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TENSILE, COMPRESSIVE, AND SHEAR PROPERTIES OF A 64-kg/m³ POLYURETHANE FOAM AT LOW TEMPERATURES

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Tensile, Compressive, and Shear Properties of a 64-kg/m^3 Polyurethane Foam at Low Temperatures

J. M. Arvidson, L. L. Sparks, and Chen Guobang

Polyurethane foam, having a density of 64 kg/m^3, was tested at 295, 111, 76, and 4 K. The material properties reported are Young's modulus, proportional limit, yield strength (at 0.2% offset), tensile, shear, and compressive strengths, and elongation (elastic and plastic). To perform these tests, a unique apparatus was developed. This apparatus permits tension, compression, and shear testing of materials at any temperature ranging from 295 to 1.8 K. Strain is measured with a concentric, overlapping-cylinder capacitance extensometer that is highly sensitive and linear in output.

Key words: compressive strength; elongation; foam; insulation; low temperatures; mechanical properties; proportional limit; shear strength; tensile strength; yield strength; Young's modulus.

1. INTRODUCTION

Polyurethane foams are used in many structural as well as insulating applications in which knowledge of material performance in extreme environments (e.g., at liquefied natural gas, liquid nitrogen, and liquid helium temperatures) is essential. Accurate data, predictive capability, and standardized methods and materials improve the selection and development of materials for these applications. The mechanical properties reported here are part of a broader effort to understand and predict the thermal and mechanical behavior of expanded plastics (foams) in cryogenic environments.

The tensile, compressive, and shear properties of polyurethane foam, having a density of 64 kg/m^3, were determined using a test fixture developed specifically for this program [1]. This fixture provides the capability of determining the above material properties at any temperature from ambient (295 K) to 1.8 K. Tests can be done in a cold gaseous atmosphere or in liquids, such as helium (4 K), nitrogen (76 K), and dry ice and alcohol (195 K). The fixture has also been designed to test materials at the above temperatures while under static pressures ranging from subatmospheric to approximately 0.3 MPa (43.7 psia).

A strain extensometer that was developed for use with soft viscoelastic materials utilizes concentric overlapping cylinders and the change in electrical capacitance to detect specimen strain [2]. This type of extensometer does not attach directly to the specimen, so the effect of instrumentation on the experimental results is negligible (verified to contribute $<2.5 \times 10^{-8}$ m for our specimen geometry). The extensometer works well in cryogenic environments, is accurate, and is linear for large strains [3,4]. The capacitance extensometer system designed for this work had a linearity range in excess of 2.5 cm when used with the current foam specimen geometry (2.9-cm diameter by 9.9-cm length).

Similar extensometers can be designed for specific sensitivities and extents of linearity [5]. As long as the capacitance extensometer is situated in a stable fluid (i.e., single phase and nonboiling) the resultant is a very high signal-to-noise ratio. These sensors function in gases as well as in liquids and the device is only sensitive to the dielectric constant of the test medium. The original calibration of the system, for example, can be performed at room temperature in air. To conduct a test in any other medium (e.g., liquid nitrogen) the original calibration need only be corrected for the change in dielectric constant [6].

2. MATERIAL CHARACTERIZATION

The material tested in this study is a nominal 64-kg/m^3 polyurethane foam designated as GM35. This amorphous organic polymer is a thermosetting foam. Our supply of this material was obtained from the NBS Office of Standard Reference Materials (OSRM) in Gaithersburg, Maryland. The OSRM distributed this and other expanded plastics for the Products Research Committee [7,8]. These materials were commercially produced and designated as General Materials.

The bulk supply of GM35 was a 0.1-m x 0.6-m x 0.6-m slab (figure 1a). The orientation of the elongated cell axis for the material used in the physical properties tests was determined optically from statistical evaluation of photomicrographs. The ratios of cell height to cell width for the principal orthogonal planes of the physical test specimens were: $x/y = 0.94 \pm 0.34$, $z/x = 1.60 \pm 0.65$, $z/y = 1.51 \pm 0.58$. The uncertainties given represent estimates of one standard deviation. The cell orientations relative to the orthogonal axes of the bulk slab are shown in figure 1b.

The density of this resin-gas composite was found to be 62.22 ± 0.28 kg/m³, 62.52 ± 0.11 kg/m³, and 62.56 ± 0.13 kg/m³ after conditioning at 23°C and 24, 50, and 92 percent relative humidity respectively. The uncertainties given are estimates of one standard deviation.

3. SPECIMENS

Test specimens taken from the x/y or z/x plane in the bulk supply (see figure 1) are designated "longitudinal" when loaded parallel to the z direction. Conversely, specimens taken from the x/y plane and loaded parallel to either the x or y direction are designated "transverse".

The tensile specimens were rods 9.9-cm long and 2.9-cm in diameter. This specimen was used to determine Young's modulus, proportional limit, yield strength (at 0.2% offset) , and elongation (extrapolated using ultimate tensile strength). For the determination of ultimate tensile strength, a reduced section specimen was used. Its gage length was 5.1 cm and its diameter was 1.9 cm. All tensile specimens were epoxied to polycarbonate grips, which were threaded to accomodate the tensile pull-rod system. The reduced-section geometry forced fracture to occur within the gage length, thereby eliminating the effect of biaxial stresses at the grip ends.

The compression specimens were 2.54-cm long and 2.9-cm in diameter. These specimens did not require grips.

Shear specimens were 1.9 cm x 2.54 cm x 0.4 cm. The specimens were epoxied to two flat plates and each plate was attached to the upper and lower tensile pull-rod system, respectively. An aluminum cylinder was slipped over the specimen and plates to help maintain alignment and minimize induced torque during testing. In addition, the cylinder has a built-in resistive heater that is controlled by a thermocouple to produce and maintain the desired test temperature.

4. TEST PROCEDURES

Most tests were conducted at 295 K(air), 111 K(gaseous helium), 76 K(liquid nitrogen), and 4 K (liquid helium). To minimize thermal shock to the specimen, the liquid helium or nitrogen was transferred at a very slow rate. The tensile and compressive properties included: Young's modulus, proportional limit, yield strength (at 0.2 percent offset), tensile and compressive strengths, and elongation (elastic and plastic).

Since an ASTM shear strength test method is not available for soft cellular materials such as these foams, several methods were carefully considered, and a version of the guillotine-type shear test was selected. Many specimen geometries (thicknesses and widths) were tested to find the best combination that most consistently failed in shear. At least three tests were conducted at each temperature; in some cases, more tests were run to determine material variability. Prior to testing, all specimens were "conditioned" in an environmental chamber for not less than four days at 23°C and 50 percent relative humidity. Each specimen was tested shortly after removal from the environmental chamber. All tests were conducted in a conventional compression/tension test machine at a strain rate of 5×10^{-3} min^{-1}. (Varying the rate from 5×10^{-4} to 5×10^{-2} min^{-1} had no measurable effect on results.)

5. RESULTS

Results are presented in figures 2 through 15 and tables 1 through 6. The bars on the figures indicate the data spread from replicate tests. Scatter is typically higher for compression and shear than for tensile tests; this is because the compressive and shear tests are more sensitive to problems such as misalignment (tensile specimens self-align during the test). Unlike the 32-kg/m³ foam that was tested previously [1], the cell orientation of the 64-kg/m³ material agreed very well with the bun-line orientation (i.e., the vertical or "rise" direction is denoted as longitudinal). Tensile results shown in figures 2 through 6 are Young's modulus, ultimate strength, and strain-versus-temperature, as well as stress-versus-strain curves for all temperatures. In addition to the above properties, compressive results include yield strength (at 0.2% offset), proportional limit versus temperature, and a typical load-versus-displacement curve, as shown in figures 7 through 14. The shear results are given in figure 15.

Tensile, Young's modulus, proportional limit, yield strength, ultimate strength, and shear strength values all increase as temperature decreases from 295 K to 4 K. The longitudinal orientation results have the highest values. As shown in figure 4, tensile strain decreases with temperature, and the material becomes brittle at temperatures below 111 K. The compressive Young's modulus versus temperature, as shown in figure 7, indicates a decrease in mean values from 111 K to 76 K, for both longitudinal and transverse specimens. The same behavior was also noted for a 32-kg/m^3 polyurethane foam material that was previously tested [1]. Using the Student's "t" test for small sample size, the longitudinal and transverse compressive data were calculated for 76 and 111 K. The results indicate a level of confidence of >99.95% for the transverse and 88% for longitudinal tests that the mean compressive modulus at 76 K is lower than the mean compressive modulus at 111 K [9]. Figure 11 indicates a deformation capability during compression at low temperatures. However, since the polyurethane material is incapable of true plastic deformation at cryogenic temperatures, this apparent plastic strain is caused by individual cells that collapse during testing. Figures 12 and 13 show the stress-versus-strain behavior of longitudinal and transverse specimens at 295, 111, 76, and 4 K. Figure 14 is an actual record of load-versus-displacement for a typical specimen. The load drops illustrate points at which individual or multiple cells fail under stress. Owing to material variability, the stress-strain graphs were plotted as smooth curves, which do not show the cell failure phenomena. Each stress-strain curve, at a given temperature and orientation, is the average of three or more specimens tested.

6. DISCUSSION

Polyurethane foam behavior is typical of polymers in general, with large mechanical property changes such as a complete loss of ductility and a doubling of E_T (Young's modulus-tension) following a temperature reduction from 295 K to 4 K. Certain longitudinal properties, like shear strength and E_C (Young's modulus-compression), exhibit maximum values between the two extreme temperature limits; however this is probably not a true material behavior but an effect influenced by material variability and orientation irregularities.

The anomalous behavior of compressive Young's modulus as shown in figure 7 appears to be a real effect. As stated previously, the 32-kg/m^3 polyurethane foam tested exhibited the same drop in modulus from 111 to 76 K. In addition, a third density of polyurethane foam (96-kg/m^3) has recently been tested and it shows the same trend.

Sectioning after testing revealed that cell orientation varied slightly from the orientation of the mold axes (see figure 1). It is generally thought that foam specimens from the center of a large billet have uniform cells oriented with respect to the vertical, but this is not true of foams formed on a continuous or bun-line production facility. The cell orientation reflects the movement of the foaming resin. However, as shown in this higher density foam, the problem of cell orientation with respect to vertical is not as severe as with less dense materials. Cells in the x-z plane of the material reported here have only a 86 to 87° inclination to the x-axis (figure 1).

