Predicting the Compressive Properties of Rigid Urethane Foam

S. L. DE GISI and THOMAS E. NEET, *Bendix Kansas City, Materials Engineering Organization 814-2, Kansas City, Missouri 64141*

Synopsis

The classic equation[1] in use throughout the urethane industry to predict the compressive properties of rigid foams is

$$\text{compressive property} = K(\text{density})^a. \tag{1}$$

The value of K and a need to be determined experimentally for each foam system at a given temperature. By evaluating the compressive properties of 14 different rigid urethane foams, a was defined as 1.75 for all materials at all test temperatures. General equations for predicting the foam's compressive properties over a temperature range of −65° to 325°F (−54° to 204°C) were then developed. These general equations appear to be reasonably accurate in predicting the compressive properties of any rigid urethane at any temperature up to the foam's softening point. The equations are of the form shown above with K being a function of temperature only. Finally, the K term was defined as a function of temperature. The equations developed for predicting the compressive strength and modulus of the rigid urethane foams are:

$$\text{compressive strength} = (8.09 - 0.0178T)\,\text{density}^{1.75} \tag{2}$$

for T equal to or greater than 77°F (25°C), and

$$\text{compressive modulus} = (191 - 0.369T)\,\text{density}^{1.75} \tag{3}$$

for T equal to or greater than −65°F (−54°C), where the compressive strength and modulus are in pounds per square inch and density is pounds per cubic foot. These equations are valid up to the softening point of the foam.

DISCUSSION

Scope and Purpose

An earlier project[2] defined the effect of density and temperature on the compressive strengths and moduli of eleven different rigid polyurethane foams. These relationships were developed by a conventional least-squares data fit to the equation

$$\text{compressive property} = K(\text{density})^a \tag{1}$$

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TABLE I
Foam System Materials

Material	Polyol type	Isocyanate type	Hydroxyl number	Water, % in system	Amine equivalent	Mix Ratio, % isocyanate
A	ester	polymeric/TDI[a]	605	1.12	135	66.1
B	ester	polymeric	605	0.79	152	69.6
C	ether	polymeric	905	0.69	134	67.9
D	ether	polymeric	351	0.56	134	54.9
E	ester	TDI	605	0.46	145	64.5
F	ether	TDI	905	0.47	145	73.4
G	ether	TDI	560	0.16	133	59.2
H	ester	TDI	495	1.35	138	64.4
I	ester	TDI	530	1.75	170	75.0
J	ester	TDI	550	0.74	135	62.0
K	ester	TDI	530	0.47	135	61.0
L	ester	TDI	420	0.80	139	57.8
M	ester	TDI	700	2.04	133	72.0
N	ester	TDI	700	1.22	133	68.1

a Polymeric, 80%/toluene diisocyanate, 20%.

The analyses were conducted under the erroneous assumption that the least-squares technique would find the "best fit" line for the data. In that work, K and a were dependent on both temperature and the specific foam system. A later study[3] showed that at high strains, a_1 could be defined as 1.75 for all materials and temperatures. Furthermore, general equations representing the compressive strengths of the materials were developed in which K was a function of temperature only. In that light, this project reanalyzed the previous static compression data along with new data on several additional foams to determine (1) if one a would be applicable to all materials and temperatures, (2) if general equations could be developed to represent all materials at specific test temperatures, and (3) if K could be defined as a function of temperature so that it would not need to be emperically developed for specific temperatures.

Activity

Efforts on this project were directed toward meeting three goals. First, for the classic equation,

$$\text{compressive property} = K(\text{density})^a \tag{1}$$

one common a was developed for all of the rigid urethane foams at all test temperatures. Then, general equations representing all materials at specific test temperatures were evaluated. Finally, K was defined as a function of temperature.

Development of a Constant a

Fourteen different rigid polyurethane foams were tested to determine the effect of material density and test temperature on the compressive properties of the foams. The materials, along with pertinent formulation information, are listed in Table I. Each of these foams was molded to at least four differ-

TABLE II
Maximum Exothermic Temperature and Softening Point of Urethane Foams

Material	Maximum exothermic temperature		Softening point[a]	
	° F	° C	° F	° C
A	318	(159)	367	(186)
B	355	(180)	417	(214)
C	340	(171)	405	(207)
D	320	(160)	270	(132)
E	335	(169)	282	(139)
F	385	(197)	413	(212)
G	360	(182)	273	(134)
H	300	(149)	270	(132)
I	310	(154)	270	(132)
J	375	(192)	286	(141)
K	365	(185)	264	(129)
L	320	(160)	29	(126)

[a] Determined by thermomechanical analysis.

ent densities in 4- by 6- by 12-in. (102 by 152 by 305 mm) billets. Test specimens were then cut from the cores of these billets. This was done to minimize density variations in the test coupons as well as to eliminate the effects of processing and formulating variables. Previously, it had been established,[4,5] for foam poured in relatively large billets, that the compressive

TABLE III

Comparison of Measured and Calculated Compressive Strength as a Function of Density at 77° F (25° C) for Material D[a]

Measured density, lb/ft³[b]	Measured strength, psi[c]	Calculated strength, psi	Difference psi	Error, %[d]
9.55	305.00	304.83	0.17	−0.06
9.64	313.00	310.01	2.99	0.96
9.62	305.00	308.85	−3.85	−1.25
9.50	300.00	301.96	−1.96	−0.65
9.63	305.00	309.43	−4.43	−1.43
9.50	303.00	301.96	1.04	0.34
9.59	308.00	307.12	0.88	0.29
9.57	305.00	305.97	−0.97	−0.32
9.61	307.00	308.28	−1.28	−0.41
9.56	305.00	305.40	−0.40	−0.13
14.70	660.00	662.01	−2.01	−0.30
14.32	630.00	631.56	−1.56	−0.25
14.12	640.00	615.79	24.21	3.93
14.39	640.00	637.12	2.88	0.45
14.55	650.00	649.91	0.09	0.01
14.76	665.00	666.88	−1.88	−0.28
14.43	630.00	640.31	−10.31	−1.61
14.42	640.00	639.51	0.49	0.08
14.31	640.00	630.76	9.24	1.46
14.51	642.00	646.70	−4.70	−0.73
19.04	1060.00	1054.11	5.89	0.56
18.93	1040.00	1043.18	−3.18	−0.31
18.85	1040.00	1035.27	4.73	0.46
18.94	1040.00	1044.17	−4.17	−0.40
18.75	1030.00	1025.41	4.59	0.45
18.76	1040.00	1026.40	13.60	1.33
18.96	1060.00	1046.16	13.84	1.32
18.97	1040.00	1047.15	−7.15	−0.68
18.91	1040.00	1041.20	−1.20	−0.12
18.72	1030.00	1022.46	7.54	0.74
24.93	1700.00	1711.45	−11.45	−0.67
24.63	1680.00	1674.60	5.40	0.32
24.84	1680.00	1700.36	−20.36	−1.20
24.37	1670.00	1642.95	27.05	1.65
24.23	1620.00	1626.01	−6.01	−0.37
24.68	1680.00	1680.72	−0.72	−0.04
24.14	1600.00	1615.17	−15.17	−0.94
24.39	1620.00	1645.37	−25.37	−1.54
24.31	1630.00	1635.68	−5.68	−0.35
24.46	1650.00	1653.87	−3.87	−0.23

[a] Compressive strength equals $5.27 \times \text{density}^{1.80}$

[b] 1 lb/ft³ equals 16.01 kg/m³.

