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PREDICTING COMPRESSIVE STRENGTH OF URETHANE FOAMS AT HIGH STRAINS

PDO 6989172, Final Report

T. E. Neet, Project Leader

Project Team:
J. H. Carder
B. C. Cole

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Prepared for the
United States Atomic Energy Commission
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Bendix Kansas City Division

DISCLAIMER

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Equations for predicting the restrained compressive strength of rigid urethane foam at any density and strain were developed on this project. General equations representing all of the foam systems studied were defined for foam strengths at -65 and 77°F (-54 and 25°C). Specific equations for each foam system were also prepared for these test temperatures. While no general equation could be developed for the foams tested at 250°F (121°C), specific equations for the individual materials were prepared for these test temperatures.

THE BENDIX CORPORATION

KANSAS CITY DIVISION

KANSAS CITY, MISSOURI

A prime contractor for the
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SUMMARY

Equations have been developed for predicting the compressive strength of rigid urethane foams at any density and strain. The equation presently in use throughout the urethane industry states that the compressive strength of a foam is equal to a constant times the density raised to a power

$$CS = K_1 D^{a_1}.$$

However, this equation[1] is valid only to about 10 percent strain. The new equation reported here is

$$CS = K_1 D^{a_1} + K_2 D^{a_2} \left(\frac{D}{1\text{-strain}}\right)^{a_3}. \qquad (1)$$

This appears to adequately predict the strength of restrained urethane foam samples at almost any point on a stress/strain curve.

Equation 1 can be simplified by assigning values to variables a_1, a_2, and a_3. From this experimental work, the equation becomes

$$CS = K_1 D^{1.75} + K_2 D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^{4}. \qquad (2)$$

These values for the a_1 and a_2 constants are valid from at least -65 to 250°F (-54 to 121°C). Constants K_1 and K_2 vary respectively with the temperature range from approximately 12.5 and 0.0027 at -65°F to 3.0 and 0.0008 at 250°F.

The general equations which describe the compressive strengths of any of the five urethane foams studied are

$$CS = 12.50D^{1.75} + 0.00270D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^{4} \qquad (3)$$

for -65°F (-54°C) tests and

$$CS = 7.75D^{1.75} + 0.00149D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^{4} \qquad (4)$$

for foams tested at 77°F (25°C). No general equation could be developed for foams tested at 250°F (121°C). Individual data from all five foam systems did fit Equation 2 as previously mentioned. At this temperature, constants K_1 and K_2 varied from 1.21 to 6.10 and 0.00019 to 0.00116 respectively.

DISCUSSION

SCOPE AND PURPOSE

A standard equation in use throughout the urethane industry states that the compressive strength of a rigid urethane foam is equal to a constant times the density raised to a power

$$CS = K_1 D^{a_1}.$$

However, this equation is only valid for the early portions of a stress/strain curve generally between 6 and 10 percent deflection. This work was conducted to develop a new equation capable of adequately predicting the strength of a restrained urethane foam at these and higher strains.

PRIOR WORK

Several recent development programs have sought to obtain compressive strengths of specified urethane foams at high degrees of compression. These projects were concerned only with obtaining the desired data for calculations on the energy absorbing capabilities of the materials, not compiling the results into a more generalized, usable form.

ACTIVITY

The compression deflection curves for three toluene diisocyanate-polyester prepolymer/polyester polyol urethane foams, BKC Rigifoam 6003-6*, Stafoam AA 606**, and CPR 1040-10***, one polymeric isocyanate/polyether polyol material, BKC Thermathane 7510-6*, and one toluene diisocyanate-polyester prepolymer/polyether polyol foam, BC1220**, were studied to determine the relationship between compressive strength, density, and percent compression. All of these materials are carbon dioxide-blown urethane foams.

These evaluations were conducted at three test temperatures, -65, 77, and 250°F (-54, 25, and 121°C). Specimens 1.129 inches

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*Bendix Kansas City
**Expanded Rubber & Plastics Corporation
***Upjohn Company

(28.68 mm) in diameter by 1.000 inch (25.40 mm) high were cut from the cores of billets poured to densities of between 8 and 30 pounds per cubic foot (130 and 480 kg/m^3). These samples were taken from the centers of the foam blocks so that the strengths obtained would truly represent the material.[2,3] The specimens were compression tested in a fixture that restrained the cylindrical surfaces of the test coupons. The data obtained were then used to develop the equations.