Specimens tested previously in liquid nitrogen [1] appeared to have slightly lower shear strength values than those tested at the same temperature in cold helium gas. This may be an indication of environmental sensitivity. Nitrogen at low temperatures is deleterious to a number of other polymeric materials. Thermoplastics have exhibited crazing or reduced fracture strengths, or both when tensile tested in cold liquid or gaseous nitrogen, but not in vacuum or helium environments [10]. Environmental effects must ultimately be taken into account in design applications.

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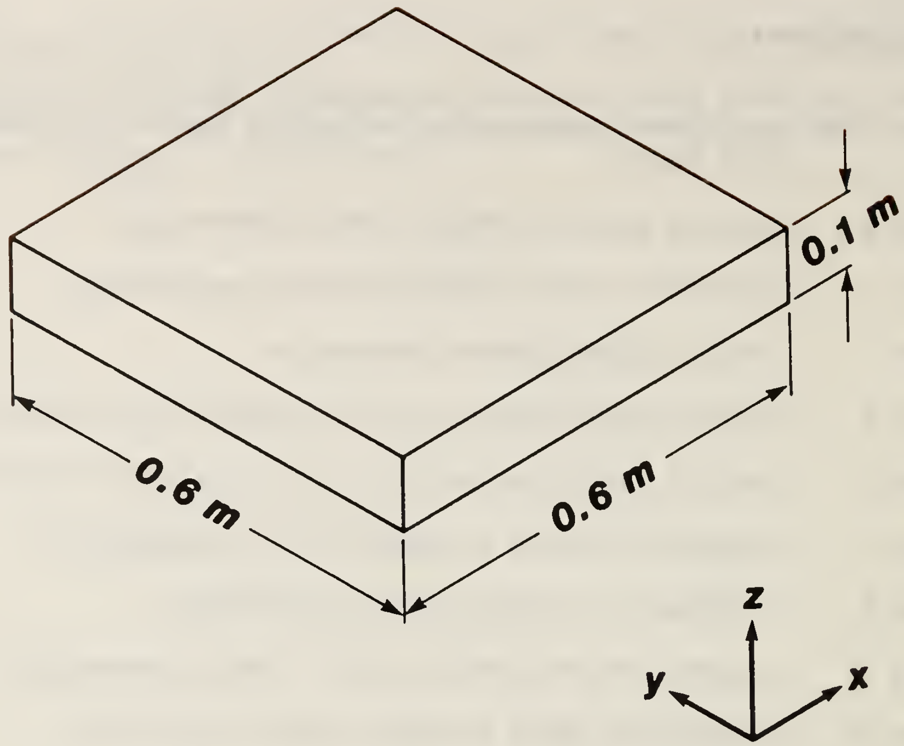
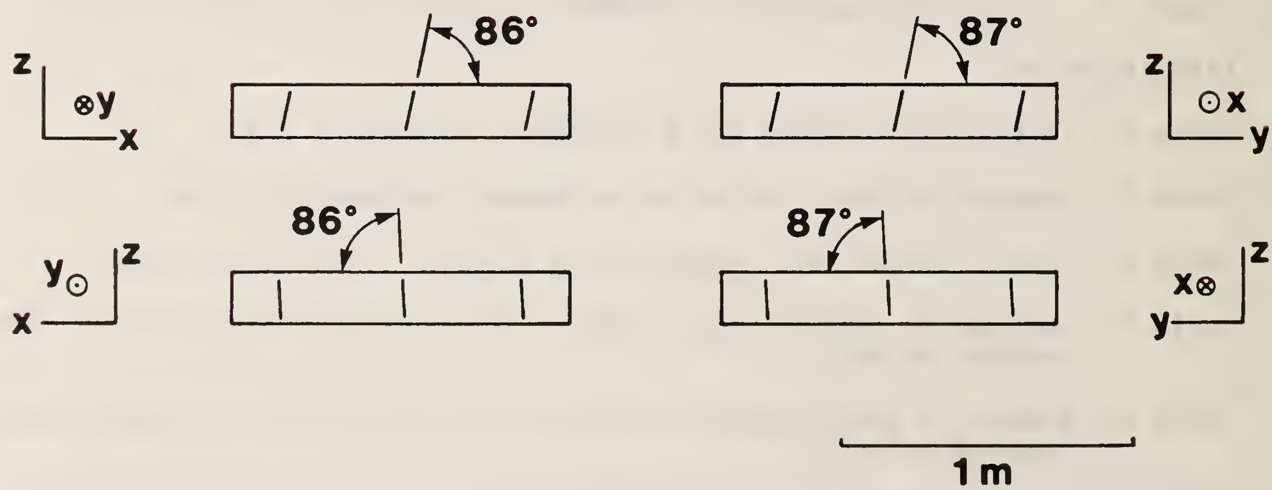


a)



b)

Figure 1(a). Bulk supply of bun-line-produced, 64-kg/m³ polyurethane foam.

(b). Cell orientation relative to the major coordinate axes of the bulk supply.

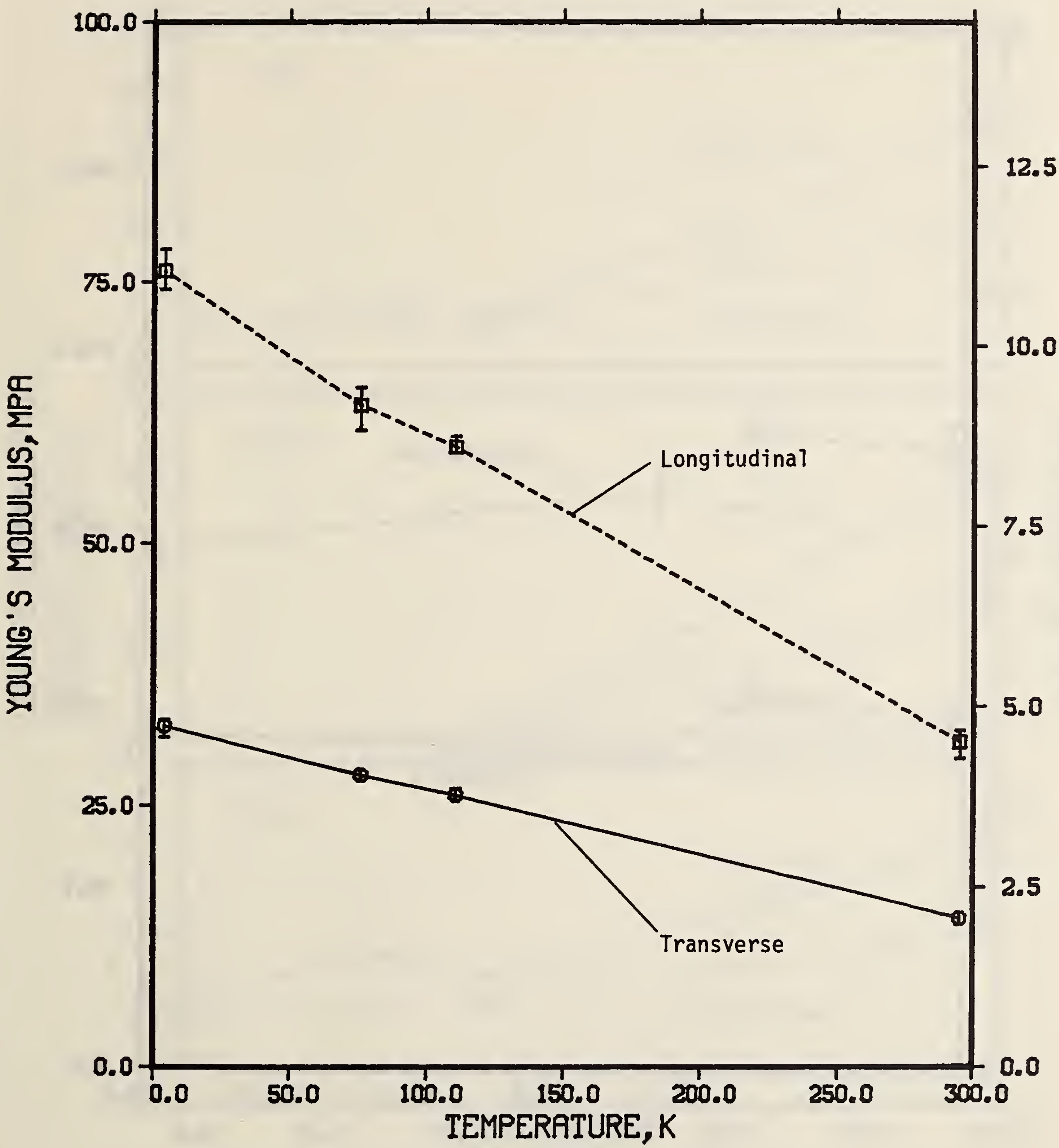


Figure 2. Tensile Young's modulus versus temperature.