[c] 1 psi equals 6895 Pa.
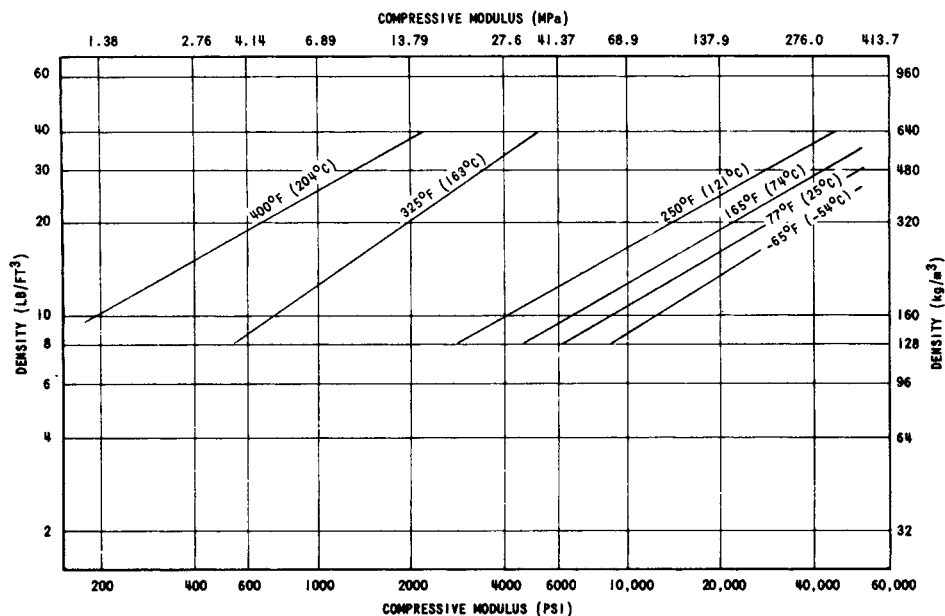
[d] Average absolute error is 0.72%.

Fig. 1. Example of compressive modulus vs. density lines for material D at different temperatures.

properties of the material are independent of processing conditions, such as mold or material preheat, cure time, and cure temperature, and such formulation variables as the catalyst type and concentration. This assumes, of course, that the exothermic heat of reaction is enough to adequately cure the foam. This was the case with these foams as evidenced by the maximum exothermic temperatures shown in Table II. When a packing factor of at least 2:1 is maintained, the foam's compressive properties are usually independent of the foam rise direction. Thus, samples taken from the cores of these billets should yield representative strength results for that isocyanate/polyol system.

The densities of the test coupons were determined. Then the 1.000-in. (25.40 mm) cube specimens were compression tested according to ASTM

TABLE IV
Equations and Average Errors for Compressive Properties[a] of Material D
at Various Test Temperatures

Test temperature		Compressive strength			Compressive modulus		
°F	°C	K	a	Average error, %	K	a	Average error, %
−65	(−54)	7.62	1.85	1.2	311	1.60	2.9
77	(25)	5.27	1.80	0.7	173	1.71	2.1
165	(74)	4.45	1.73	1.3	127	1.72	4.7
250	(121)	2.76	1.70	1.4	68.2	1.77	2.9
325	(163)	0.77	1.70	4.2	25.8	1.44	7.6
400	(204)	0.22	1.85	2.3	3.01	1.78	2.4
		- -	0.77A[b]	1.9A	- -	1.72A	3.8A

[a] Compressive property (psi) = $K \times$ density (lb/ft^3)^a.
[b] Average.

D695-69 at temperatures ranging from $-65°$ to $400°F$ ($-54°$ to $204°C$). These compressive property (strength or modulus)/density combinations were then fit to the equation

$$\text{compressive property} = K(\text{density})^a. \tag{1}$$

In the previous work,[1] these data were analyzed using a conventional least-squares approach. However, later studies showed this technique to be biased toward the higher end of the density/compressive property scale. This occurs because the conventional least-squares method is based on minimizing the distance from the actual data points to the predicted line. By this method, an error of 100 in 1,000,000 psi is considered to be equivalent to an error of 100 psi in 0.1 psi. The least-squares technique was modified to minimize the percentage error of the data points to the predicted line. This new program selected values of K and a that satisfied this minimum "average absolute error" condition. Table III shows example results of such calculations for the compressive strength of material D tested at $77°F$ ($25°C$).

This modified least-squares program was used to calculate the compressive property versus density equations for each foam system at each test temperature. Again using material D as an example, equations like those shown in Table III were developed. While these equations were correct based on the experimental data, they represented a family of lines that were, at best, physically improbable. Figure 1 shows the compressive modulus versus density lines at the various temperatures for the equations in Table IV. The line slopes exhibit a somewhat random nature. These lines would be expected to be parallel, especially in the lower temperature regions. At high temperatures where the polymer softens, the lines could conceivably spread, thereby appearing to converge at some low density and strength. In this manner, a would decrease as the temperature increased. As shown in Table III and evidenced by the other 13 foam systems, the a's assumed random values. There was no pattern either between or within the different materials. The simplest solution to the random a problem was to assume it was caused by data scatter or experimental error.

However, if this data scatter assumption is valid, it should be possible to

TABLE V
Equations and Average Errors for Compressive Properties[a] of Material D
at Various Test Temperatures

Test temperature		Compressive strength		Average error, %	Compressive modulus		Average error, %
°F	°C	K	a		K	a	
-65	(-54)	9.40	1.77	1.1	225	1.72	3.9
77	(25)	5.70	1.77	1.1	170	1.72	2.1
165	(74)	4.04	1.77	1.5	127	1.72	4.8
250	(121)	2.30	1.77	2.4	80.0	1.72	3.3
325	(163)	0.63	1.77	4.8	11.6	1.72	8.0
400	(204)	0.28	1.77	3.6	3.6	1.72	3.2
		. . .	. . .	2.4A[b]	. . .	. . .	4.2A

[a] Compressive property (psi) = $K \times$ density (lb/ft^3)^a.
[b] Average.

force a family of lines all having the same slope through the data points. Also, this "force fit" should not significantly alter the average absolute error of the prediction. Using material D as an example, average a's for compressive strength and modulus were established at 1.77 and 1.72, respectively. Table V shows the equations developed using these a's. While the average

TABLE VI
Comparison of Measured and Calculated Compressive Strength as a Function of Density at 77°F (25°C) for Material D Using an Assumed a of 1.77[a]