After several trials to determine the correct equation, the following model was selected to define the average compressive strength, CS, as a function of the initial sample density, D, and the strain.

$$CS = K_1 D^{a_1} + K_2 D^{a_2} \left(\frac{D}{1\text{-strain}} \right)^{a_3}$$

The term

$$K_1 D^{a_1}$$

appears to explain the difference between the densities while the following term compensates for the increase in sample strength resulting from increased compression.

$$K_2 D^{a_2} \left(\frac{D}{1\text{-strain}} \right)^{a_3}$$

Naturally, these five variables can all be altered to yield several equations which all fit the experimental data reasonably well. However, in the interest of simplifying the equation, it would be advantageous to maintain at least three of the five variables as constants. Previous studies[4] have shown that in the equation

$$CS = K_1 D^{a_1}$$

the a_1 term can be held constant over a relatively wide temperature range. This being the case, it was assumed a_2 and a_3 could also be constant. Computerized searching techniques were employed to find the equation that would best represent all of the data at any one of the test temperatures. Two equations were developed; one each at -65 and 77°F (-54 and 25°C) test temperatures. These equations used the same values for a_1, a_2, and a_3.

$$CS = K_1 D^{1.75} + K_2 D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$$

The K_1 and K_2 values were, of course, different for the equations representing each temperature. The values for these constants were, respectively, 12.50 and 0.00270 at -65°F and 7.75 and 0.00149 at 77°F. At a test temperature of 250°F (121°C), no one equation could be found to represent all five foam systems. This was undoubtedly caused by the softening of some of the polymers at this temperature. An equation of the same form as Equation 2 did fit the data from each individual foam system. The values of K_1 and K_2 need to be adjusted for each material. These values range from 1.21 to 1.60 for K_1 and 0.00019 to 0.00116 for K_2.

At the -65°F (-54°C) test temperature, the general equation for predicting the foam's compressive strength at any density and strain is

$$CS = 12.50 D^{1.75} + 0.00270 D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4 .$$

Figure 1 graphically depicts the effect of the degree of compression on the restrained compressive strength of rigid urethane foams of various densities. In general, all five of the foams studied fit this equation and these lines reasonably well. Table 1, for example, shows the average value of the absolute percentage deviation of the data points from these lines for all materials, while Table 2 shows the actual deviations for one of the materials, BC 1220.

As can be seen from the BC 1220 example, the general equation provides a reasonably good predicted fit for the actual data.

Also, specific equations of the same form as Equation 2 were developed for each foam system at the -65°F (-54°C) test temperature. These equations and the average absolute error of the data points from the predicted values are shown in Table 3.

At the 77°F (25°C) test temperature, the general equation for predicting the compressive strength of the foam at any density and strain is

$$CS = 7.75 D^{1.75} + 0.00149 D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4 .$$