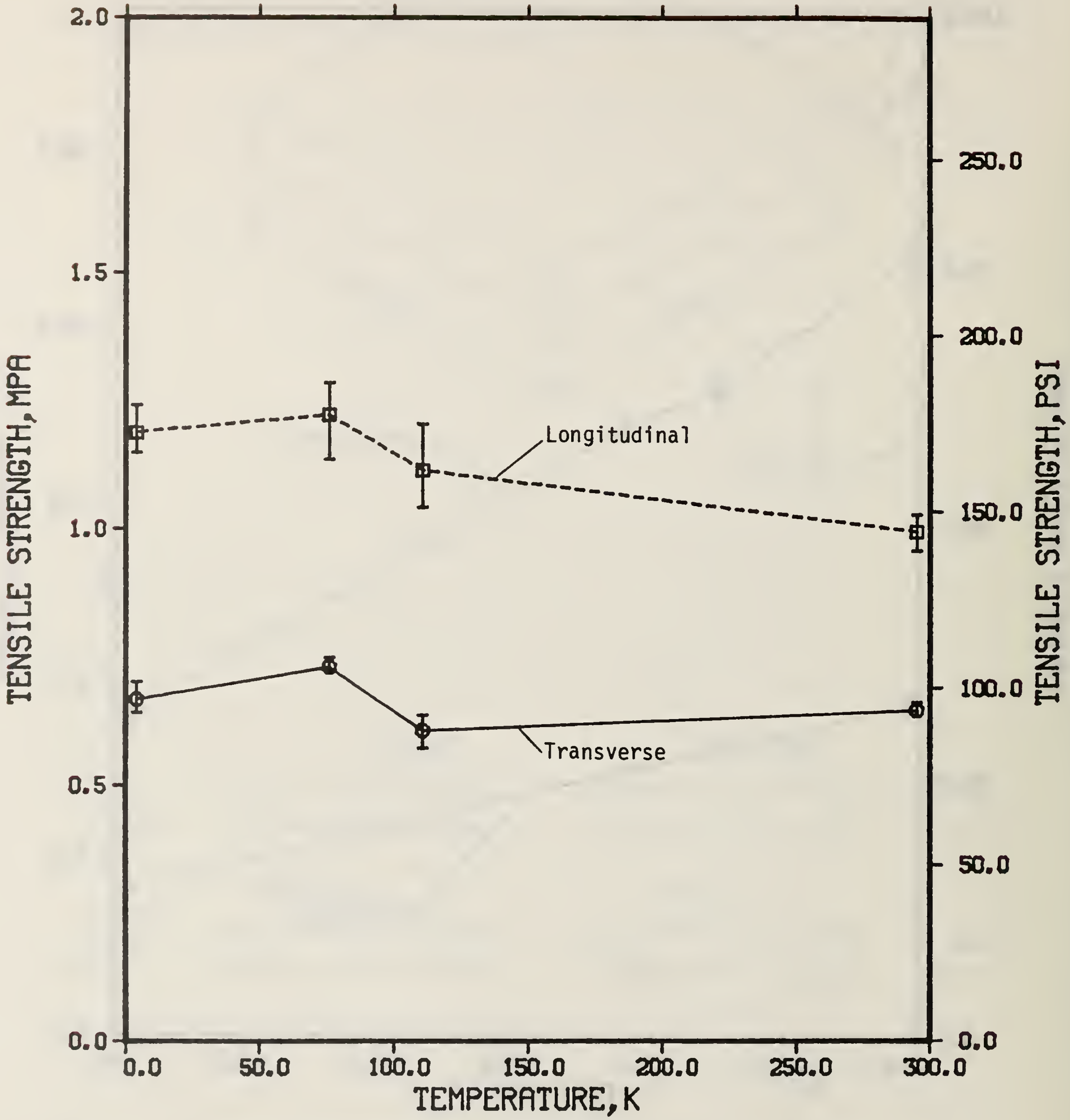


Figure 3. Ultimate tensile strength versus temperature.

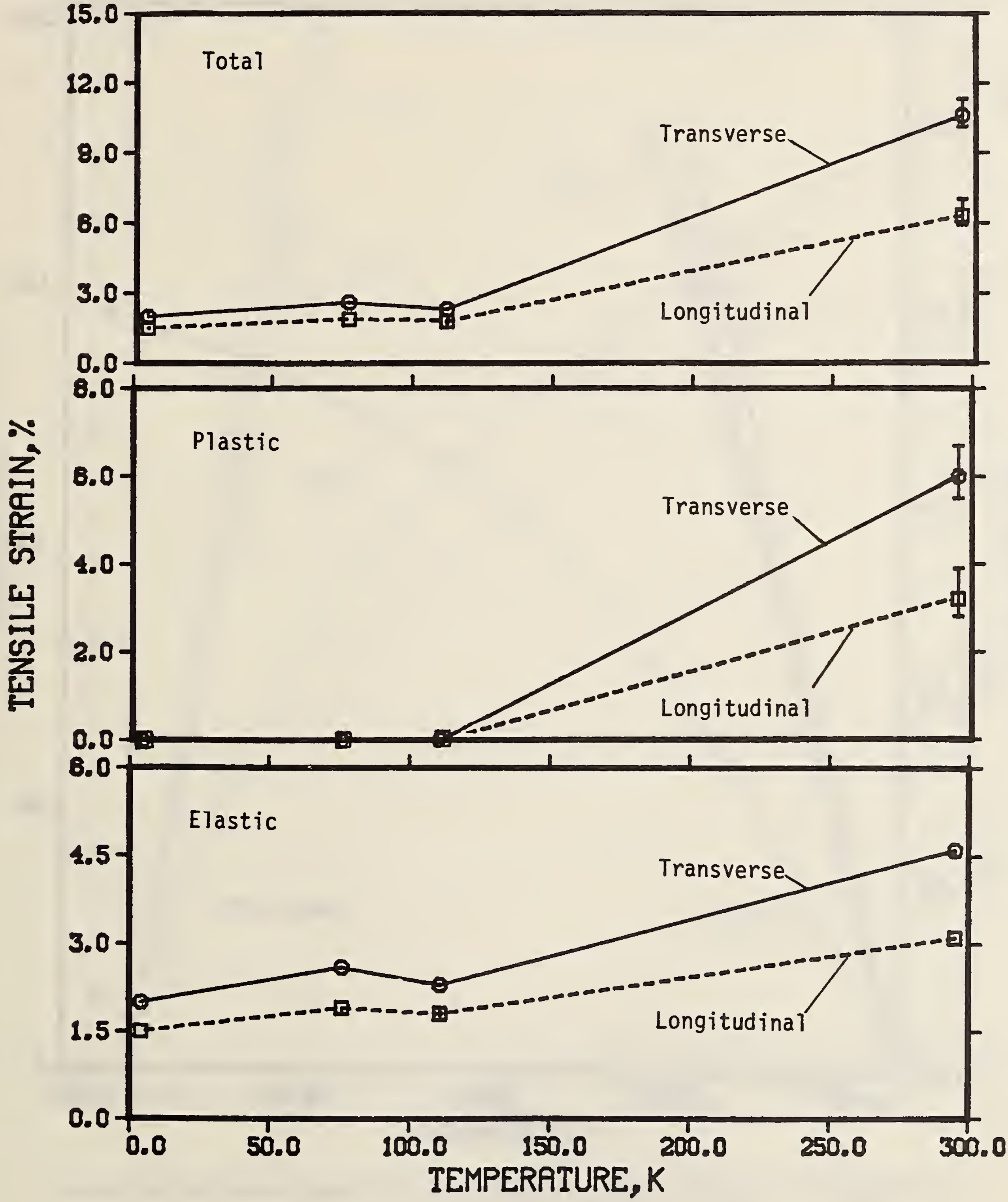


Figure 4. Tensile strain versus temperature.

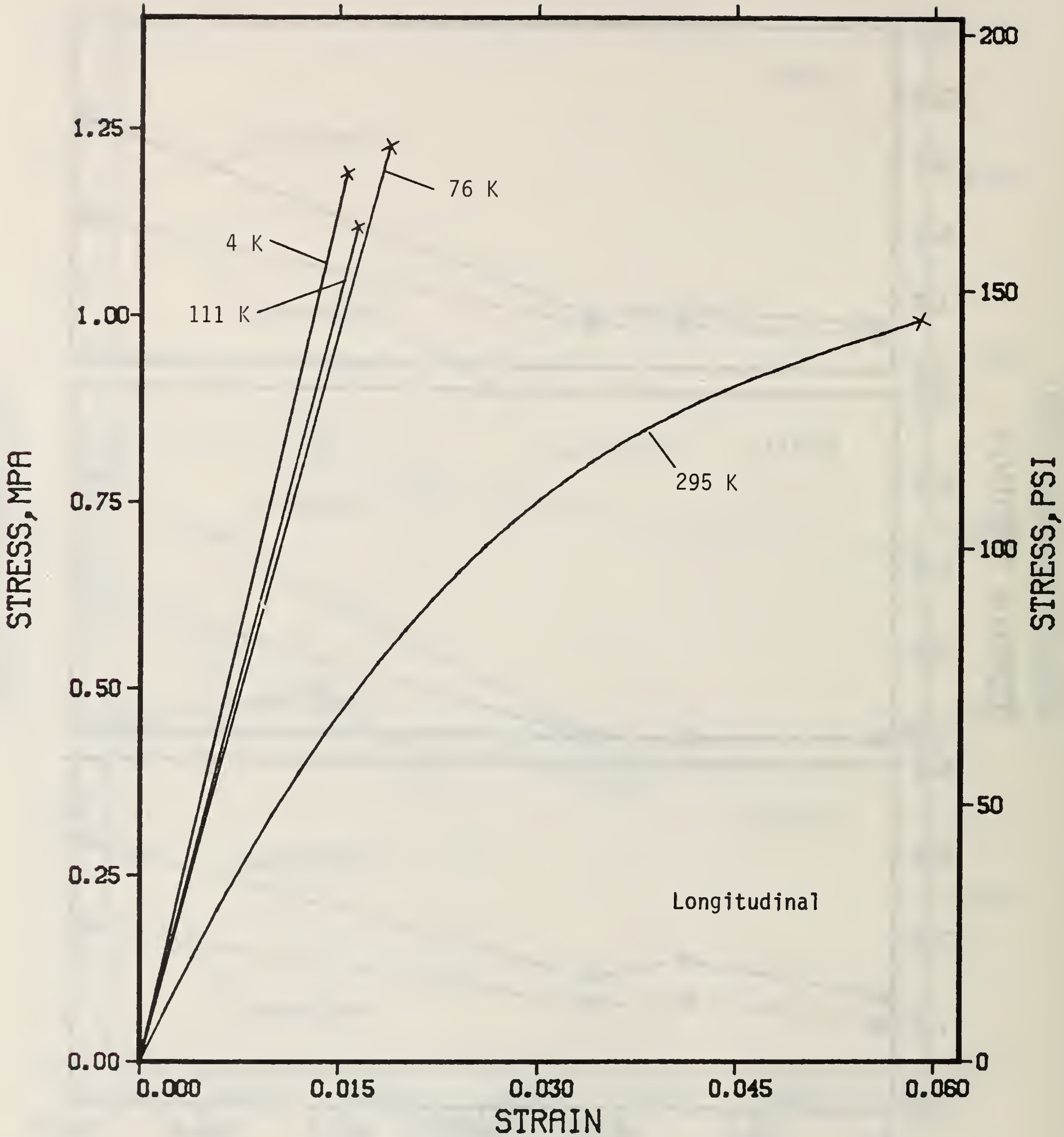


Figure 5. Tensile stress versus strain (longitudinal orientation).