Measured density, lb/ft³[b]	Measured strength, psi[c]	Calculated strength, psi	Difference, psi	Error, %[d]
9.55	305.00	309.37	−4.37	−1.43
9.64	313.00	314.55	−1.55	−0.50
9.62	305.00	313.40	−8.40	−2.75
9.50	300.00	306.51	−6.51	−2.17
9.63	305.00	313.97	−8.97	−2.94
9.50	303.00	306.51	−3.51	−1.16
9.59	308.00	311.67	−3.67	−1.19
9.57	305.00	310.52	−5.52	−1.81
9.61	307.00	312.82	−5.82	−1.90
9.56	305.00	309.95	−4.95	−1.62
14.70	660.00	663.78	−3.78	−0.57
14.32	630.00	633.72	−3.72	−0.59
14.12	640.00	618.13	21.87	3.42
14.39	640.00	639.21	0.79	0.12
14.55	650.00	651.84	−1.84	−0.28
14.76	665.00	668.59	−3.59	−0.54
14.43	630.00	642.36	−12.36	−1.96
14.42	640.00	641.57	−1.57	−0.25
14.31	640.00	632.93	7.07	1.10
14.51	642.00	648.67	−6.57	−1.04
19.04	1060.00	1049.27	10.73	1.01
18.93	1040.00	1038.56	1.44	0.14
18.85	1040.00	1030.80	9.20	0.88
18.94	1040.00	1039.53	0.47	0.05
18.75	1030.00	1021.14	8.86	0.86
18.76	1040.00	1022.11	17.89	1.78
18.96	1060.00	1041.47	18.53	1.75
18.97	1040.00	1042.45	−2.45	−0.24
18.91	1040.00	1036.62	3.38	0.33
18.72	1030.00	1018.25	11.75	1.14
24.93	1700.00	1690.73	9.27	0.55
24.63	1680.00	1654.88	25.12	1.50
24.84	1680.00	1679.94	0.06	0.00
24.37	1670.00	1624.09	45.91	2.75
24.23	1620.00	1607.61	12.39	0.76
24.68	1680.00	1660.83	19.17	1.14
24.14	1600.00	1597.05	2.95	0.18
24.39	1620.00	1626.45	−6.45	−0.40
24.31	1630.00	1617.02	12.98	0.80
24.46	1650.00	1634.72	15.28	0.93

[a] Compressive strength equals 5.70 × density[1.77].
[b] 1 lb/ft³ equals 16.01 kg/m³.
[c] 1 psi equals 6895 Pa.
[d] Average absolute error is 1.11%.

absolute error did increase slightly, the results are still within the limits of normal experimental error. Table VI shows the calculations which determined the K value for the compressive strength of material D tested at 77°F (25°C) and assuming a 1.77 average a.

Other work[3] has established that an equation of the form

$$\text{compressive strength} = K_1 \, \text{density}^{a_1} + K_2 \, \text{density}^{a_2} \left(\frac{\text{density}}{1 - \text{strain}} \right)^{a_3} \quad (4)$$

can be used to predict the rigid urethane foam compressive strengths at high strains over a temperature range of at least −65° to 250°F (−54° to 121°C). The values of a were further defined as: $a_1 = 1.75$, $a_2 = -\frac{1}{3}$, $a_3 = 4$.

From this, it seemed logical that a could be assigned a value of 1.75. This would have the advantage of reducing the equations for all of the foam systems to one unknown K. This was tried with material D. The results are shown in Table VII. As can be seen by comparing the per cent errors in Tables IV, V, and VII, little additional error was created by changing the random a's in Table IV to the constant 1.75 in Table VII.

The remaining 13 foam systems were treated in the same manner as material D. First, the equation for the compressive property at each test temperature was established. Then, the a values were adjusted to give the same slope to each temperature line representing one material. Finally, the line slope was forced to be 1.75. The "average absolute errors" were compared through each phase of the calculations to assure that each new equation was essentially as accurate as the one it superseded. The result of this work, the K values for each foam system, are summarized in Tables VII and IX.

Development of the General Equation

In a prior publication,[3] one equation for each test temperature of −65° and 77°F (−54° and 25°C) was reported to be valid for all foams tested at those temperatures. The a_1 value in that work was 1.75. Based on that, and since 1.75 seemed to function well as a constant a for the 14 foam systems, data from all materials tested at a common temperature were grouped together. These were studied to determine if a representative K value could be found

TABLE VII
Equations and Average Errors for Compressive Properties of Material D at
Various Test Temperatures Using a Constant a of 1.75[a]

Test temperature		Compressive strength		Average error, %	Compressive modulus		Average error, %
°F	°C	K	a		K	a	
−65	(−54)	9.90	1.75	1.2	208	1.75	4.4
77	(25)	6.08	1.75	1.7	155	1.75	2.3
165	(74)	4.26	1.75	1.3	116	1.75	4.9
250	(121)	2.44	1.75	1.9	73.2	1.75	3.0
325	(163)	1.75	1.75	4.4	10.5	1.75	8.1
400	(204)	1.75	1.75	4.1	3.30	1.75	2.6
				2.4A[b]			4.2A

[a] Compressive property (psi) = $K \times$ density (lb/ft^3)$^{1.75}$.
[b] Average.

for all materials at that temperature. Such values were found for the −65°, 77°, and 165°F (−54°, 25°, and 74°C) test temperatures. These results, along with confidence limits representing 99% confidence that 95% of the data will fall between the indicated lines, are shown in Figures 2 through 7. No valid equations were found for all foams tested at either 250° or 325°F (121° or 162°C). The large percentage errors for the computer-predicted

TABLE VIII

Compressive Strength K Values for the Various Foam Systems Using the Equation
$CS = K(\text{Density})^{1.75}$[a]

	K Values					
Material	−65°F (−54°C)[b]	77°F (25°C)	165°F (74°C)	250°F (121°C)	325°F (163°C)	400°F (204°C)
A	8.80	6.16	4.08	2.68	1.64	0.64
B	8.20	6.16	4.62	3.44	2.43	1.13
C	10.80	7.44	6.06	4.44	3.18	2.10
D	9.90	6.08	4.26	2.44	0.66	0.29
E	11.00	6.72	4.74	2.56	0.41	—
F	9.70	7.76	5.76	4.52	2.64	—
G	11.90	7.20	4.62	2.20	0.15	—
H	11.40	7.68	6.30	4.24	0.64	—
I	11.40	6.80	5.52	2.52	—	—
J	10.80	6.56	5.28	3.00	0.17	—
K	9.60	6.16	4.44	2.48	0.16	—
L	11.40	6.80	4.86	1.28	0.13	—
M	12.00	7.76	6.42	4.84	2.43	—
N	11.00	6.96	5.22	4.12	0.99	—

[a] The average absolute error was 3.2%. Values of percentage range from 1.2 to 8.4.
[b] Test temperatures.