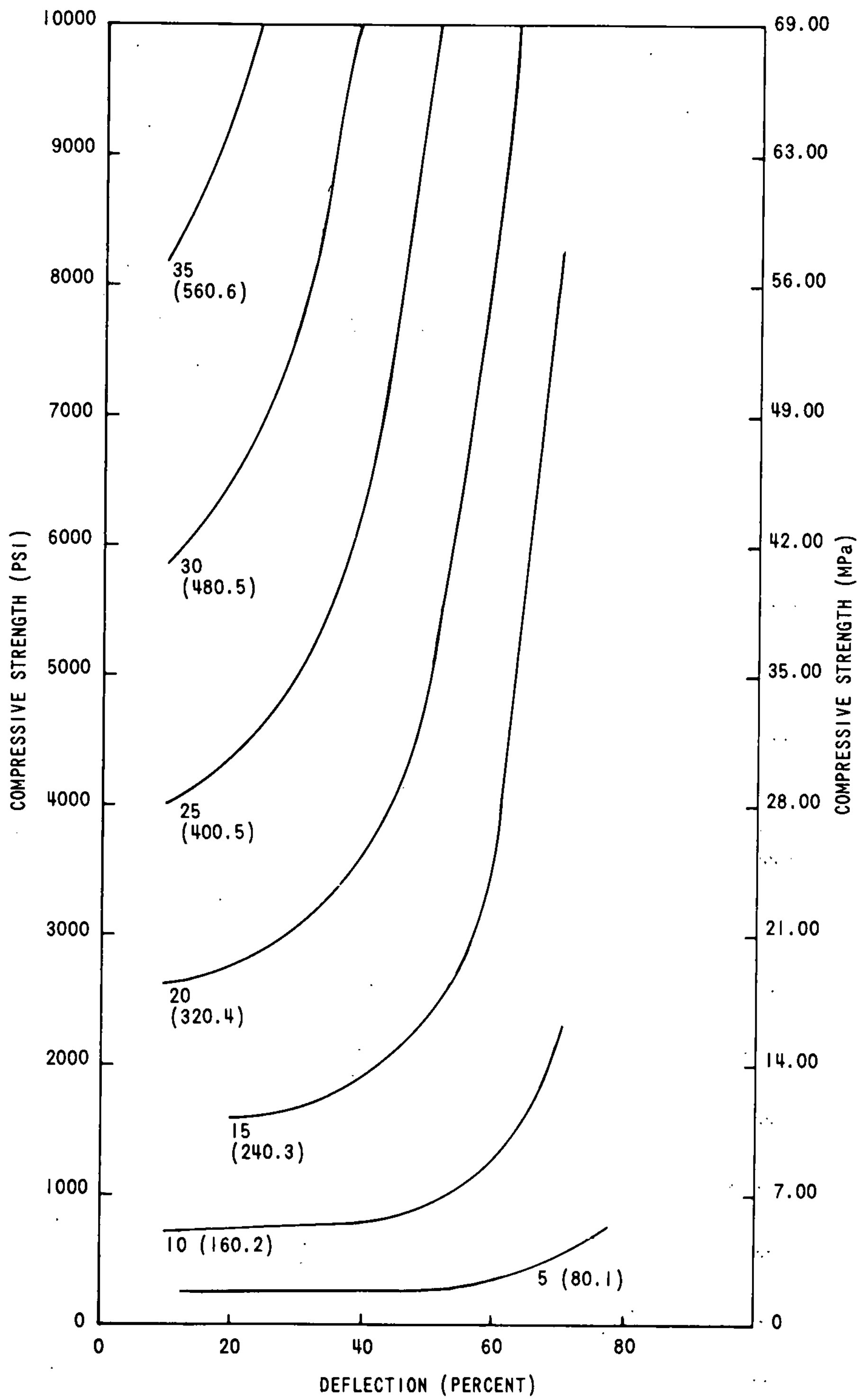

Figure 1. Predicted -65°F (-54°C) Compressive Strength of Urethane Foam at Various Densities (lb/ft^3) (kg/m^3)

Table 1. Average Absolute Percentage Deviation of the Data Points From the General Equation Predicted Line

Material	Deviation in Percent at Indicated Test Temperature	
	-65°F (-54°C)*	77°F (25°C)**
All Materials	7.75	5.84
BKC Rigifoam 6003-6	5.38	3.22
Stafoam AA 606	10.33	5.40
CPR 1040-10	7.21	8.92
BKC Thermalthane 7510-6	8.16	6.45
BC 1220	6.78	5.31

$$*12.50D^{1.75} + 0.00270D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$$

$$**7.75 \cdot D^{1.75} + 0.00149D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$$

Figure 2 graphically displays the restrained compressive strength of the foams at various densities and strains. The strengths of all five materials can be predicted reasonably well from the equation, as evidenced by the average absolute errors for the 77°F test shown in Table 1. Table 4 shows the actual deviations of the experimental from the predicted values for the BC 1220 foam. Specific equations of the same form as Equation 2 were derived for each foam system. These equations and the average absolute error of the data points from the predicted values are shown in Table 3.

No general equation could be developed for the foam tested at 250°F (121°C). However, specific equations of the same general form were found for each foam system at this test temperature. These are shown in Table 3.