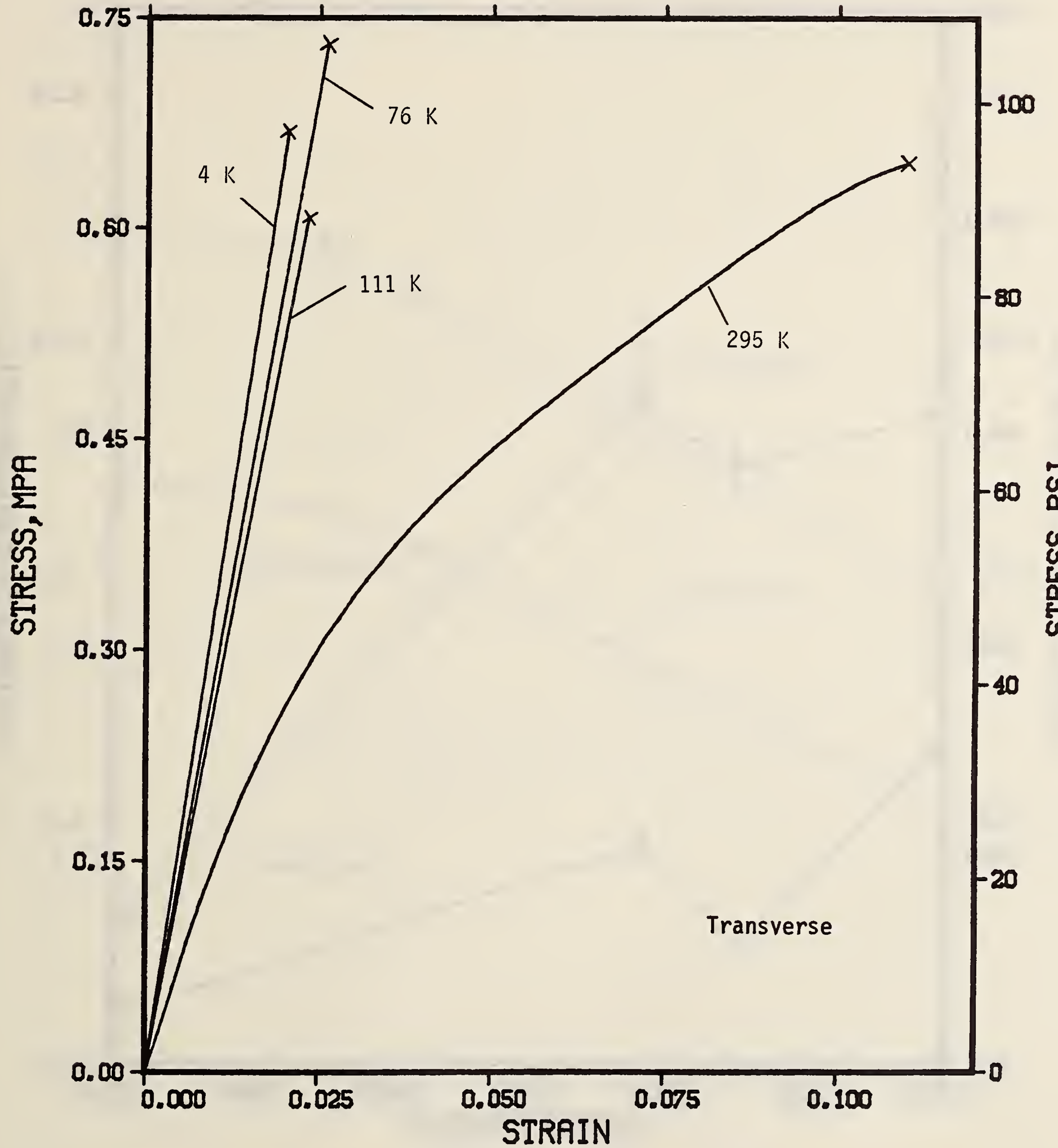


Figure 6. Tensile stress versus strain (transverse orientation).

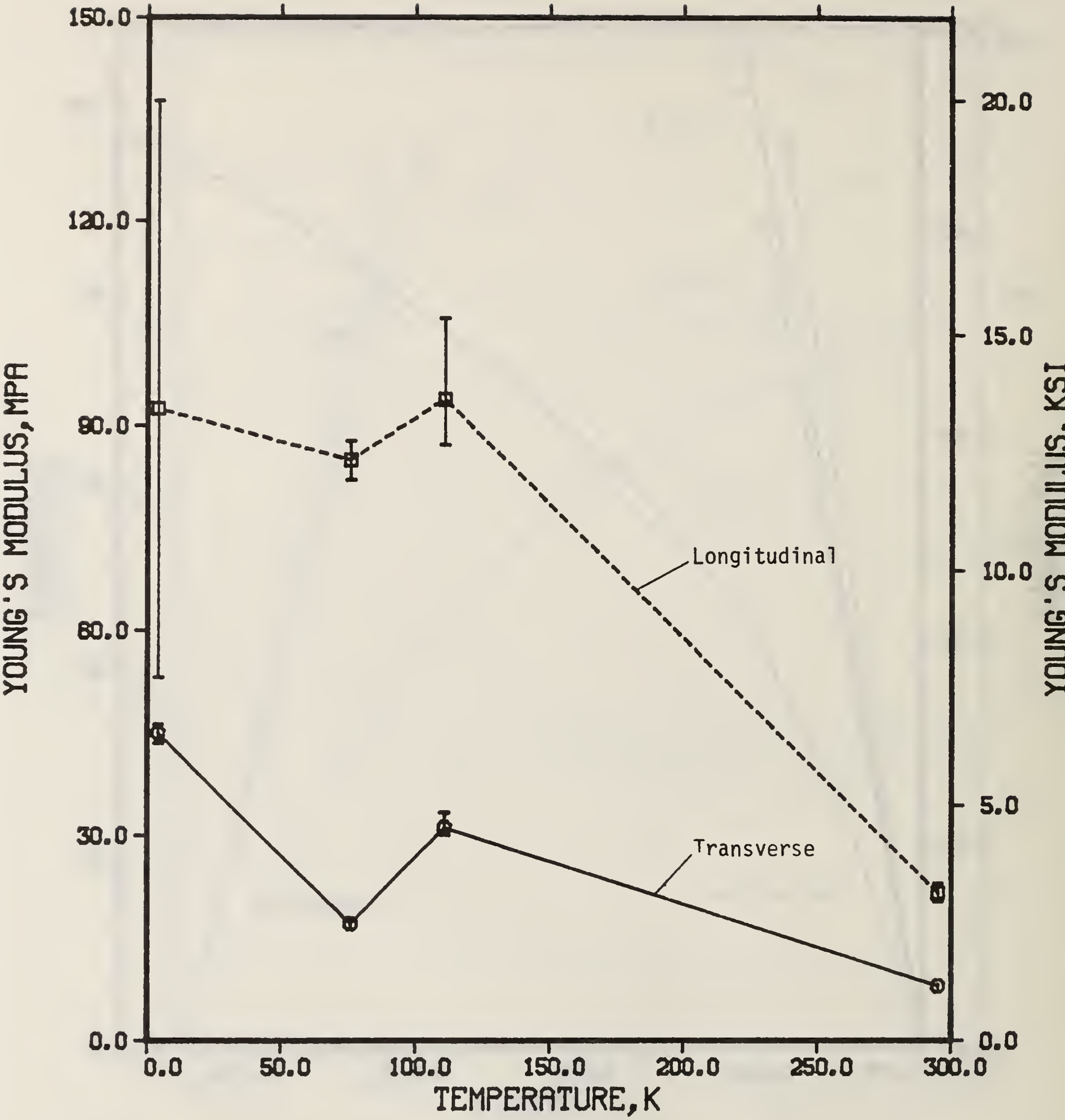


Figure 7. Compressive Young's modulus versus temperature.

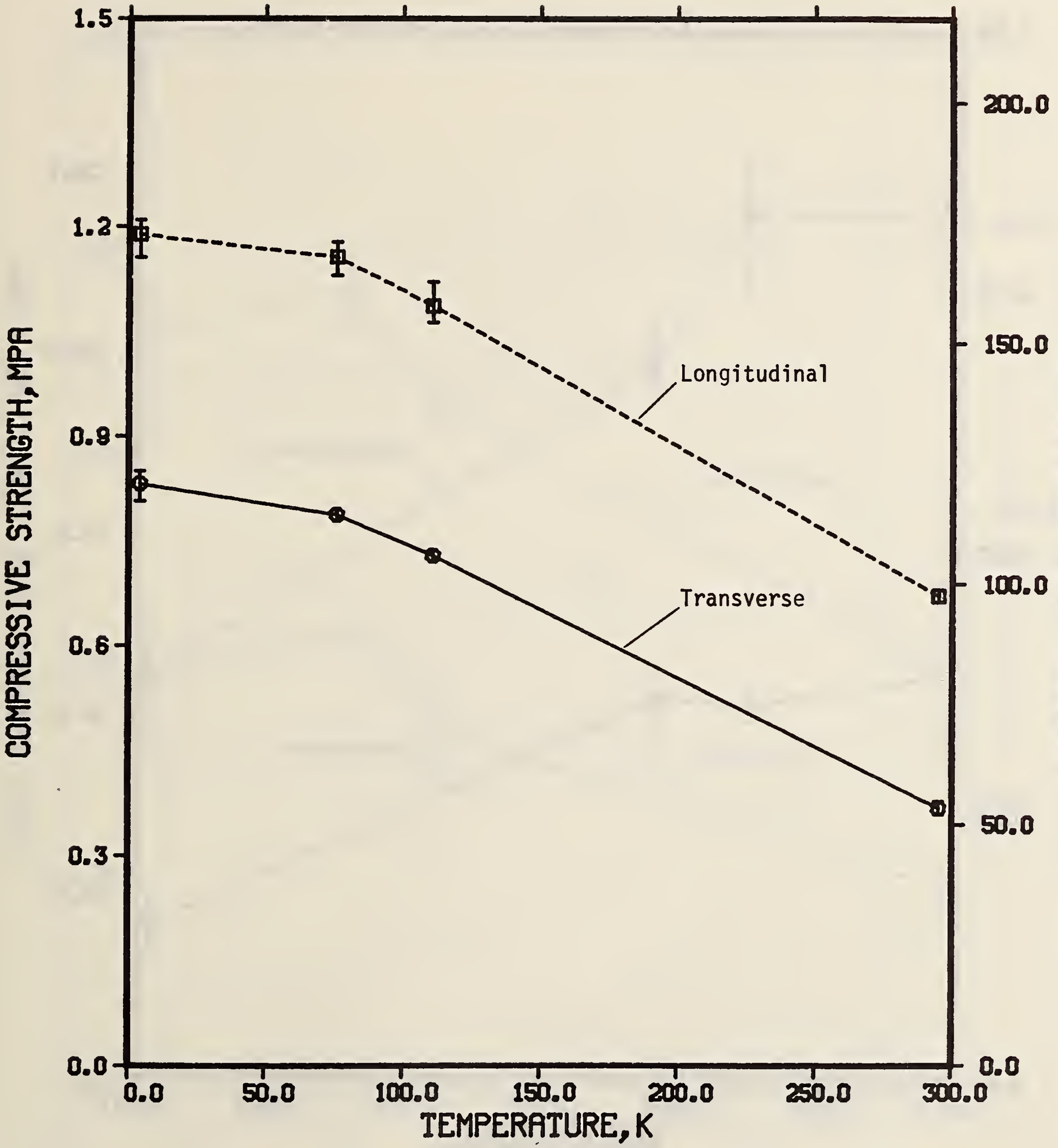


Figure 8. Compressive strength versus temperature.