TABLE IX

Compressive Modulus K Values for the Various Foam Systems Using the Equation
$CM = K(\text{Density})^{1.75}$[a]

	K Values					
Material	−65°F (−54°C)	77°F (25°C)	165°F (74°C)	250°F (121°C)	325°F (163°C)	400°F (204°C)
A	186	144	97.2	62.0	37.6	12.0
B	172	131	98.4	75.0	57.6	22.1
C	248	191	166	114	82.4	51.6
D	208	155	116	73.2	10.5	3.30
E	214	158	128	80.4	5.40	—
F	212	157	132	120	80.0	—
G	244	187	156	88.0	1.64	—
H	232	180	145	108	14.0	—
I	220	169	143	73.0	—	—
J	204	164	144	98.0	1.82	—
K	176	142	108	78.6	1.72	—
L	246	189	156	42.0	1.50	—
M	234	171	156	138	88.8	—
N	230	175	150	129	37.6	—

[a] The average absolute error was 5.5%. Values of percentage range from 2.3 to 9.8.
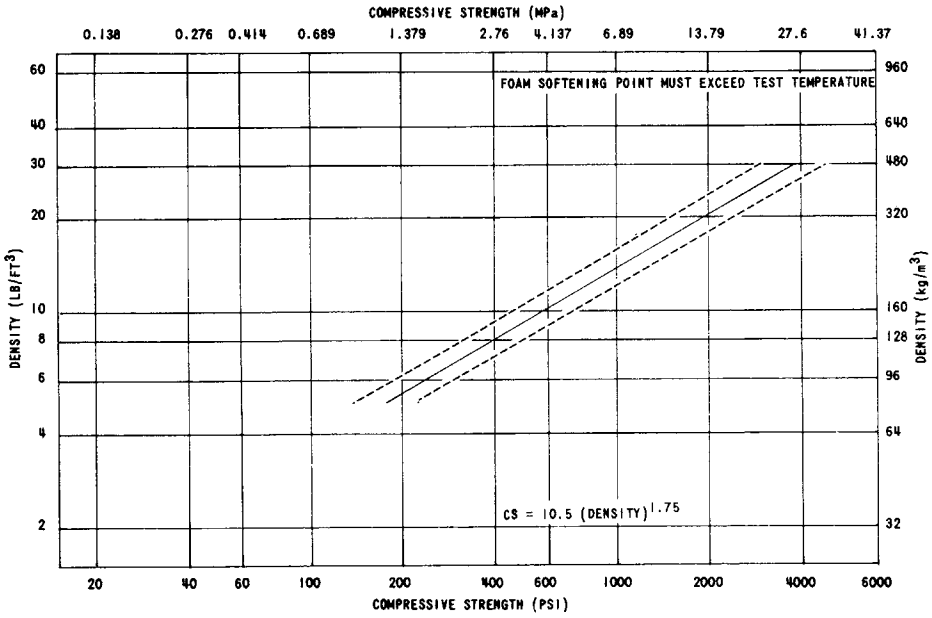[b] Test temperature.

Fig. 2. Compressive strength vs. density for rigid urethane foams tested at −65°F (−54°C).
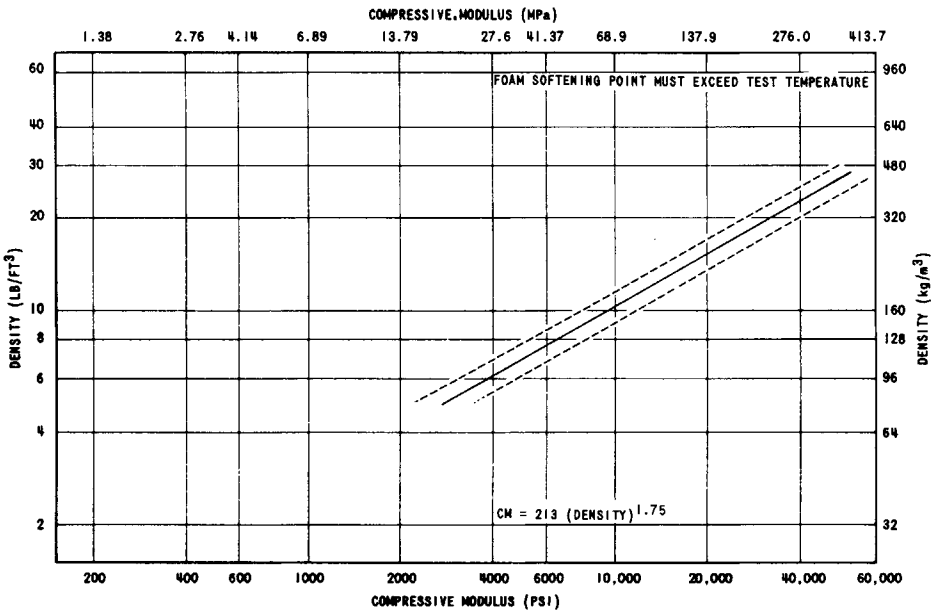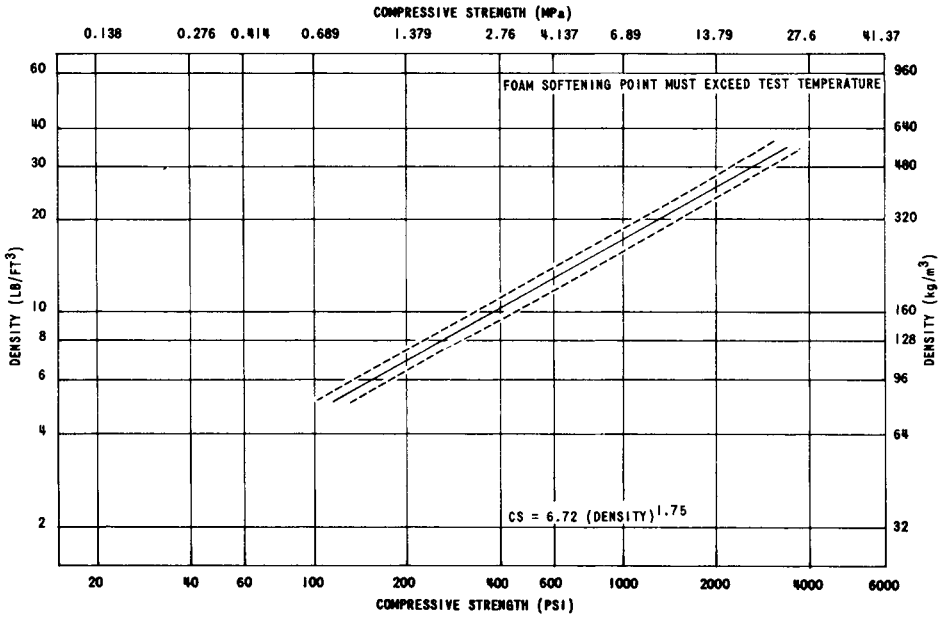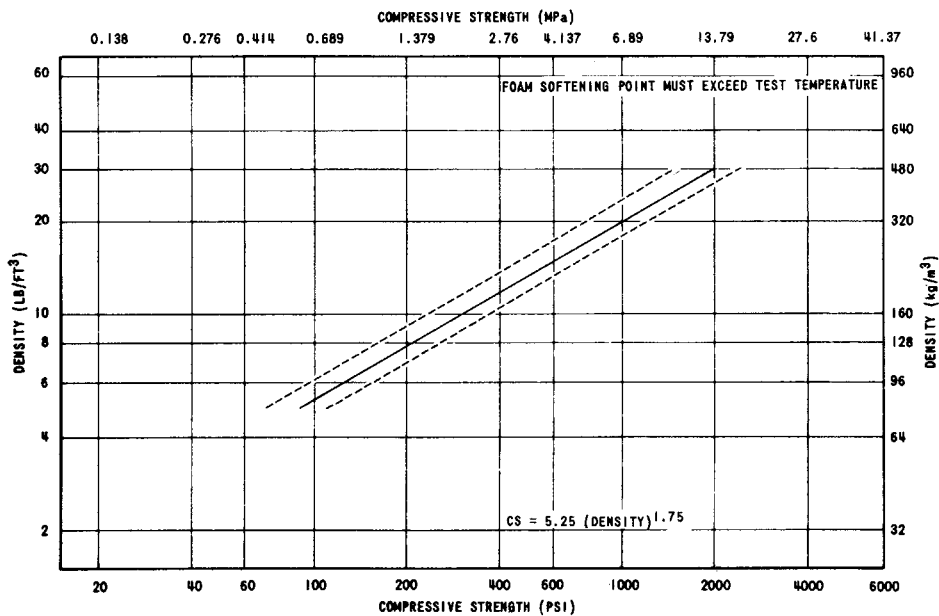

