastics

ELISE McABEE and DAVID W. LEVI, *Feltman Research Laboratories, Picatinny Arsenal, Dover, N. J.*

Synopsis

Tensile strength data at high and low rates of loading were obtained for a glass-reinforced polyester and a glass-reinforced epoxy. Analysis of the data by a rate method indicated that such a method may be used to predict behavior of polymers from limited test data.

INTRODUCTION

Glass-reinforced polymers are used in a wide variety of engineering applications. Often a knowledge of long-term mechanical behavior is of prime importance in the design of items. In this work the effects of rates of loading and of temperature on mechanical properties of two of these materials have been studied, and an effort is made to show how limited test data may be used for prediction of failure times or mechanical strength for such reinforced polymers.

EXPERIMENTAL

Materials

The glass-reinforced polyester was furnished by Raytheon Corp. and consisted of $^1/_8$-in. (nominal) thick panels formed by hand lay-up. The following information was furnished by Raytheon Corp. relative to the fabrication: vacuum pressure no greater than 12 psi; temperature-gelled under heat lamps and postcured 3 hr at 250°F; reinforcement, 181 cloth with Garan finish; resin, Stypol 25. The glass-reinforced epoxide was prepared by hand lay-up (nominal $^1/_8$-in. thick panels). 181 Glass cloth was used with Epon 828 (Shell Chemical Co.) epoxide.

Testing

Tensile specimens were machined to conform to the ASTM Test Method D-638, type I specimen.[1] Groups of specimens were prepared consisting of two specimens from each of three panels.

Static tests were conducted in a Model TTB Instron Testing Machine. Tests were carried out using constant rates of crosshead separation of 0.02, 0.2, 0.4, 0.6, and 2.0 in. per minute.

The high-rate equipment and procedures have been described elsewhere.[2] Load was applied so that failure would occur at approximately 10, 80, and 600 millisec. Table I gives the data.

TABLE I
Stress Rupture Data for Glass-Filled Polyester and Epoxy

t_f, sec		S/T, psi/°K	
Polyester	Epoxy	Polyester	Epoxy
	Temperature 213°K		
308	207	204	260
264	193	193	277
123	176	225	251
98	151	201	261
78[a]	81	242	229
0.110	81	391	278
0.108	81	394	285
0.108	75	344	283
0.104	14.8	321	277
0.096	14.3	373	297
0.096	13.7	266	265
0.094	13.6	347	281
0.086	0.180	324	412
0.088	0.168	276	485
0.080	0.164	268	432
0.014	0.160	398	381
0.014	0.158	386	413
0.0136	0.148	381	402
0.0134	0.115	370	378
0.0128	0.016	387	459
0.0107[a]	0.015	345	437
	0.015		422
	0.015		422
	Temperature 233°K		
68[a]	219	192	272
0.109	218	265	267
0.102	199	262	233
0.102	186	250	223
0.101	83	262	256
0.092	80	187	246
0.089	74	222	231
0.088	74	234	228
0.085	13.8	223	252
0.0107[a]	13.8	311	234
	13.2		239
	12.9		233
	0.200		373
	0.197		369
	0.175		368
	0.166		348
—	0.164		387
	0.160		367
	0.155		341
	0.138		327
	0.017		388

TABLE I (*continued*)

t_f, sec		S/T, psi/°K	
Polyester	Epoxy	Polyester	Epoxy
	0.016		412
	0.0143		425
	0.012		309
	Temperature 253°K		
209	261	167	199
201	216	165	175
109	208	185	205
108	169	154	148
65[a]	83	165	224
0.120	80	222	228
0.116	78	214	196
0.112	65	213	181
0.100	18	247	208
0.091	15	230	201
0.0107[a]	13	272	208
	13		197
	0.176		319
	0.160		302
	0.158		327
	0.158		312
	0.142		329
	0.140		321
	0.138		325
	0.1076		395
	0.015		305
	0.015		376
	Temperature 273°K		
273	240	149	205
244	229	144	179
117	217	144	159
115	209	148	141
62[a]	82	143	188
0.112	82	212	178
0.110	79	210	156
0.109	76	195	177
0.092	15	195	188
0.088	14	196	177
0.080	13	193	151
0.0101[a]	11	244	154
	0.152		292
	0.146		283
	0.126		270
	0.112		293
	0.110		303
	0.104		283
	0.082		219
	0.080		224
	0.016		341
	0.0144		315
	0.0135		296