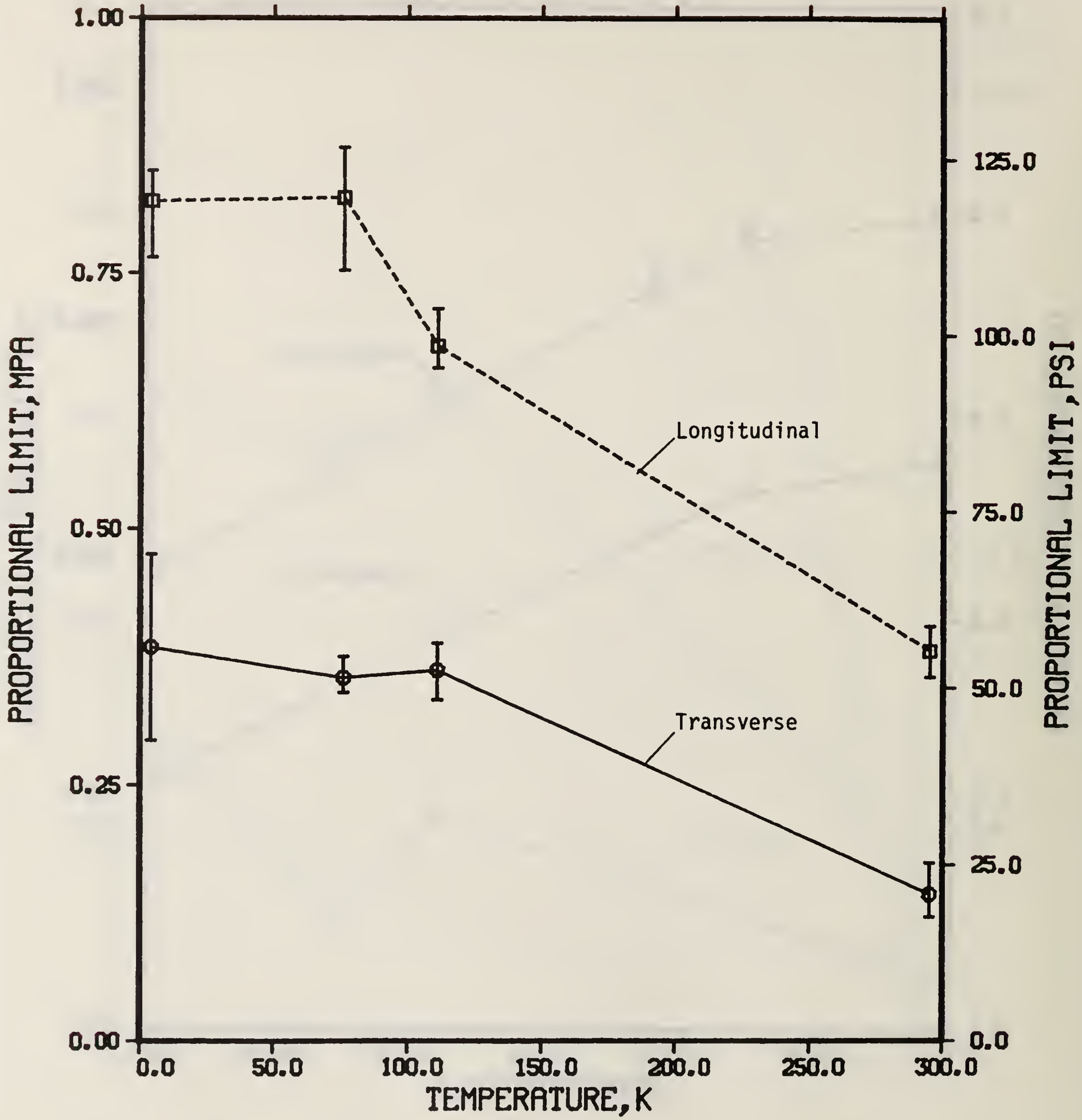


Figure 9. Compressive proportional limit versus temperature.

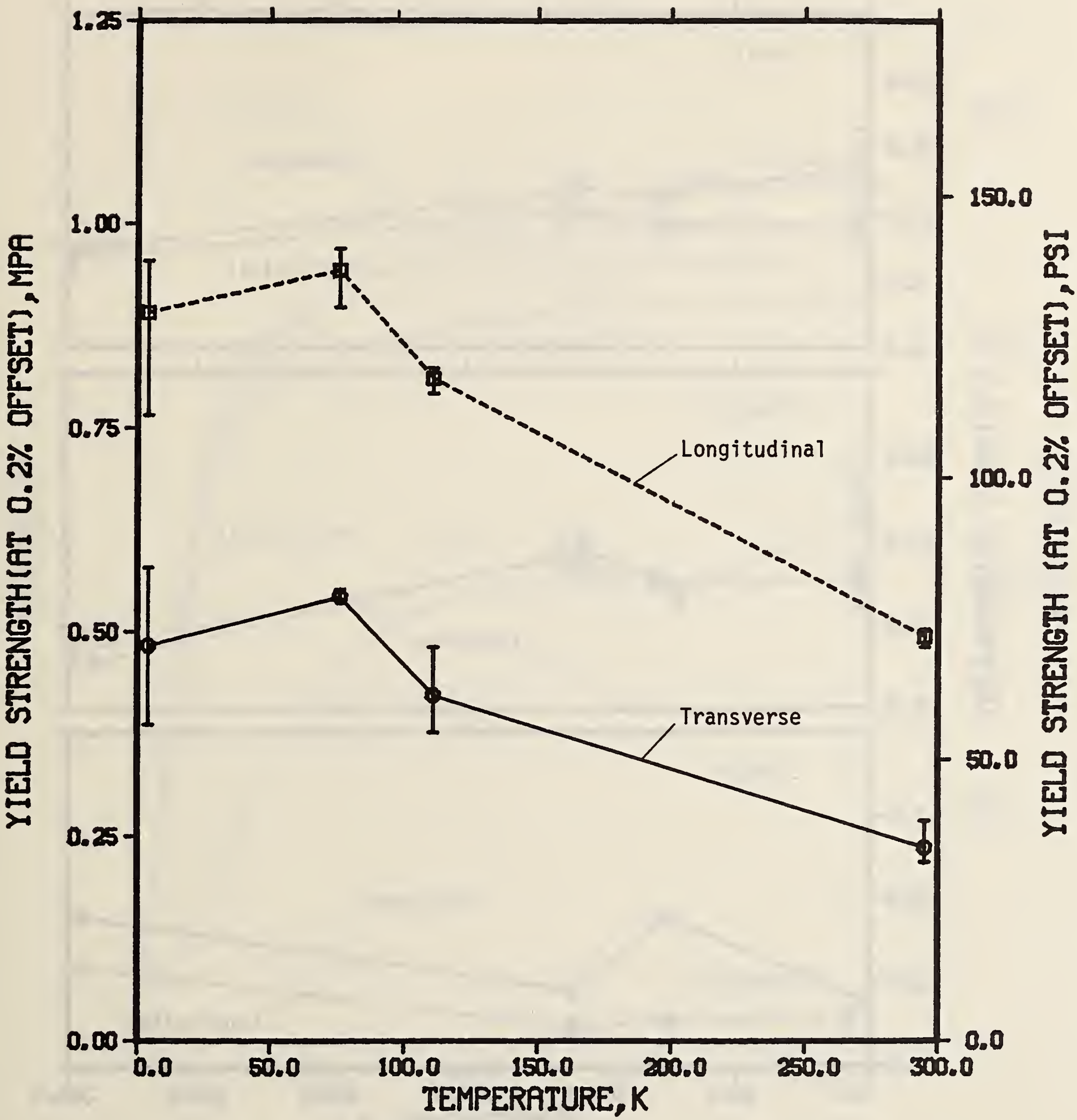


Figure 10. Compressive yield strength versus temperature.

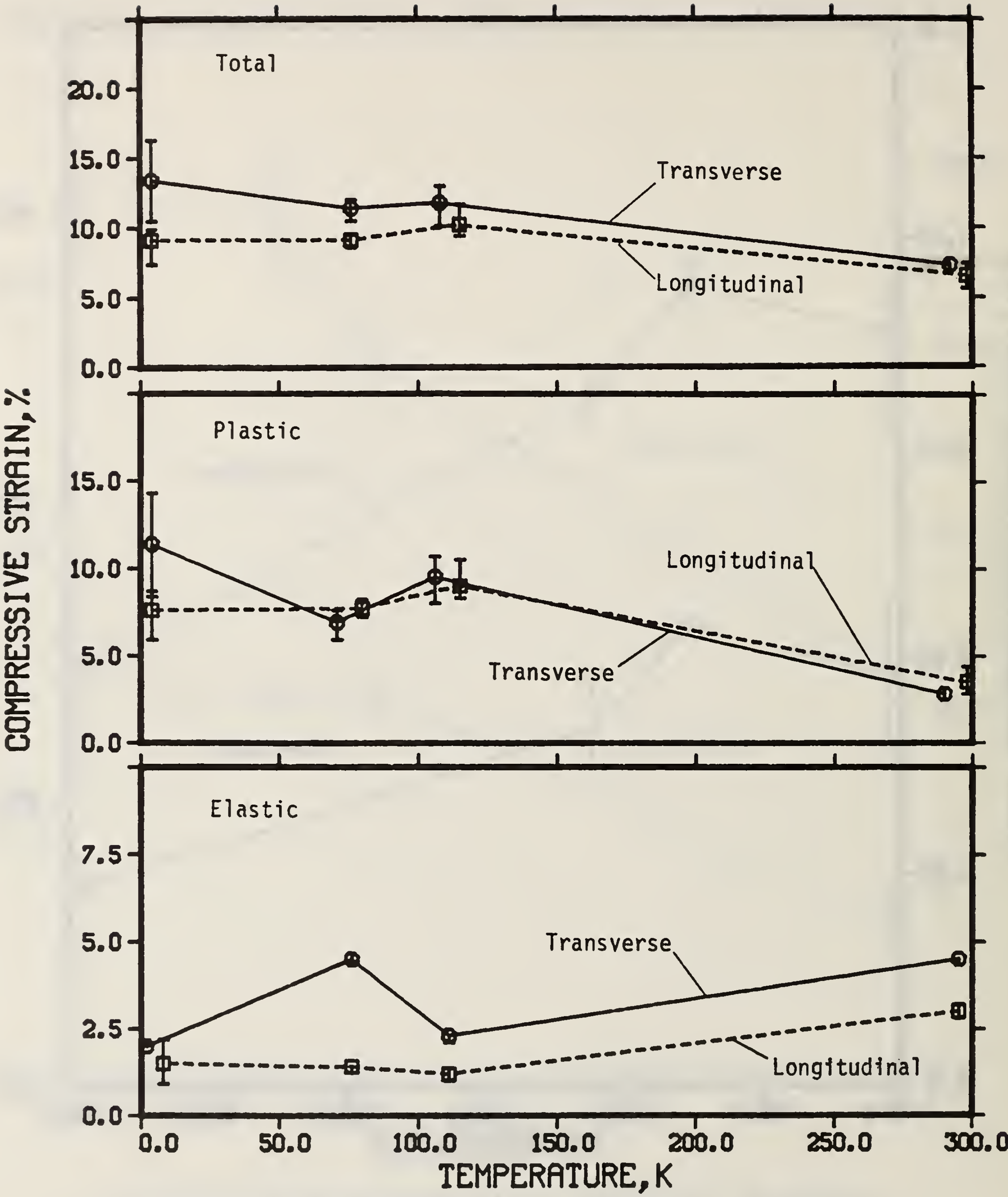


Figure 11. Compressive strain versus temperature.