Fig. 3. Compressive modulus vs. density for rigid urethane foams tested at −65°F (−54°C).

equations made these equations useless. However, when materials with soft-ening points within 10°F (6°C) (Table I) or below the test temperature were excluded from the data group, reasonable equations were developed. These results, along with confidence bands, are shown in Figures 8 through 11. Table X lists the K values for these equations.
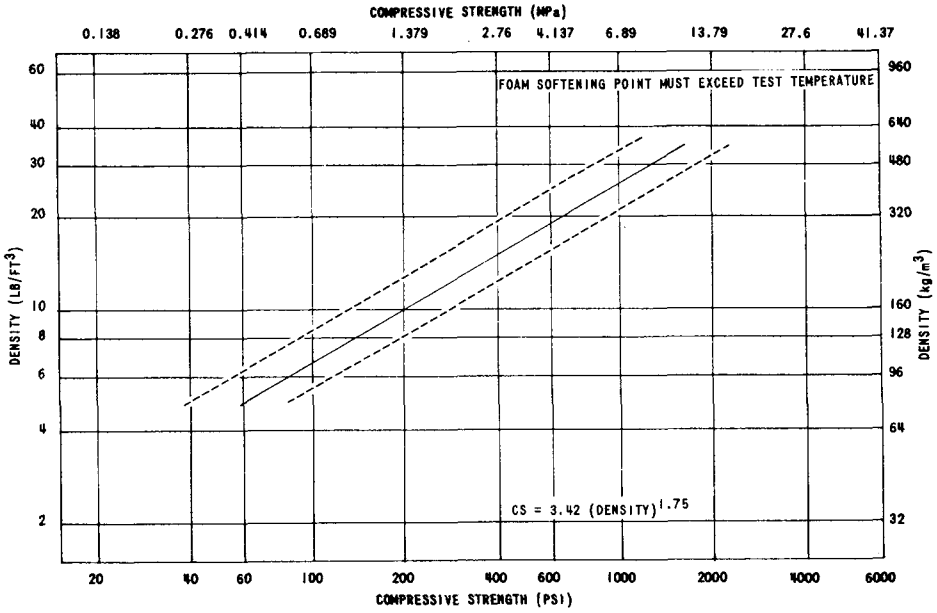
Fig. 4. Compressive strength vs. density for rigid urethane foams tested at 77°F (25°C).
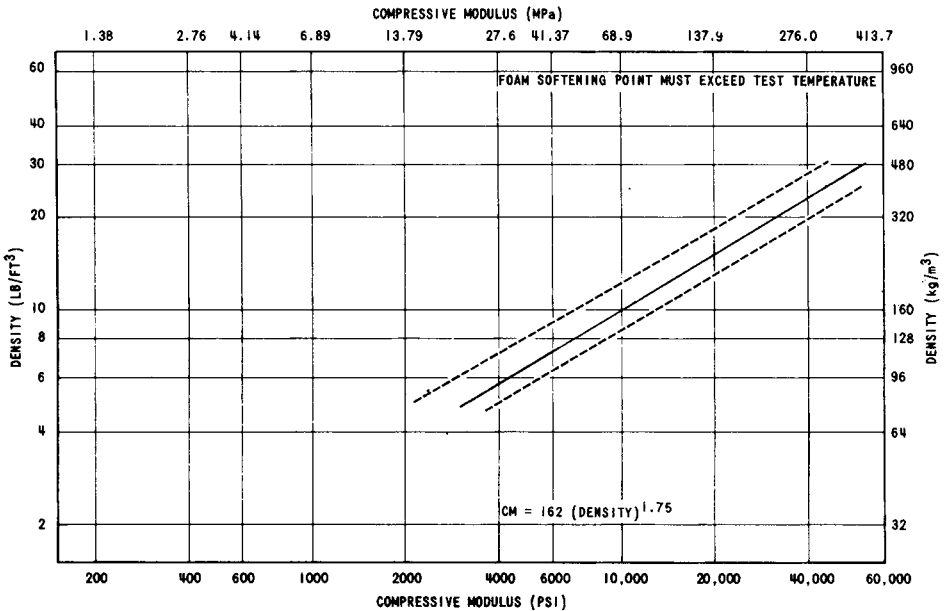
Fig. 5. Compressive modulus vs. density for rigid urethane foams tested at 77°F (25°C).

