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Bendix Kansas City Division

DISCLAIMER

EFFECTS OF AMINE CATALYSTS ON THE PHYSICAL PROPERTIES OF A RIGID URETHANE FOAM SYSTEM

MASTER

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ABSTRACT

The effects of catalyst type and concentration upon the compressive properties of a rigid urethane foam system developed at the Bendix Kansas City facility were investigated. Formulations containing six different catalysts and various concentrations of each were tested. Standard ASTM 1-inch-cube compressive specimens were prepared from both free-rise and molded billets. All data were normalized to nominal densities, 6.5 lb/ft^3 for the free-rise foam and 14.0 lb/ft^3 for the molded materials, thus enabling direct comparisons of strength values. The results of the investigation support the belief that the principal function of the catalyst in high-density molded urethane foams is to control the reaction of the foam constituents.

CONTENTS

ILLUSTRATIONS

TABLES

Section 1

SUMMARY

The effects of catalysts on the reaction kinetics of urethane foams have been explored in considerable depth by present-day researchers;[1] however, little information has been published on the effects of catalysts upon the compressive properties of such foams. It is for that reason that this investigation was conducted.

Rigifoam 6003-6, a rigid urethane foam system developed at the Bendix Kansas City facility, was selected for the study. The materials consist of a toluene-diisocyanate prepolymer (amine equivalent 145) and an E-caprolactone/pentaerythritol-polyester polyol (hydroxyl number 605).

Six different catalysts, and several concentrations of each, were the variables upon which the evaluation was predicated. Low-density (6.5-lb/ft^3 nominal density) and high-density (14.0-lb/ft^3 nominal density) billets were made from the base formulation without catalyst and with each of the catalysts at several different concentrations. The low-density billets were formed by allowing the foam to rise, unrestricted, in 1/2-gallon paper containers. The high-density billets were formed in a mold, in which the rise of the foam was restricted. The billets were cured for 4 hours at 300°F, and 12 standard 1-inch-cube compressive test specimens were machined from each billet for tests to provide average compressive properties for comparison. The tests were conducted in accordance with ASTM D-695, at 77 ± 2°F.

Errors which might result from density variations between the specimens were minimized by use of a computer to normalize the compressive properties of each specimen to the nominal density of the material from which it was made (6.5 lb/ft^3 or 14.0 lb/ft^3). Normalizing the compressive test values to a constant density enabled comparisons to be made more conveniently. The compressive properties were measured both parallel and perpendicular to the direction of foam rise. Order columns were included in the data tabulations to indicate relative directional strengths of each formulation as compared to the others. The strength ratings (1 through 22) are given in the order of declining strength. (See Tables 3 through 10.)

Analysis of the test data indicated that the type of catalyst and the catalyst concentration both affected the compressive strength of the free-rise foam. The parallel-to-rise compressive strength of the free-rise foam at yield varied between 208.9 psi and 169.5 psi, depending upon the type and concentration of the catalyst used.

The formulation containing 0.35 pbw N-methylmorpholine (NMM) rated first in parallel-to-rise direction strength. The same catalyst at 0.05 pbw concentration rated first in perpendicular strength and 11th in parallel strength. The data from all of the other formulations revealed similar behaviors. It appears that increases in parallel-to-rise strengths are dependent upon the reactivity of the foam system. Greater reactivity causes increased elongation of the cells along the rise axis, thereby increasing the compressive strength in that direction. That increase is accompanied by a strength decrease in the direction perpendicular to rise; however, the latter is not necessarily proportional to the former. (See Table 1 and Tables 3 through 6.)

Because cell elongation in the high-density foam was restricted by pressure which was developed within the mold, the compressive strengths of the molded samples were more nearly equal in both directions. Parallel-to-rise compressive strength of the molded foam at yield varied between 741.2 psi and 678.9 psi. NMM catalyst at 0.15 pbw concentration rated first in strength; Sipene at 0.10 pbw rated lowest of all the formulations tested. Although both parallel and perpendicular strengths varied in an unpredictable fashion, the range was much smaller (percentagewise) than that of the free-rise foam. The perpendicular strengths were not in the same order as the parallel strengths, and neither could be correlated with the types or concentrations of the catalysts used. (See Table 2 and Tables 7 through 10.)

Although many of the data variations implied unidentifiable sources of small inaccuracies in the tests, the overall results appear to support the following conclusions.

- Both type and concentration of the catalyst have some influence upon the directional compressive strength properties of low-density, free-rise foams.

- Neither the type nor the concentration of the catalyst has any significant effect upon the compressive strength properties of the molded foams; and

- The principal function of the catalyst in high-density, molded urethane foams is to control the reactivity of the foam to improve processability and optimize the molding process.

Section 2

EXPERIMENTAL PROCEDURE

A carbon-dioxide-blown, rigid-urethane-foam system, Rigifoam 6003-6, developed by the Bendix Kansas City facility, was chosen for this study.[2] The system is composed of a toluene diisocyanate prepolymer (amine equivalent 145) and an E-caprolactone/pentaerythritol-polyester polyol (hydroxyl number 605). The formulation is shown below.