(*continued*)

TABLE I (*continued*)

t_f, sec		S/T, psi/°K	
Polyester	Epoxy	Polyester	Epoxy
Temperature 296°K			
740[a]	293	119	158
600[a]	252	125	166
59[a]	239	120	156
58[a]	231	128	155
34[a]	78	140	179
33[a]	72	136	183
22[a]	70	142	168
20[a]	68	137	157
6.7[a]	15	146	156
6[a]	13	140	164
0.61[a]	12	155	176
0.6[a]	11	157	156
0.082[a]	0.132	182	259
0.082[a]	0.115	175	252
0.01[a]	0.105	219	236
0.0097	0.100	203	252
	0.096		252
	0.088		246
	0.014		269
	0.014		262
	0.0135		261
	0.0132		260
Temperature 323°K			
383	243	87	133
367	241	109	143
299	219	81	121
108	214	105	111
106	86	97	153
58[a]	77	106	135
0.091	71	133	127
0.084	64	150	148
0.082	14	140	134
0.076	13	136	148
0.071	13	140	117
0.070	13	122	126
0.0098[a]	0.116	180	232
	0.113		218
	0.092		234
	0.091		235
	0.088		202
	0.084		202
	0.084		200
	0.078		207
	0.0137		225
	0.0132		214
	0.013		220
	0.012		220

TABLE I (*continued*)

t_f, sec		S/T, psi/°K	
Polyester	Epoxy	Polyester	Epoxy
	Temperature 353°K		
361	202	75	141
301	197	76	124
86	189	69	125
84	178	77	116
58[a]	71	83	135
0.079	68	111	134
0.077	63	106	114
0.077	58	121	105
0.071	14	104	125
0.071	14	116	136
0.070	13	112	125
0.009[a]	13	154	130
	0.092		178
	0.089		168
	0.086		178
	0.086		181
	0.085		200
	0.083		180
	0.080		182
	0.075		167
	0.013		197
	0.012		201
	0.0084		82

[a] Indicates average of five values.

RESULTS AND DISCUSSION

Several investigators[3–6] have found 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. The relation may be written[3,4] in the form

$$\log t_f = \log C - \log T + (\Delta F^{\neq}/2.3RT) + bS/T, \qquad (1)$$

where $\Delta F^{\neq}$ is the apparent free energy of activation for failure, S is the stress, and C and b are constants.

Isothermal data can be plotted according to

$$\log t_f = D + bS/T. \qquad (2)$$

Plots of log t_f versus S/T are shown for the glass-reinforced polyester in Figure 1 and for the glass-reinforced epoxy in Figure 2. The slope, b, was estimated by drawing the best parallel straight lines through each set of data (static or high rate) at the various temperatures. Although the scatter was quite troublesome, such parallel straight lines did appear to fit the data reasonably well. The scatter made it difficult to estimate D by extrapolation to $S/T = 0$. However, since the b values were known, log