As shown in Figures 2 through 11 and Table X, the equations predicting the compressive properties of all foams are good up to a 165°F (74°C) test temperature. By the time 250°F (163°C) is reached, the data begin to show considerably more scatter. This is probably caused by the complex thermal stability effect of the resin hydroxyl numbers, urethane-to-urea bond ratios, and isocyanate types taken in combination. Other research has shown that
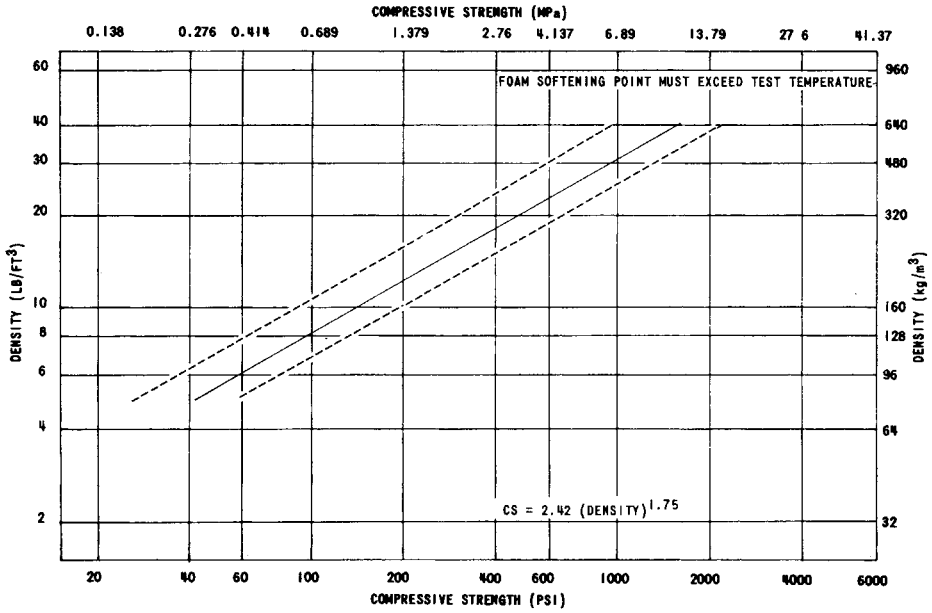
Fig. 6. Compressive strength vs. density for rigid urethane foams tested at 165°F (74°C).
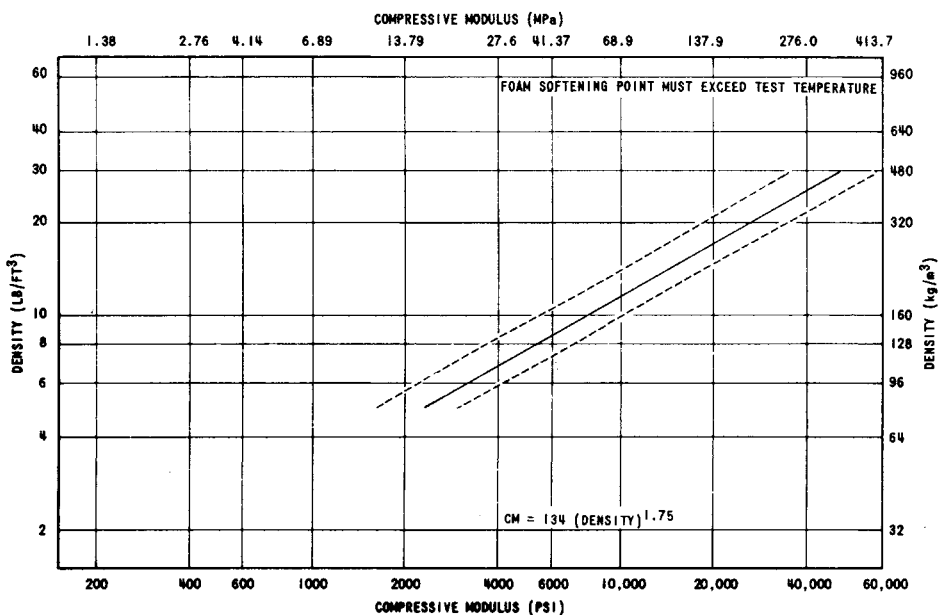
Fig. 7. Compressive modulus vs. density for rigid urethane foams tested at 165°F (74°C).

increasing the crosslink density (increasing resin hydroxyl number),[6] increasing water for the blowing reaction (decreasing the urethane/urea bond ratio),[7,8] and using polymeric isocyanates as opposed to toluene diisocyanate[9,10] all increase the thermal stability of the polymer. However, the effects of these thermal stability improvements are not apparent in the lower

Fig. 8. Compressive strength vs. density for rigid urethane foams tested at 250°F (121°C).
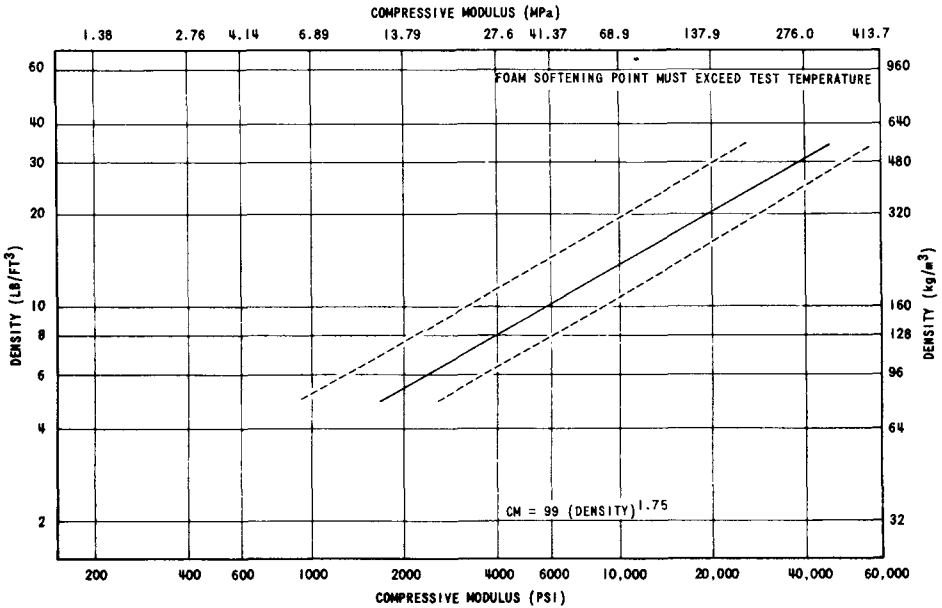
Fig. 9. Compressive modulus vs. density for rigid urethane foams tested at 250°F (121°C).

temperature regions. In the case of isocyanate types and urethane/urea bond ratios, no significant effect can be seen until the temperature exceeds 200°F (93°C).[8,11] While some testing was done at 400°F (204°C), no composite graphs are reported because of the limited number of foams evaluated at that temperature.

Fig. 10. Compressive strength vs. density for rigid urethane foams tested at 325°F (163°C).
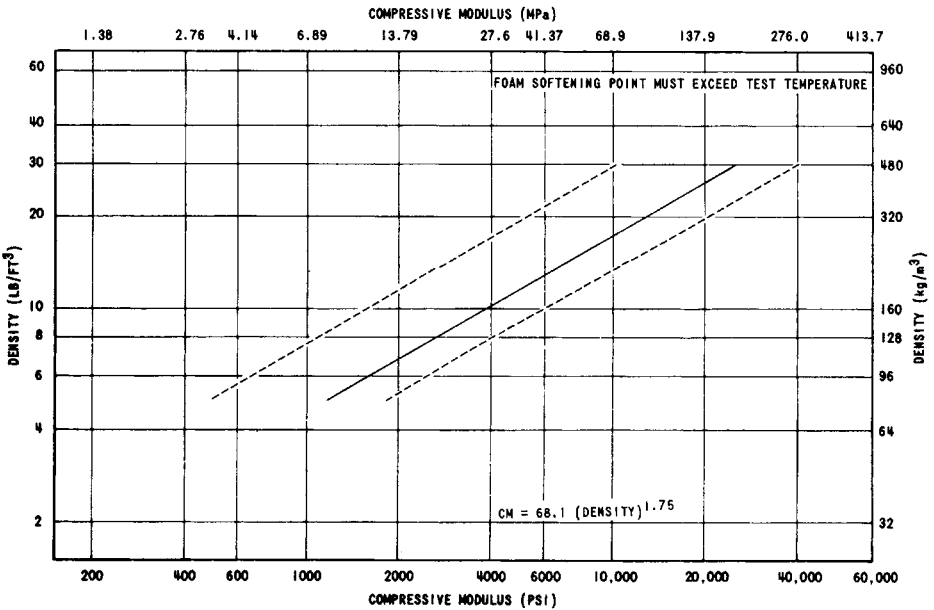
Fig. 11. Compressive modulus vs. density for rigid urethane foams tested at 325°F (163°C).