R-Component	Amount (pbw)
Polyester resin	100.00
Distilled water	1.20
Cell stabilizer (Union Carbide L5320)	0.75
Catalyst	As listed below
T-Component	185.80
Catalyst Type	Amount (pbw)
No Catalyst	0.00
N-methylmorpholine (NMM)	0.05
	0.15
	0.25
	0.35
	0.45
	0.50
Tetramethylbutane Diamine (TMBDA)	0.05
	0.10
	0.15
Dabco (Houdry Chemical Co.)	0.05
	0.10
	0.15
Sipene UC (Alcolac Chemical Corp.)	0.05
	0.10
	0.15
Polycat-8 (Abbot Laboratories)	0.05
	0.10
	0.15
Polycat-13 (Abbot Laboratories)	0.50
	1.00
	2.00

Free-rise samples of 6.5-lb/ft^3 nominal density and molded foam samples of 14.0-lb/ft^3 nominal density were prepared under uniform mixing conditions. A Conn (Conn Manufacturing Co.) mixer was used to mix the formulations under the conditions shown below.

Parameter	Free-Rise Foam 6.5-lb/ft^3 Density	Molded Foam 14.0-lb/ft^3 Density
Mix weight	400.0 grams	1400.0 grams
Pour weight	300.0 grams	1220.0 grams
Mixing time	*	*
Mixer speed	1500 rpm	1500 rpm
Mixing blade	2-inch double	4-inch single
Temperature	77 ± 2°F	77 ± 2°F

*Mixing times varied between 45 and 75 seconds, depending upon the the type of catalyst and the concentration. Mixing time was adjusted to permit approximately the same degree of reaction in all of the batches before they were transferred to the molds.

Free-rise samples were allowed to expand to a nominal density of 6.5 lb/ft^3 in 1/2-gallon paper containers. Those billets were used to form compressive test specimens and to determine the effects of the catalysts and various catalyst concentrations upon the reactivity of the material.[3]

Other billets were made by restricting the foam to a density of 14.0 lb/ft^3 in a 4- by 6- by 12-inch aluminum mold which was preheated to 125°F. The direction of foam rise was parallel to the 12-inch dimension of the mold. All of the billets, both high-density and low-density, were cured for 4 hours at 300°F.

One-inch cubes were machined to an accuracy of ± 0.005 inch from each of the billets. Those specimens were compressive tested at 77 ± 2°F in accordance with ASTM D-695: 6 were tested in the parallel-to-rise direction; 6 were tested perpendicular-to-rise. The compressive modulus, the compressive strength at 6-percent and 10-percent deflection, the yield strength, and the density of each type of specimen were determined. For convenience in evaluating the data, all compressive values were normalized to the nominal density of the billets: 6.5 lb/ft^3 for the free-rise foam, and 14.0 lb/ft^3 for the molded foam. The normalized compressive values were grouped by catalyst type and content.

The data normalization for density differences between similar specimens was accomplished by programming the data for a computer and determining values of the constants A and B for the following equation:[4]

$$\text{Compressive Property (Strength or Modulus)} = A(\text{Density})^B. \quad (1)$$

The computer programs were run for each of the four following cases:

Case 1. Samples tested parallel to the direction of foam rise, including all types of catalysts and catalyst concentrations;

Case 2. Samples tested parallel to the direction of foam rise, but treating each catalyst and catalyst concentration separately;

Case 3. Samples tested perpendicular to the direction of foam rise, including all types of catalysts and concentrations; and

Case 4. Samples tested perpendicular to the direction of foam rise, but treating each catalyst and concentration separately.

The normalized compressive properties were predicted by means of Equation 2:

$$\frac{\text{Predicted Compressive Property}}{\text{Experimental Compressive Property}} = \left(\frac{6.5 \text{ or } 14.0}{\text{Experimental Density}}\right)^B. \quad (2)$$

The predicted compressive properties obtained by comparing Case 1 to Case 2 and Case 3 to Case 4 differed by less than 1 percent; therefore, the data were normalized by using the value of B obtained from the Case 1 program for material tested parallel-to-rise, and the value obtained from Case 3 for the material tested perpendicular-to-rise.

The values of B determined by the computer programs are as follows.

Compressive Property	Values of B	
	Parallel to Rise	Perpendicular to Rise
Modulus	1.73	2.05
Strength		
at 6% strain	1.55	2.16
at 10% strain	1.67	2.04
Yield	1.85	2.08

The values of the constant B listed above at 10-percent strain are comparable to the 1.4 to 1.7 range of B-values reported in the literature for foam tested parallel to the direction of rise.[5]

Section 3

RESULTS

The compressive properties of the free-rise foam, normalized to a density of 6.5 lb/ft^3, are shown in Table 1. Like properties of the molded foam, normalized to a density of 14.0 lb/ft^3, are listed in Table 2. Each value listed in those and the following tables is the average of six specimens from the same foam billet.