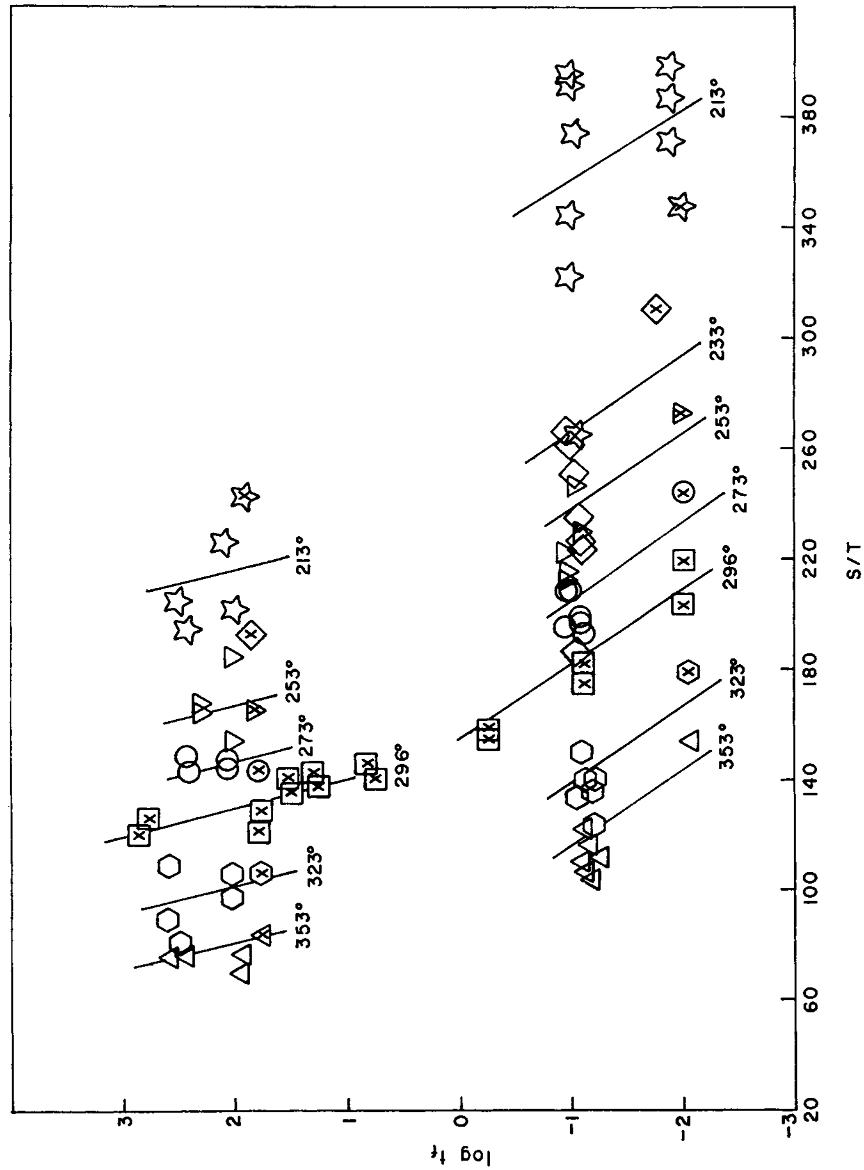

Fig. 1. Stress rupture data at several temperatures for glass-filled polyester: X refers to average of 5 determinations; temperatures are °K.