Establishing K as a Function of Temperature

The equations that have been presented in this report are valid at the test temperatures indicated. However, these equations do not permit prediction of the foam's compressive properties at intermediate temperatures. To correlate K with temperature, Figure 12 was prepared. For compressive modulus, the equation for K is

$$K_m = 191 - 0.369T(°F). \tag{5}$$

The line is linear between a temperature range of −65° to 325°F (−54° to 163°C). For compressive strength, the equation

$$K_s = 8.09 - 0.0178T(°F) \tag{6}$$

applies from 77° to 325°F (25° to 163°C). This relationship does not hold at −65°F (−54°C) because of significant differences in the shapes of the stress/strain curves as shown in Figure 13. At temperatures of 77°F (25°C) and above, the stress/strain curves have a sharp inflection point at 3% to 5% strain. Above this inflection point, the tangent modulus decreases rapidly and the curves exhibit a yield point with a flat plateau. The decrease in the tangent modulus at −65°F (−54°C) is not nearly as severe, resulting in significantly higher compressive strengths at comparable strains. Since this work was based on the yield stress or maximum stress obtained up to 10% strain, this would cause the K value for the −65°F (−54°C) tests to be discontinuous with respect to the K values for the other temperatures. The data in Figure 12 confirm this. The compressive modulus prediction is not affected by this inflection point argument because the modulus is computed prior to that point.

Therefore, by substituting eqs. (5) and (6) into eq. (1), the predictor equations for compressive strength and modulus become

$$\text{compressive strength} = (8.09 - 0.0178T) \text{ density}^{1.75} \tag{2}$$

for T equal to or greater than 77°F (25°C), and

$$\text{compressive modulus} = (191 - 0.369T) \text{ density}^{1.75} \tag{3}$$

for T equal to or greater than −65°F (−54°C), where compressive strength and modulus are in pounds per square inch and density is pounds per cubic foot.

Accomplishments

This work resulted in the development of general equations representing the compressive properties of all foam systems. As reported by other re-

TABLE X

K Values for all Foams at Various Test Temperatures Using a Constant a of 1.75[a]

Test temperature		Compressive strength[b]		Average error, %	Compressive strength[b]		Average error, %
°F	°C	K	a		K	a	
−65	(−54)	10.5	1.75	11.5	213	1.75	10.3
77	(25)	6.72	1.75	7.0	162	1.75	9.8
165	(74)	5.25	1.75	11.2	134	1.75	14.5
250	(121)	3.42	1.75	18.2	99.0	1.75	21.3
325	(163)	2.42	1.75	18.8	68.1	1.75	29.6

[a] Softening point of foam represented by these values must exceed the test temperatures.

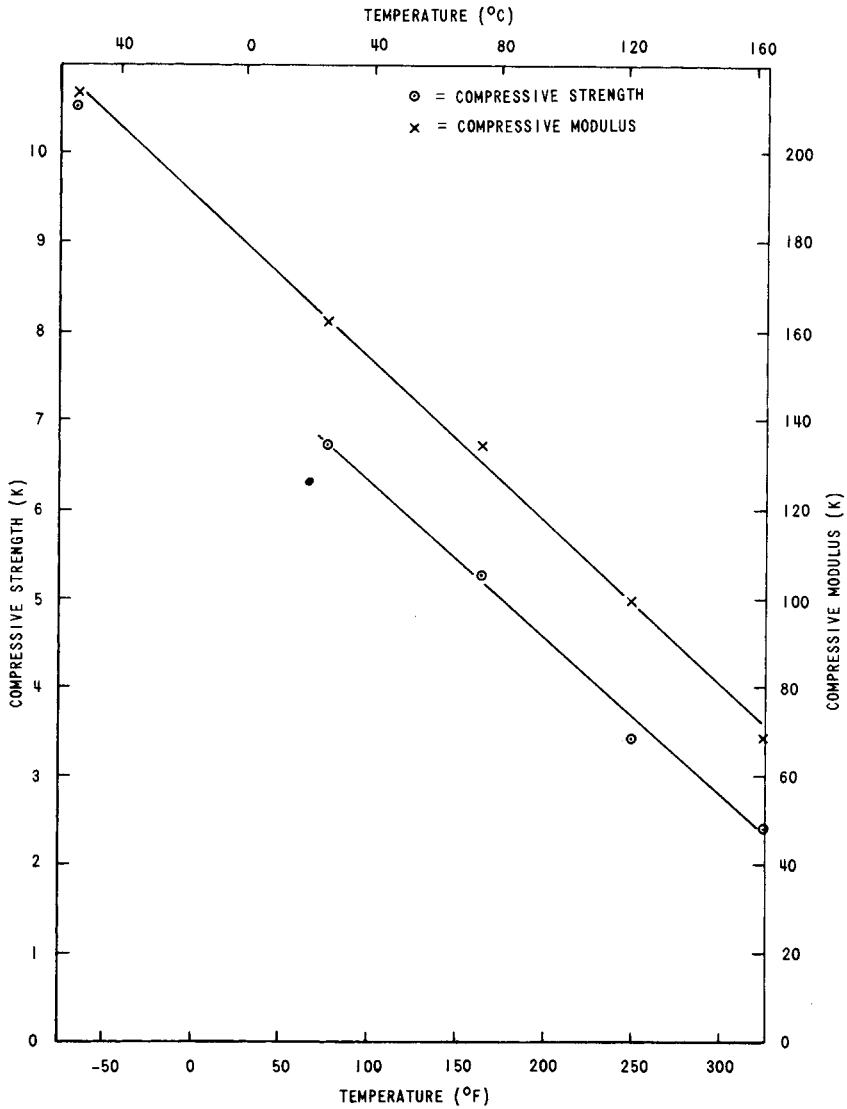[b] Compressive strength or modulus (psi) = K × density (lbs/ft³)$^{1.75}$.

Fig. 12. Compressive strength and modulus K values vs. temperature for rigid urethane foam.

searchers, these equations take the form

$$\text{compressive property} = K(\text{density})^a. \tag{1}$$

However, where other researchers[12] have placed the value of a between 1.4 and 1.7, this report proposes that a be established as 1.75. Figure 14 shows the proposed new equation and tolerance band in conjunction with previously published and accepted work.[13] This new equation generally falls within but creates a narrower tolerance band than did the previous work.