ACCOMPLISHMENTS

A new equation for predicting the restrained compressive strength of rigid urethane foams at various densities and strains has been empirically determined. This equation has the form

Table 2. Data for BC 1220 Material Tested at -65°F (-54°C)

Original Density (lb/ft^3)	(kg/m^3)	Strain (Percent)	Actual Strength (psi)	(MPa)	Predicted Strength* (psi)	(MPa)	Error** (Percent)
9.45	(151.4)	10	656.0	(4.523)	652.2	(4.497)	0.6
		20	698.0	(4.813)	661.5	(4.561)	5.2
		30	729.0	(5.026)	679.1	(4.682)	6.8
		40	767.0	(5.288)	715.3	(4.932)	6.7
		50	869.0	(5.992)	799.7	(5.514)	8.0
		60	1211.0	(8.350)	1034.5	(7.133)	14.6
9.45	(151.4)	70	2350.0	(16.203)	1895.0	(13.066)	19.4
14.32	(229.4)	10	1332.0	(9.184)	1389.0	(9.577)	-4.3
		20	1436.0	(9.860)	1431.9	(9.873)	-0.1
		30	1538.0	(10.604)	1512.7	(10.430)	1.6
		40	1666.0	(11.487)	1679.0	(11.576)	-0.8
		50	2180.0	(15.031)	2066.4	(14.247)	5.2
		60	3520.0	(24.270)	3147.7	(21.703)	10.6
14.32	(229.4)	70	7750.0	(53.435)	7098.2	(48.941)	8.4
18.79	(301.0)	10	2290.0	(15.789)	2313.0	(15.948)	-1.0
		20	2508.0	(17.292)	2429.2	(16.749)	3.1
		30	2736.0	(18.864)	2648.1	(18.258)	3.2
		40	3200.0	(22.063)	3097.9	(21.359)	3.2
		50	4498.0	(31.013)	4149.5	(28.610)	7.7
18.79	(301.0)	60	7980.0	(55.021)	7071.9	(48.759)	11.4
22.88	(366.5)	10	3574.0	(24.642)	3389.5	(23.370)	5.2
		20	3980.0	(27.441)	3628.1	(25.015)	8.8
		30	4428.0	(30.530)	4077.9	(28.116)	7.9
		40	5564.0	(38.363)	5004.5	(34.505)	10.1
22.88	(366.5)	50	8492.0	(58.551)	7162.9	(48.697)	15.7

*Predicted from the general equation $CS = 12.50D^{1.75} + 0.00270D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$

**Average absolute error is 6.78 percent

Table 3. Specific Predictor Equations for Each Foam System

Material	Equation	Average Absolute Error, (Percent)
	-65°F (-54°C) Test Temperature	
BKC Rigifoam 6003-6	$12.10D^{1.75} + 0.00302D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$	4.42
Stafoam AA606	$12.24D^{1.75} + 0.00210D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$	4.92
CPR 1040-10	$12.95D^{1.75} + 0.00287D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$	4.92
BKC Thermalthane 7510-6	$12.60D^{1.75} + 0.00245D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$	7.24
BC 1220	$12.51D^{1.75} + 0.00320D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$	3.46
	77°F (25°C) Test Temperature	
BKC Rigifoam 6003-6	$7.72D^{1.75} + 0.00152D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$	3.27
Stafoam AA606	$7.60D^{1.75} + 0.00133D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$	2.99
CPR 1040-10	$8.42D^{1.75} + 0.00125D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$	8.65
BKC Thermalthane 7510-6	$8.20D^{1.75} + 0.00145D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$	5.47
BC 1220	$7.50D^{1.75} + 0.00161D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$	3.62
	250°F (121°C) Test Temperature	
BKC Rigifoam 6003-6	$3.82D^{1.75} + 0.00077D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$	7.03
Stafoam AA606	$5.02D^{1.75} + 0.00079D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$	4.08
CPR 1040-10	$1.21D^{1.75} + 0.00019D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$	4.42
BKC Thermalthane 7510-6	$6.10D^{1.75} + 0.00116D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$	5.41
BC 1220	$3.70D^{1.75} + 0.00077D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$	6.67