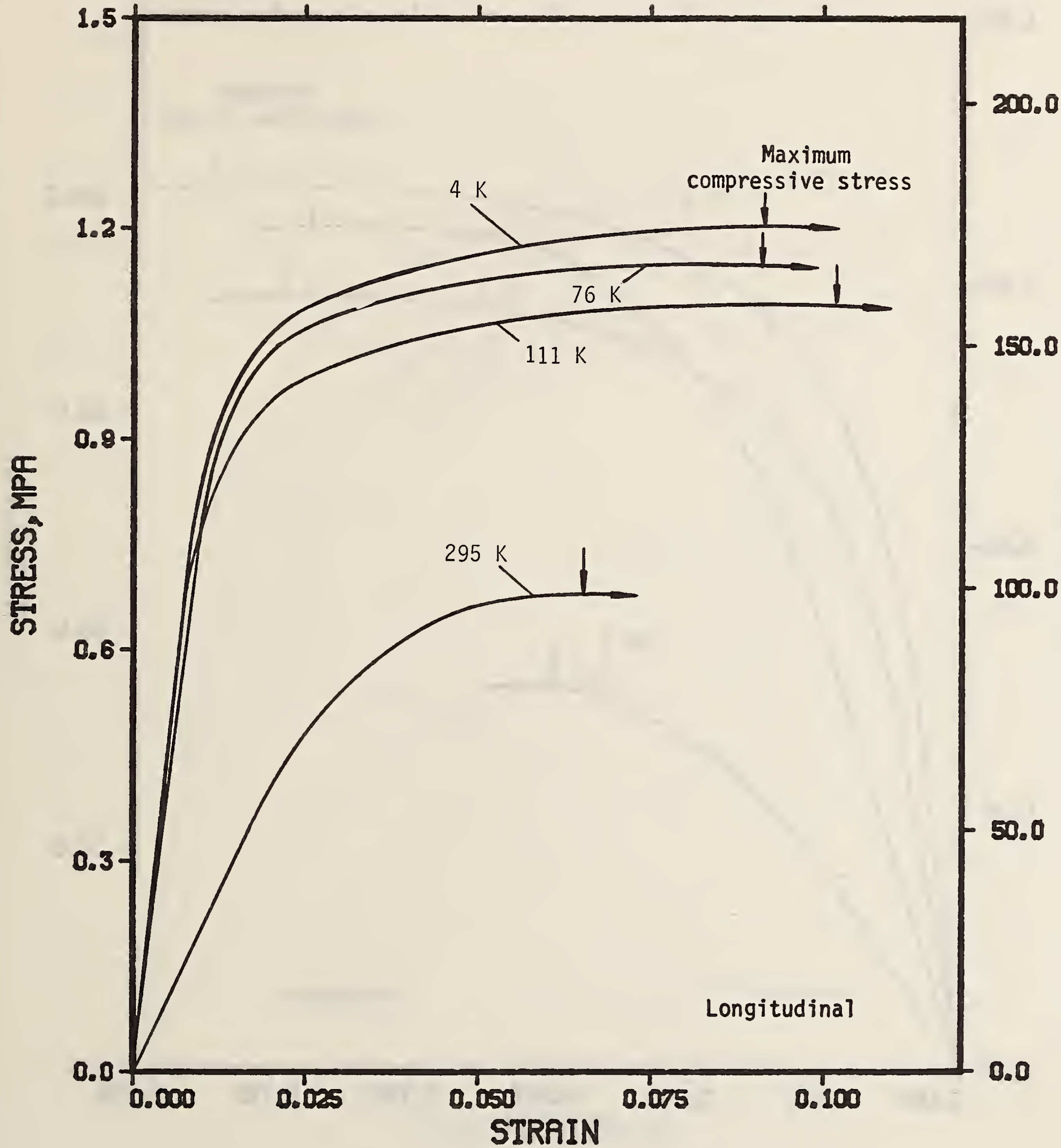


Figure 12. Compressive stress versus strain (longitudinal orientation).

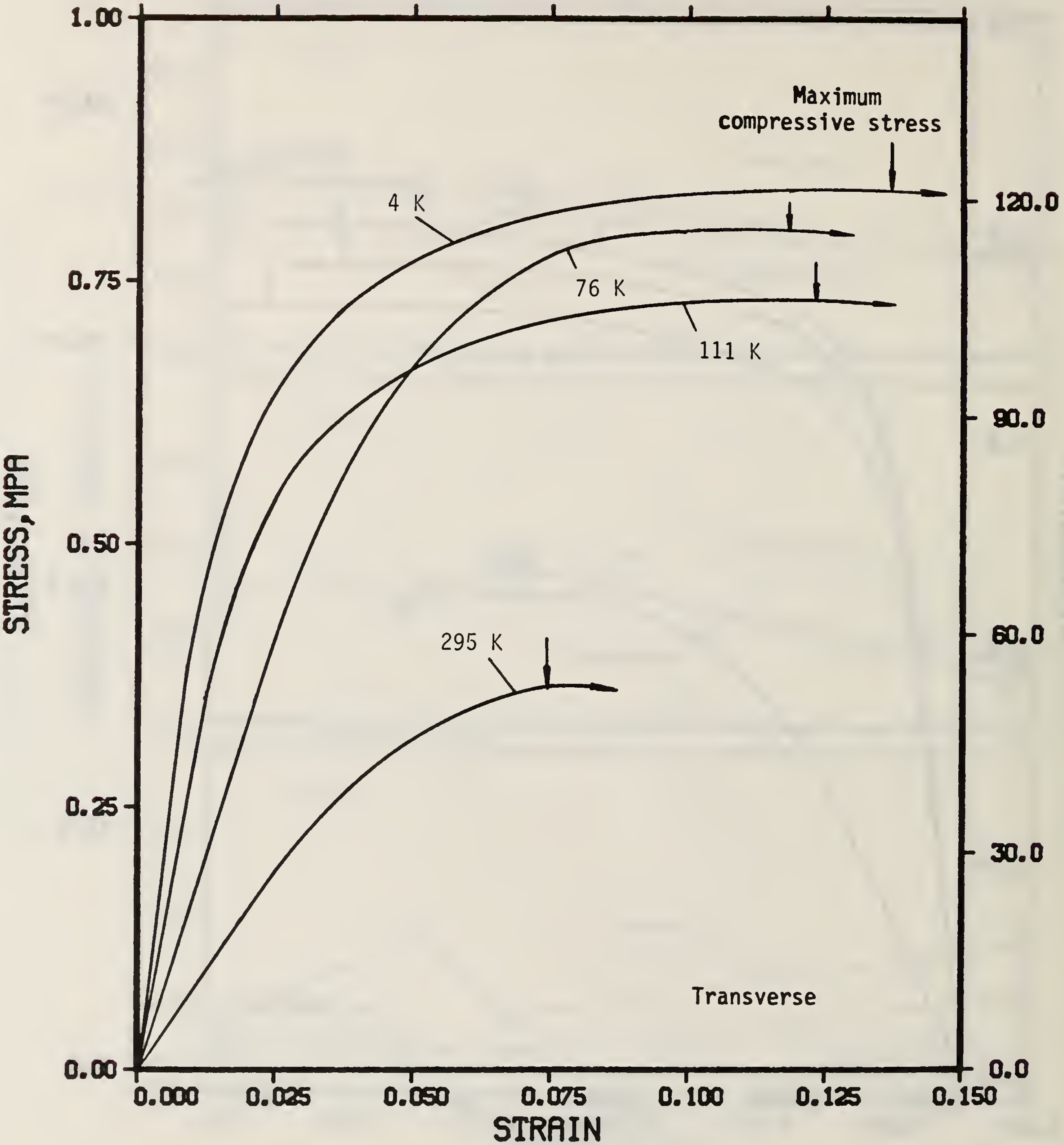


Figure 13. Compressive stress versus strain (transverse orientation).