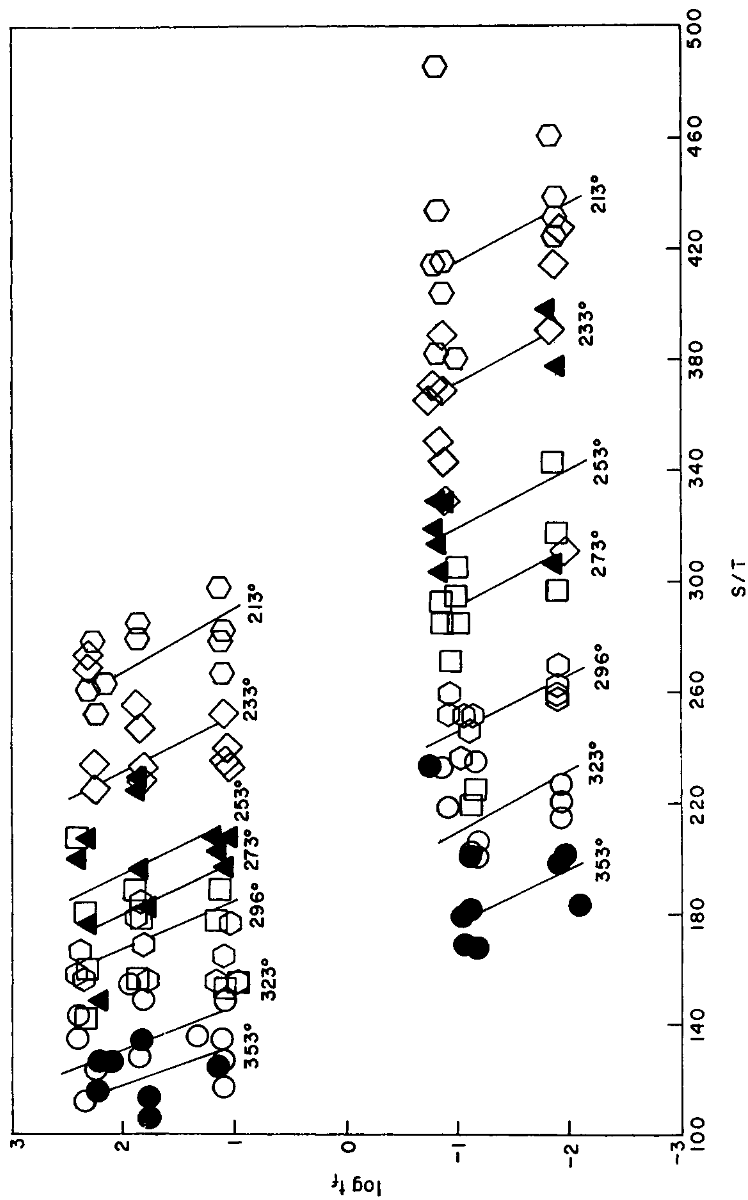

Fig. 2. Stress rupture data at several temperatures for glass-filled epoxy; temperatures are °K.

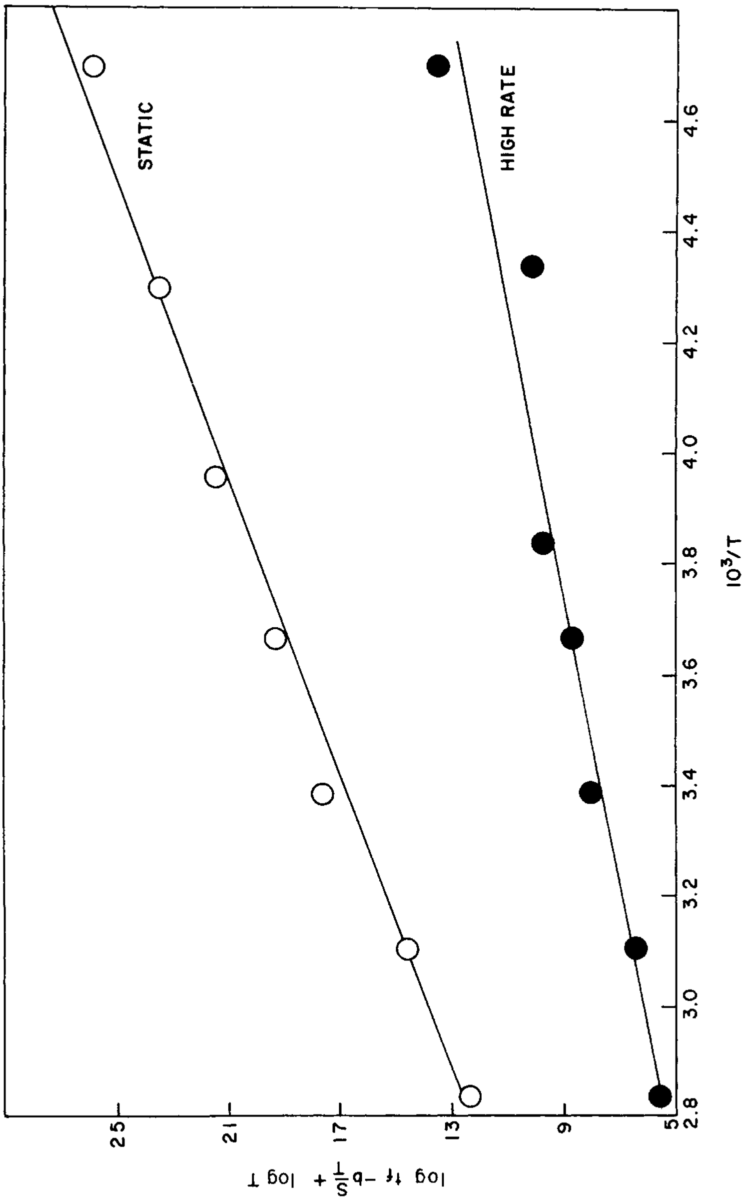

Fig. 3. Arrhenius plot for glass-reinforced polyester.