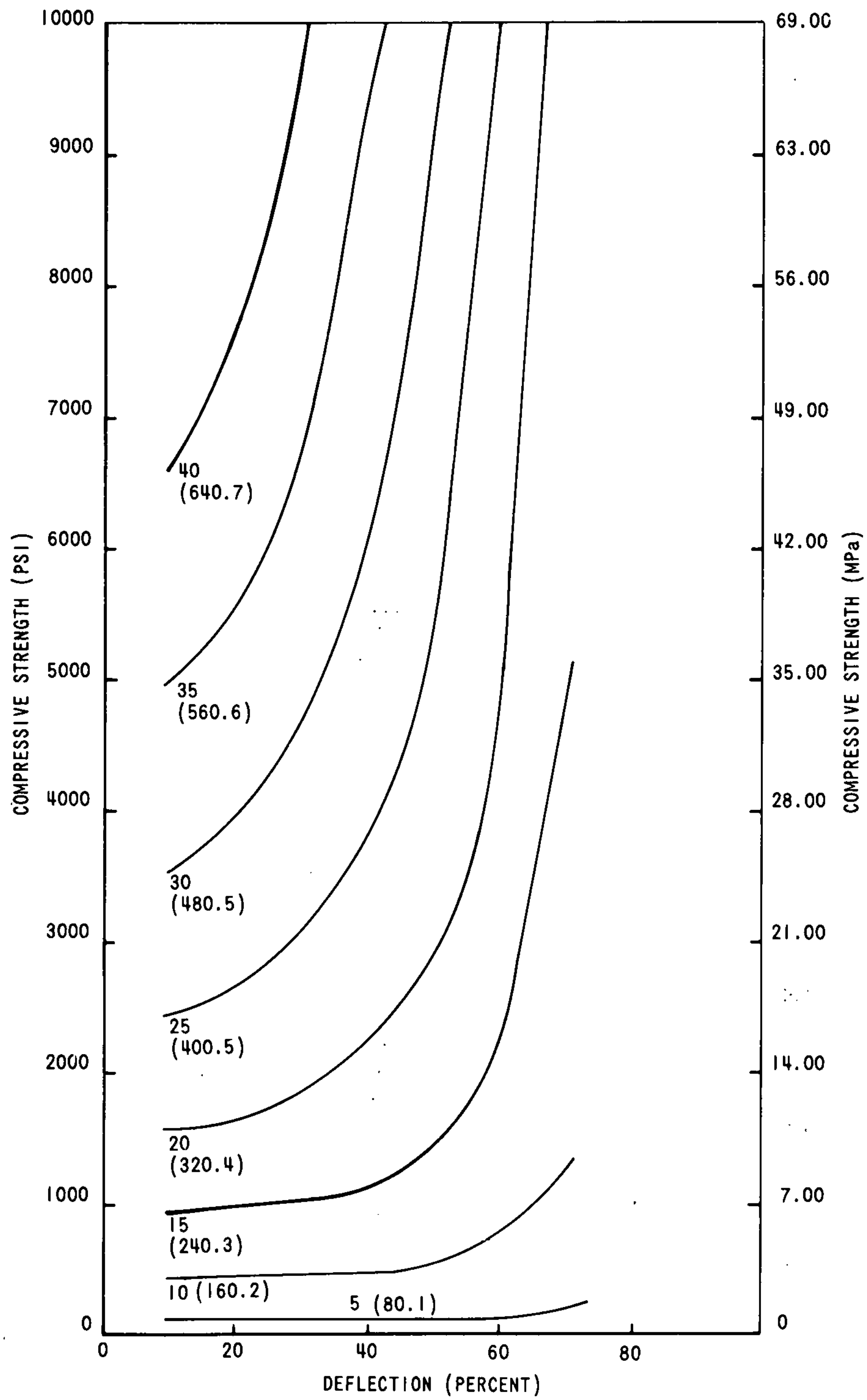

Figure 2. Predicted 77°F (25°C) Compressive Strength of Urethane Foam at Various Densities (lb/ft^3) (kg/m^3)

Table 4. Data for BC 1220 Material Tested at 77°F (25°C)