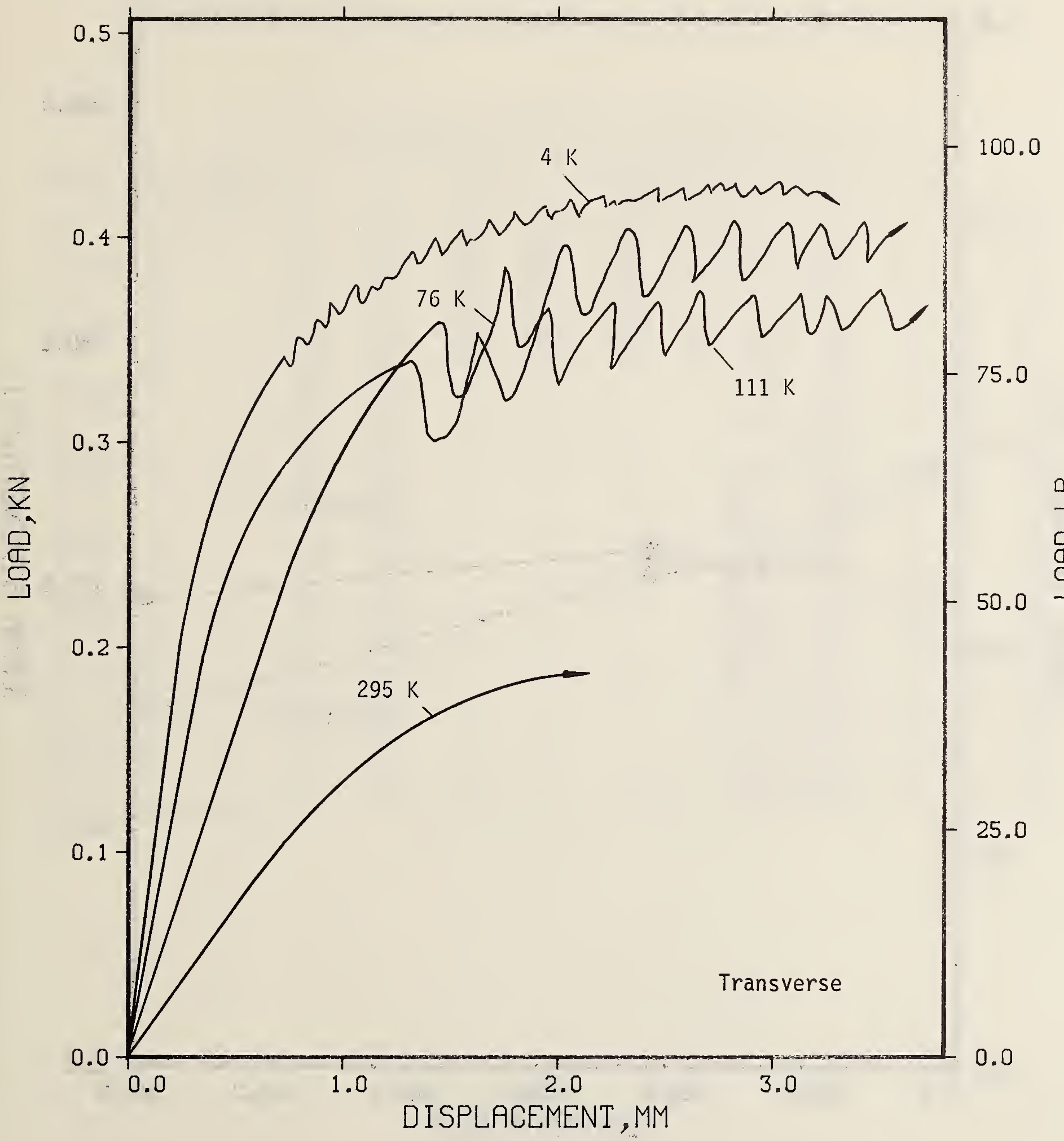


Figure 14. Compressive load versus displacement (transverse orientation).

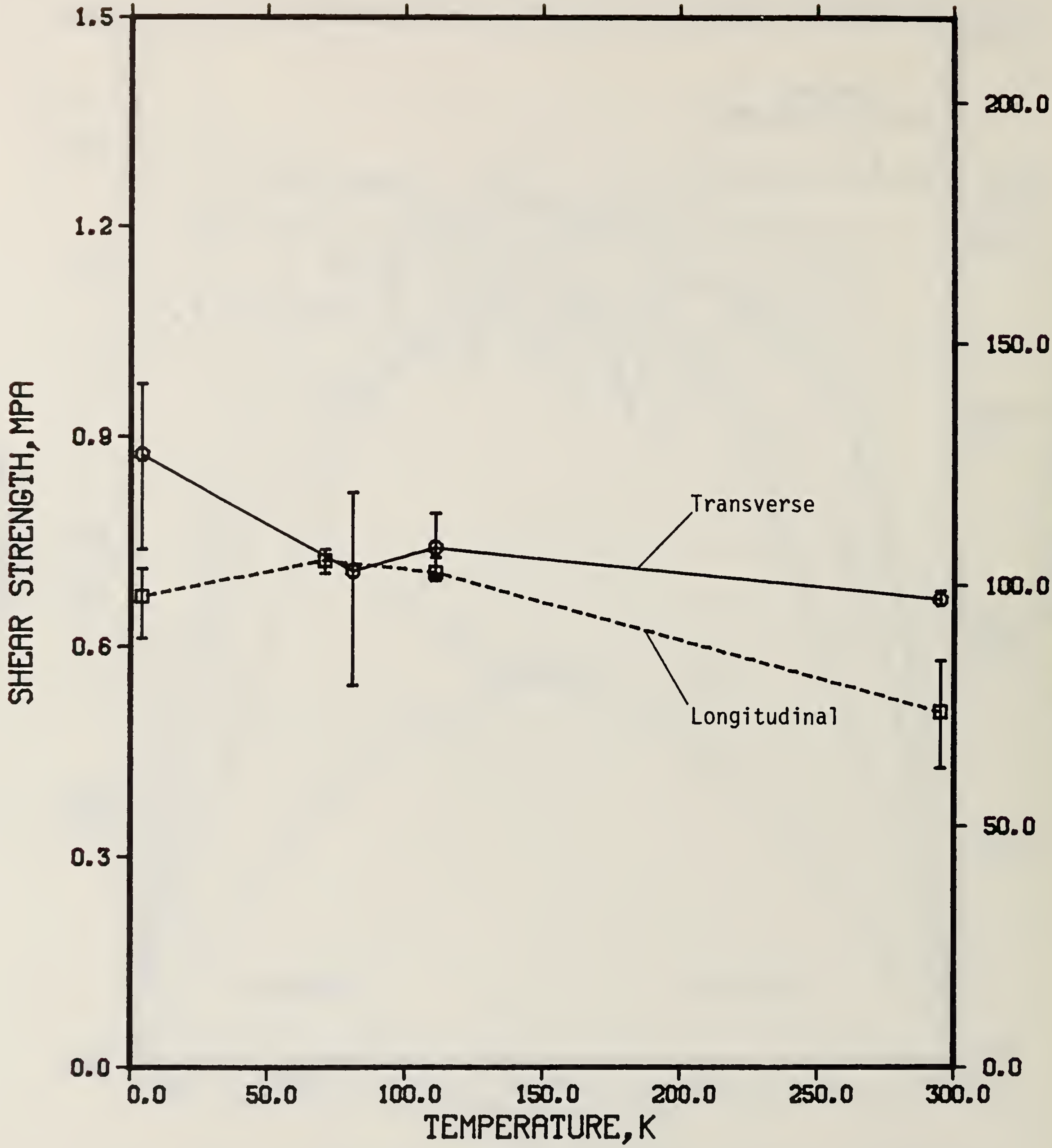


Figure 15. Shear strength versus temperature (longitudinal and transverse).

Table 1. Tensile test results for a 64-kg/m^3 polyurethane foam

Specimen number	Test temp., K	Specimen orientation[a]	Young's modulus, MPa	Young's modulus, psi	Proportional limit, MPa	Proportional limit, psi	Yield strength (at 0.2% offset) MPa	Yield strength (at 0.2% offset) psi	Ultimate tensile strength MPa	Ultimate tensile strength psi	Tensile strain, % Elastic	Tensile strain, % Plastic	Tensile strain, % Total
2LT,1LRT	295	L	31.63	4587	0.304	44.09	0.572	82.96	1.027	148.95	3.1	2.8	5.9
4LT,3LRT	295	L	32.13	4660	0.315	45.68	0.602	87.31	0.957	138.79	3.1	2.8	5.9
6LT,5LRT	295	L	29.51	4280	0.338	49.02	0.636	92.24	1.000	145.03	3.1	3.9	7.0
		$\bar{x}$ =	31.09	4509	0.319	46.26	0.603	87.50	0.995	144.26	3.1	3.2	6.3
2TT,1TRT	295	T	14.59	2116	0.156	22.63	0.262	38.00	0.639	92.67	4.5	5.8	10.3
4TT,3TRT	295	T	14.00	2030	0.145	21.03	0.252	36.55	0.662	96.01	4.6	6.7	11.3
10TT,9TRT	295	T	14.08	2042	0.171	24.80	0.262	38.43	0.638	92.53	4.6	5.5	10.1
		$\bar{x}$ =	14.22	2063	0.157	22.82	0.260	37.66	0.646	93.74	4.6	6.0	10.6
22LT,15LRT	111	L	58.80	8528	-	-	-	-	1.204	174.61	1.9	0	1.9
24LT,17LRT	111	L	58.75	8521	-	-	-	-	1.041	150.98	1.9	0	1.9
34LT,21LRT	111	L	60.20	8730	-	-	-	-	1.101	159.68	1.7	0	1.7
		$\bar{x}$ =	59.25	8593	-	-	-	-	1.115	161.76	1.8	0	1.8
24TT,19TRT	111	T	25.58	3710	-	-	-	-	0.637	92.38	2.4	0	2.4
26TT,23TRT	111	T	25.84	3748	-	-	-	-	0.611	88.61	2.3	0	2.3
42TT,25TRT	111	T	26.63	3862	-	-	-	-	0.573	83.10	2.3	0	2.3
		$\bar{x}$ =	26.02	3774	-	-	-	-	0.607	88.03	2.3	0	2.3
8LT,9LRT	76	L	64.97	9423	-	-	-	-	1.136	164.75	1.9	0	1.9
12LT,11LRT	76	L	60.80	8818	-	-	-	-	1.286	186.51	1.8	0	1.8
14LT,13LRT	76	L	63.91	9269	-	-	-	-	1.247	180.85	1.9	0	1.9
		$\bar{x}$ =	63.23	9170	-	-	-	-	1.223	177.37	1.9	0	1.9
12TT,11TRT	76	T	27.82	4035	-	-	-	-	0.750	108.77	2.6	0	2.6
14TT,13TRT	76	T	28.31	4106	-	-	-	-	0.723	104.86	2.6	0	2.6
16TT,17TRT	76	T	27.68	4014	-	-	-	-	0.721	104.57	2.6	0	2.6
		$\bar{x}$ =	27.94	4052	-	-	-	-	0.731	106.07	2.6	0	2.6
16LT,19LRT	4	L	78.14	11333	-	-	-	-	1.172	169.97	1.5	0	1.5
18LT,23LRT	4	L	75.78	10990	-	-	-	-	1.242	180.13	1.5	0	1.5
32LT,25LRT	4	L	74.26	10770	-	-	-	-	1.149	166.64	1.6	0	1.6
		$\bar{x}$ =	76.06	11031	-	-	-	-	1.188	172.25	1.5	0	1.5
18TT,15TRT	4	T	33.19	4814	-	-	-	-	0.702	101.81	2.0	0	2.0
20TT,27TRT	4	T	32.99	4785	-	-	-	-	0.641	92.96	2.0	0	2.0
30TT,31TRT	4	T	31.54	4574	-	-	-	-	0.662	96.01	2.1	0	2.1
		$\bar{x}$ =	32.57	4724	-	-	-	-	0.668	96.93	2.0	0	2.0