Also, while most other researchers have limited their equations to 77°F (25°C) conditions, this project has offered compressive property predicting equations covering a range from −65° to 325°F (−54° to 163°C). The equations for compressive strength, in psi, as a function of density in pounds per cubic foot, are
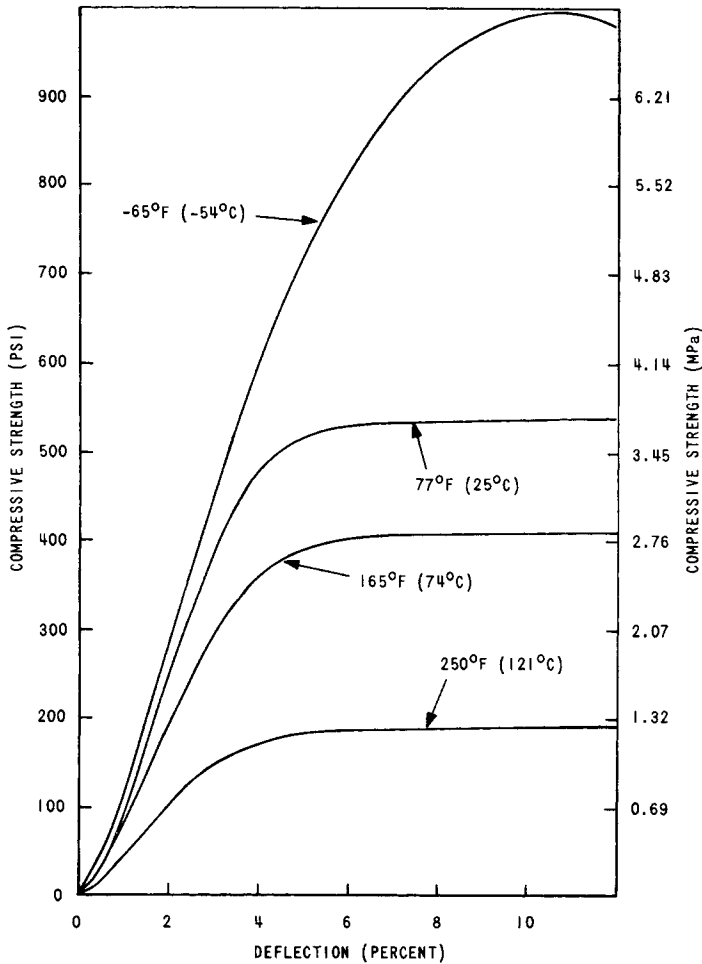
Fig. 13. Typical stress/strain curves for rigid polyurethane foams at various test temperatures.

$$\text{compressive strength} = 10.52 \times \text{density}^{1.75} \text{ at } -65°\text{F } (-54°\text{C}) \qquad (7)$$

$$\text{compressive strength} = 6.72 \times \text{density}^{1.75} \text{ at } 77°\text{F } (25°\text{C}) \qquad (8)$$

$$\text{compressive strength} = 5.25 \times \text{density}^{1.75} \text{ at } 165°\text{F } (74°\text{C}) \qquad (9)$$

$$\text{compressive strength} = 3.42 \times \text{density}^{1.75} \text{ at } 250°\text{F } (121°\text{C}) \qquad (10)$$

$$\text{compressive strength} = 2.42 \times \text{density}^{1.75} \text{ at } 325°\text{F } (163°\text{C}) \qquad (11)$$

The equations for compressive modulus, in psi, as a function of density are

$$\text{compressive modulus} = 213 \times \text{density}^{1.75} \text{ at } -65°\text{F } (-54°\text{C}) \qquad (12)$$

$$\text{compressive modulus} = 162 \times \text{density}^{1.75} \text{ at } 77°\text{F } (25°\text{C}) \qquad (13)$$

$$\text{compressive modulus} = 134 \times \text{density}^{1.75} \text{ at } 164°\text{F } (74°\text{C}) \qquad (14)$$

$$\text{compressive modulus} = 99 \times \text{density}^{1.75} \text{ at } 250°\text{F } (121°\text{C}) \qquad (15)$$

$$\text{compressive modulus} = 68 \times \text{density}^{1.75} \text{ at } 325°\text{F } (163°\text{C}) \qquad (16)$$
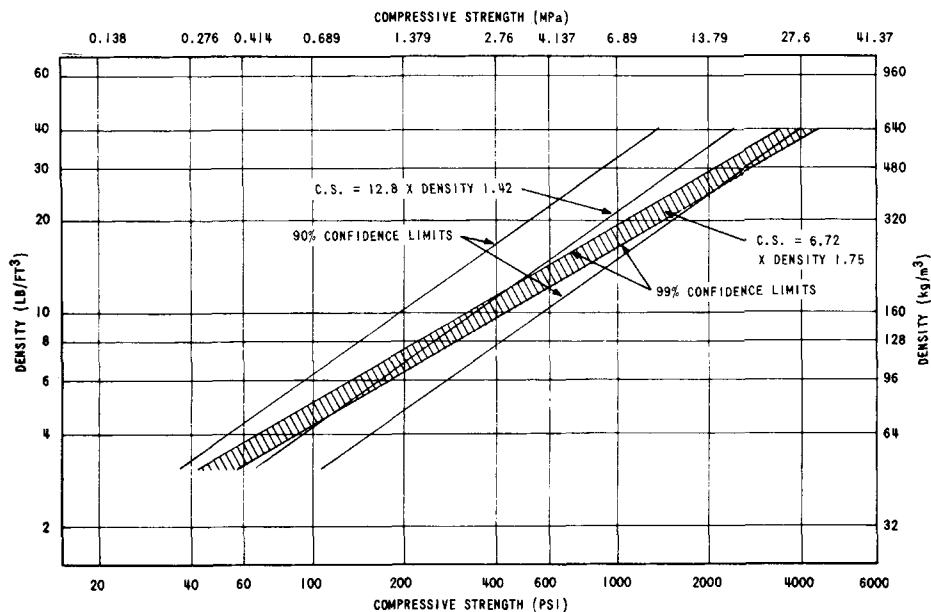
Fig. 14. Comparison of previously published and newly developed compressive strength vs. density lines and tolerance bands at 77°F (25°C).

In addition, the value of K was further defined as a function of temperature. The equation for the compressive strength K at temperature equal to or greater than 77°F (25°C) is

$$K_s = 8.09 - 0.0178T(°F). \tag{6}$$

By substitution into eq. (1),

$$\text{compressive strength} = (8.09 - 0.0178T)\,\text{density}^{1.75} \tag{2}$$

for T equal to or greater than 77°F (25°C). Similarly, from eqs. (1) and (5), the equation for compressive modulus is

$$\text{compressive modulus} = (191 - 0.369T)\,\text{density}^{1.75} \tag{3}$$

for T equal to or greater than −65°F (−54°C). These equations are not valid as the foam approaches or exceeds its softening point. While all of these equations are based on carbon dioxide-blown foams, the equations should also be valid for fluorocarbon-blown materials. Other studies have found "no significant differences in strength values ... between foams made with the two types of blowing agents."[13]

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