Original Density (lb/ft^3) (kg/m^3)	Strain (Percent)	Actual Strength (psi) (MPa)	Predicted Strength* (psi) (MPa)	Error** (Percent)
9.46 (151.4)	10	396.0 (2.730)	408.5 (2.817)	-3.2
	20	405.0 (2.792)	413.7 (2.852)	-2.1
	30	419.4 (2.892)	423.4 (2.919)	-1.0
	40	435.0 (2.999)	443.4 (3.057)	-1.9
	50	511.0 (3.523)	490.1 (3.379)	4.1
	60	701.0 (4.833)	620.1 (4.275)	11.5
9.46 (151.4)	70	1352.0 (9.322)	1095.9 (7.556)	18.9
14.46 (231.6)	10	812.5 (5.602)	882.9 (6.087)	-8.7
	20	866.3 (5.973)	907.4 (6.256)	-4.7
	30	917.5 (6.326)	953.5 (6.574)	-3.9
	40	1020.0 (7.033)	1048.7 (7.231)	-2.8
	50	1318.8 (9.093)	1269.8 (8.755)	3.7
	60	2048.5 (14.124)	1886.4 (13.006)	7.9
14.46 (231.6)	70	4437.5 (30.596)	4143.4 (28.568)	6.6
18.95 (303.5)	10	1342.0 (9.253)	1463.5 (10.091)	-9.1
	20	1466.0 (10.108)	1529.8 (10.548)	-4.4
	30	1594.0 (10.990)	1654.0 (11.404)	-3.8
	40	1868.0 (12.879)	1910.1 (13.170)	-2.3
	50	2550.0 (17.582)	2507.9 (17.291)	1.7
18.95 (303.5)	60	4320.0 (29.786)	4170.4 (28.754)	3.5
23.16 (371.0)	10	2100.0 (14.479)	2154.3 (14.853)	-2.6
	20	2391.0 (16.485)	2292.0 (15.803)	4.1
	30	2690.0 (18.547)	2551.5 (17.592)	5.1
	40	3262.0 (22.491)	3085.4 (21.273)	5.4
	50	4640.0 (31.992)	4331.7 (29.866)	6.6
23.16 (371.0)	60	8530.0 (58.813)	7801.8 (53.792)	8.5

*Predicted from the general equation $CS = 7.75D^{1.75} + 0.00149D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^4$

**Average absolute error is 5.31 percent

$$CS = K_1 D^{a_1} + K_2 D^{a_2} \left(\frac{D}{1\text{-strain}}\right)^{a_3}.$$

This equation can be further defined, at least over the -65 to 250°F (-54 to 121°C) temperature range studied, as

$$CS = K_1 D^{1.75} + K_2 D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^{4}.$$

Thus, the power factors, a_1, a_2, and a_3, become constants, leaving K_1 and K_2 to explain the differences between materials at various test temperatures.

The general equation

$$CS = 12.50^{1.75} + 0.00270D^{-1/3} \left(\frac{D}{1\text{-strain}}\right)^{4}$$

was then developed to predict the restrained compressive strength of a rigid urethane foam at -65°F (-54°C), while the equation

$$CS = 7.75D^{1.75} + 0.00149D^{-1/3}\left(\frac{D}{1\text{-strain}}\right)^{4}$$

predicts the strength at 77°F (25°C). At 250°F, no general equation can be developed. However, equations of the Equation 2 form can be found for each specific foam system.

REFERENCES

[1]C. J. Benning, *Chemistry and Physics of Foam Formulation.* Volume 1, New York: Wiley Interscience, 1969, p 221.

[2]S. L. DeGisi and T. E. Neet, "Effect of Amine Catalysts on the Physical Properties of a Rigid Urethane Foam System, *Journal of Cellular Plastics,* Volume 7, Number 4, August 1971, pp 165-201.

[3]S. L. DeGisi and T. E. Neet, "Effect of Amine Catalysts on the Compressive Properties of Urethane Foam," *Journal of Cellular Plastics,* Volume 9, Number 4, August 1973, pp 174-181.

[4]R. A. Daniel, *Compressive Testing of Polyurethane Foams* (Topical Report). UNCLASSIFIED. Bendix Kansas City: BDX-613-1036, To be published.