[a] L: longitudinal; T: transverse

Table 2. Compressive test results for a 64-kg/m³ polyurethane foam

Specimen number	Test temp., K	Specimen orientation[a]	Young's modulus, MPa	Young's modulus, psi	Proportional limit, MPa	Proportional limit, psi	Yield strength (at 0.2% offset), MPa	Yield strength (at 0.2% offset), psi	Maximum compressive strength, MPa	Maximum compressive strength, psi	Compressive strain, % Elastic	Compressive strain, % Plastic	Compressive strain, % Total
26LC (A)	295	L	23.08	3347	0.355	51.49	0.498	72.22	0.668	96.88	2.8	2.8	5.6
26LC (B)	295	L	20.37	2954	0.405	58.74	0.482	69.90	0.668	96.88	3.2	3.4	6.6
28LC (B)	295	L	21.63	3137	0.382	55.40	0.504	73.10	0.680	98.62	3.0	4.4	7.4
$\bar{x}$ =			21.69	3146	0.381	55.21	0.495	71.74	0.672	97.46	3.0	3.5	6.5
32TC (A)	295	T	7.86	1140	0.121	17.55	0.222	32.20	0.360	52.21	4.4	3.1	7.5
32TC (B)	295	T	8.30	1204	0.136	19.72	0.219	31.76	- a	-	-	-	-
38TC (A)	295	T	7.95	1153	0.174	25.24	0.270	39.16	0.378	54.82	4.5	2.6	7.1
$\bar{x}$ =			8.04	1166	0.143	20.84	0.237	34.37	0.369	53.52	4.5	2.8	7.3
28LC (A)	111	L	105.81	15346	0.715	103.70	0.817	118.49	1.078	156.34	1.0	8.4	9.4
28LC (B)	111	L	87.19	12645	0.664	96.30	0.823	119.36	1.063	154.17	1.2	10.5	11.7
30LC (A)	111	L	88.72	12867	0.657	95.28	0.792	114.86	1.121	162.58	1.3	8.3	9.6
$\bar{x}$ =			93.91	13619	0.679	98.43	0.811	117.57	1.087	157.70	1.2	9.0	10.2
40TC (B)	111	T	30.07	4361	0.389	56.42	0.482	69.90	0.734	106.45	2.4	9.9	12.3
40TC (C)	111	T	30.07	4361	0.362	52.50	0.409	59.32	0.722	104.71	2.3	10.7	13.0
47TC (A)	111	T	33.46	4853	0.334	48.44	0.378	54.82	0.730	105.87	2.1	8.0	10.1
$\bar{x}$ =			31.20	4525	0.362	52.45	0.423	61.35	0.729	105.68	2.3	9.5	11.8
31LC (A)	76	L	85.13	12346	0.846	122.70	0.970	140.68	1.179	170.99	1.4	7.7	9.1
31LC (B)	76	L	87.77	12729	0.873	126.61	0.962	139.52	1.160	168.23	1.3	8.2	9.5
31LC (C)	76	L	82.03	11897	0.753	109.21	0.897	130.09	1.131	164.03	1.4	7.2	8.6
$\bar{x}$ =			84.98	12324	0.824	119.51	0.943	136.76	1.157	167.75	1.4	7.7	9.1
38TC (A)	76	T	16.80	2436	0.376	54.53	0.552	80.06	0.792	114.86	4.6	5.9	10.5
38TC (B)	76	T	17.72	2570	0.341	49.46	0.537	77.88	0.792	114.86	4.4	7.6	12.0
49TC (A)	76	T	16.85	2444	0.349	50.62	0.539	78.17	0.781	113.27	4.5	7.3	11.8
$\bar{x}$ =			17.12	2483	0.355	51.54	0.543	78.70	0.788	114.33	4.5	6.9	11.4
33LC (A)	4	L	79.55	11537	0.765	110.95	0.897	130.09	1.156	167.65	1.5	5.9	7.4
33LC (B)	4	L	53.17	7711	0.850	123.28	0.955	138.50	1.183	171.57	2.2	7.4	9.6
33LC (C)	4	L	99.43	14420	0.846	122.70	0.947	137.34	1.210	175.49	1.2	8.7	9.9
35LC (A)	4	L	137.69	19969	-	-	0.765	110.95	1.206	174.91	0.9	8.5	9.4
$\bar{x}$ =			92.46	13409	0.820	118.98	0.891	129.22	1.189	172.41	1.5	7.6	9.1
35TC (B)	4	T	43.48	6306	0.294	42.64	0.387	56.13	0.807	117.04	2.1	8.4	10.5
48TC (A)	4	T	46.29	6713	0.475	68.89	0.579	83.97	0.850	123.28	2.0	14.3	16.3
49TC (B)	4	T	45.17	6551	-	-	-	-	0.838	121.53	-	-	-
$\bar{x}$ =			44.98	6523	0.384	55.77	0.483	70.05	0.832	120.62	2.0	11.4	13.4

[a] Stress continued to increase as strain increased - no maximum reached.

Table 3. Shear strength test results for a 64-kg/m³ polyurethane foam

Specimen number	Test temperature, K	Specimen orientation	Shear strength, MPa	Shear strength, psi
SL4	295	L	0.428	61.99
SL6	295	L	0.581	84.19
SL7	295	L	0.514	74.53
			$\bar{x}$ = 0.508	73.57
ST6	295	T	0.681	98.68
ST7	295	T	0.661	95.90
ST8	295	T	0.663	96.19
			$\bar{x}$ = 0.668	96.92
SL11	111	L	0.697	101.01
SL12	111	L	0.728	105.54
SL13	111	L	0.694	100.67
			$\bar{x}$ = 0.706	102.41
ST11	111	T	0.704	102.09
ST12	111	T	0.729	105.65
ST13	111	T	0.791	114.67
			$\bar{x}$ = 0.741	107.47
SL1	76	L	0.727	105.38
SL2	76	L	0.739	107.13
SL3	76	L	0.705	102.23
			$\bar{x}$ = 0.724	104.91
ST4	76	T	0.821	119.07
ST9	76	T	0.546	79.19
ST10	76	T	0.759	110.00
			$\bar{x}$ = 0.709	102.75
SL8	4	L	0.612	88.70
SL9	4	L	0.691	100.18
SL10	4	L	0.712	103.20
			$\bar{x}$ = 0.672	97.36
ST1	4	T	0.909	131.78
ST3	4	T	0.739	107.08
ST5	4	T	0.975	141.37
			$\bar{x}$ = 0.874	126.74

Table 4. Summary of tensile test results for a 64-kg/m³ polyurethane foam (average values)

Material property	Specimen orientation	Temperature 295 K	111 K	76 K	4 K
Young's modulus, MPa (psi)	L	31.09 (4,510)	59.25 (8,590)	63.23 (9,170)	76.06 (11,030)
	T	14.22 (2,060)	26.02 (3,770)	27.94 (4,050)	32.57 (4,720)
Proportional limit, MPa (psi)	L	0.319 (46.26)	-	-	-
	T	0.157 (22.82)	-	-	-
Yield strength (0.2% Offset), MPa (psi)	L	0.603 (87.50)	-	-	-
	T	0.260 (37.66)	-	-	-
Ultimate tensile strength, MPa (psi)	L	0.995 (144.26)	1.115 (161.76)	1.223 (177.37)	1.188 (172.25)
	T	0.646 (93.74)	0.607 (88.03)	0.731 (106.07)	0.668 (96.93)
Tensile strain, %					
Elastic	L	3.1	1.8	1.9	1.5
Plastic		3.2	0	0	0
Total		6.3	1.8	1.9	1.5
Elastic	T	4.6	2.3	2.6	2.0
Plastic		6.0	0	0	0
Total		10.6	2.3	2.6	2.0

Table 5. Summary of compressive test results for a 64-kg/m³ polyurethane foam (average values)

Material property	Specimen orientation	Temperature 295 K	111 K	76 K	4 K
Young's modulus, MPa (psi)	L	21.69 (3,150)	93.91 (13,620)	84.98 (12,320)	92.46 (13,410)
	T	8.04 (1,170)	31.20 (4,530)	17.12 (2,480)	44.98 (6,520)
Proportional limit, MPa (psi)	L	0.381 (55.21)	0.679 (98.43)	0.824 (119.51)	0.820 (118.98)
	T	0.143 (20.84)	0.362 (52.45)	0.355 (51.54)	0.384 (55.77)
Yield strength (0.2% Offset), MPa (psi)	L	0.495 (71.74)	0.811 (117.57)	0.943 (136.76)	0.891 (129.22)
	T	0.237 (34.37)	0.423 (61.35)	0.543 (78.70)	0.483 (70.05)
Maximum compressive strength, MPa (psi)	L	0.672 (97.46)	1.087 (157.70)	1.157 (167.75)	1.189 (172.41)
	T	0.369 (53.52)	0.729 (105.68)	0.788 (114.33)	0.832 (120.62)
Compressive strain, %					
Elastic	L	3.0	1.2	1.4	1.5
Plastic		3.5	9.0	7.7	7.6
Total		6.5	10.2	9.1	9.1
Elastic	T	4.5	2.3	4.5	2.0
Plastic		2.8	9.5	6.9	11.4
Total		7.3	11.8	11.4	13.4

Table 6. Summary of shear strength test results for a 64-kg/m^3 polyurethane foam (average values)

Test temperature, K	Specimen orientation	Shear strength, MPa	psi
295	L	0.508	73.57
	T	0.668	96.92
111	L	0.706	102.41
	T	0.741	107.47
76	L	0.724	104.91
	T	0.709	102.75
4	L	0.672	97.36
	T	0.874	126.74

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[ ] Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Polyurethane foam, having a density of 64-kg/m^3, was tested at 295, 111, 76, and 4 K. The material properties reported are Young's modulus, proportional limit, yield strength (at 0.2% offset), tensile, shear, and compressive strengths, and elongation (elastic and plastic). To perform these tests, a unique apparatus was developed. This apparatus permits tension, compression, and shear testing of materials at any temperature ranging from 295 to 1.8 K. Strain is measured with a concentric, overlapping-cylinder capacitance extensometer that is highly sensitive and linear in output.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

compressive strength; elongation; foam; insulation; low temperatures; mechanical properties; proportional limit; shear strength; tensile strength; yield strength; Young's modulus.

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