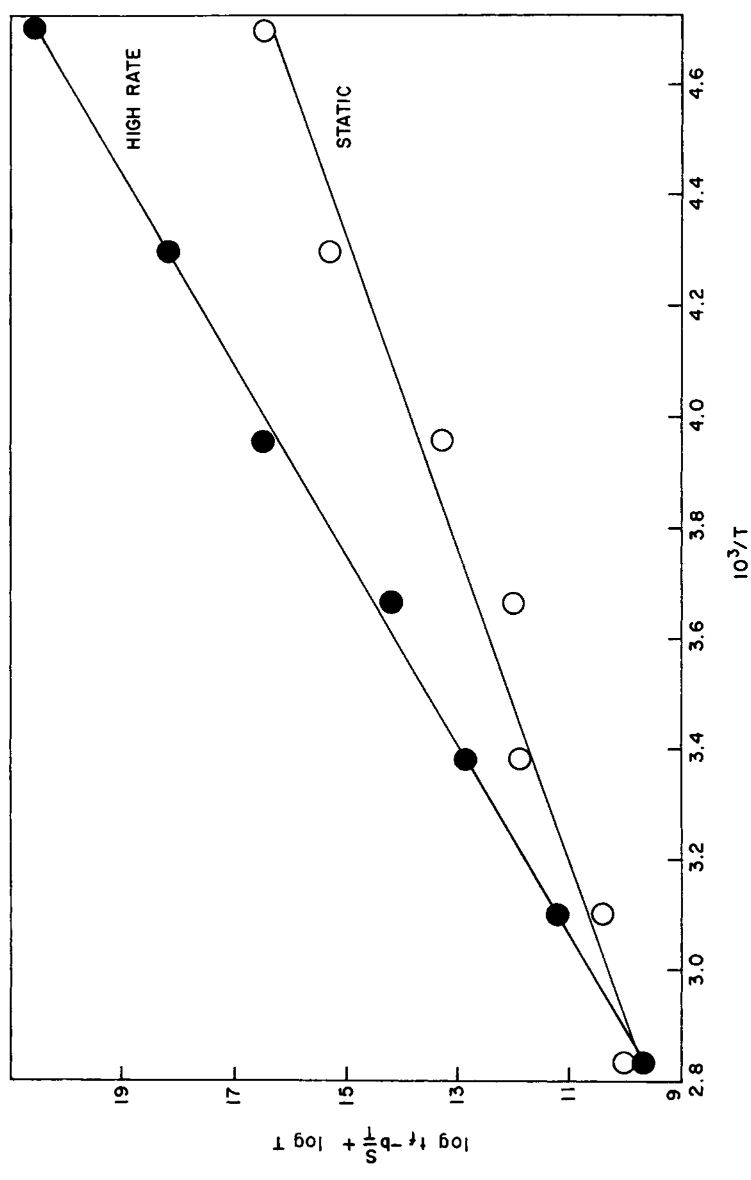

Fig. 4. Arrhenius plot for glass-reinforced epoxy.

$t_f - bS/T + \log T$ was plotted against $1/T$, as shown in Figures 3 and 4. The slope and intercept of the resulting straight lines yielded $\Delta F^{\neq}$ and C, respectively. Each experimental point in Figures 3 and 4 represents the average of the 10 to 12 determinations at that temperature. The equations for the lines in Figures 3 and 4 are:

Polyester

Static ($b = -0.10$)

$$\log t_f - bS/T + \log T = -8.3 + 7400 \left(\frac{1}{T}\right)$$

high Rate ($b = -0.036$)

$$\log t_f - bS/T + \log T = -5.6 + 3900 \left(\frac{1}{T}\right)$$

Epoxy

static ($b = -0.046$)

$$\log t_f - bS/T + \log T = -0.55 + 3600 \left(\frac{1}{T}\right)$$

high Rate ($b = -0.046$)

$$\log t_f - bS/T + \log T = -7.1 + 5900 \left(\frac{1}{T}\right)$$

The results suggest that this method of treating mechanical data for glass-reinforced polymers may be useful in predicting failure times or mechanical strength at various temperatures from limited experimental data.

References

1. ASTM Book of Standards, part 9, Philadelphia, 1961, p. 448.
2. E. McAbee and M. Chmura, *J. Appl. Polym. Sci.*, **8**, 3 (1964).
3. B. D. Coleman and A. G. Knox, *Text. Res. J.*, **27**, 393 (1957).
4. W. E. Wolstenholme and C. F. Stark, Report No. 1, Contract DA-18-035-AMC-139(A), Oct. 1964.
5. E. McAbee and D. W. Levi, *J. Appl. Polym. Sci.*, **11**, 2443 (1967).
6. E. McAbee and D. W. Levi, *J. Appl. Polym. Sci.*, **11**, 2067 (1967).

Received March 18, 1969