Tables 3 through 10 include additional columns which indicate the parallel and perpendicular strength ratings of each formulation as compared to all of the others. Those columns provide a convenient means of evaluating the relative merits of each formulation in respect to the others.

Table 11 and Figure 1 show the effect of catalyst concentration upon the perpendicular-to-parallel compressive-strength ratio.

The measure of reactivity of the free-rise foam shown in Figure 1 is the rise-rate constant,[7] and is directly related to the maximum instantaneous-velocity[3] of the foam. As a greater amount of catalyst is added, the increased reactivity of the system imparts more elongation to the cells, and the parallel-to-rise compressive strength of the foam is increased. That increase in parallel-direction strength is accompanied by a decrease in stength perpendicular to the direction of cell elongation.

Since compacting of the material in the molds tends to prevent elongation of the cells, the 14.0 lb/ft^3 molded billets exhibited compressive properties that were nearly isotropic. The differences in the parallel and perpendicular strengths were small (an average of 5.0 psi for the yield strength), with the greatest strength existing along the axis perpendicular to foam rise.

Table 1. Compressive Properties of Free-Rise Foam Normalized to 6.5 Pounds Per Cubic Foot

Catalyst Concentration	(pbw)	Tested Parallel to Foam Rise				Tested Perpendicular to Foam Rise			
		Strain (psi)		Yield	Modulus	Strain (psi)		Yield	Modulus
		6%	10%	(psi)	(psi)	6%	10%	(psi)	(psi)
No Catalyst		169.2	156.2	169.8	4714.2	153.5	151.9	157.8	3782.2
NMM	0.05	180.7	165.9	182.1	4980.3	153.2	158.6	161.5	3589.2
	0.15	188.8	168.3	189.9	5387.8	156.7	156.8	160.9	3975.1
	0.25	200.3	175.8	203.1	5893.1	144.1	145.9	147.3	3584.7
	0.35	205.2	183.5	208.8	6302.4	135.4	140.1	- -	3294.1
	0.45	191.6	174.0	196.5	5730.6	139.6	141.2	142.9	3524.0
	0.50	193.5	180.1	203.8	6160.3	136.3	138.4	148.2	3438.4
TMBDA	0.05	168.0	153.8	170.5	5078.1	135.7	136.9	138.4	3472.9
	0.10	168.6	163.4	183.3	5750.3	137.1	137.4	141.1	3543.8
	0.15	171.9	166.0	186.0	5920.7	135.3	136.7	143.3	3534.3
Dabco	0.05	179.8	162.5	180.8	5256.7	133.3	134.9	142.2	3382.5
	0.10	178.7	158.0	179.2	5511.8	130.4	134.4	135.8	3294.3
	0.15	177.2	160.2	181.9	5846.8	127.1	132.4	136.0	3173.9
Sipene	0.05	176.6	157.2	177.2	5202.3	143.8	146.1	148.8	3640.0
	0.10	179.3	160.1	179.8	5215.8	135.6	139.4	141.1	3399.2
	0.15	182.7	166.6	182.6	5751.9	131.3	130.5	135.9	3104.7
Polycat-8	0.05	177.8	158.9	178.4	5073.5	147.9	152.3	154.6	3484.6
	0.10	197.7	176.9	198.8	5862.2	139.4	143.6	145.3	3689.6
	0.15	202.2	181.2	208.1	6627.4	136.7	143.4	146.5	3514.5
Polycat-13	0.50	174.3	160.5	175.9	5480.7	140.2	143.1	147.1	3559.7
	1.00	172.4	155.9	172.8	5312.2	140.6	146.2	148.5	3582.4
	2.00	173.4	158.9	176.2	5020.2	138.8	143.0	145.4	3437.7

Table 2. Compressive Properties of Molded Foam Normalized to 14.0 Pounds Per Cubic Foot

Catalyst Concentration	(pbw)	Tested Parallel to Foam Rise				Tested Perpendicular to Foam Rise			
		Strain (psi)		Yield	Modulus	Strain (psi)		Yield	Modulus
		6%	10%	(psi)	(psi)	6%	10%	(psi)	(psi)
No Catalyst		656.4	693.1	688.1	16919	673.4	708.6	706.3	17888
NMM	0.05	700.6	716.2	723.8	19331	672.1	696.8	702.3	17844
	0.15	713.0	740.1	741.2	19137	678.9	711.3	713.8	17817
	0.25	676.4	713.9	714.2	19841	657.6	695.9	697.8	17644
	0.35	683.3	718.4	726.3	18870	693.2	730.5	--	18876
	0.45	700.2	734.3	736.0	19469	693.8	740.7	745.0	19548
	0.50	699.1	729.1	737.0	20025	694.1	729.7	--	19734
TMBDA	0.05	652.2	686.4	685.6	18057	669.0	708.3	713.8	17956
	0.10	626.0	659.0	--	17256	663.2	698.0	699.5	17882
	0.15	586.8	618.9	--	15957	665.8	696.8	712.5	18572
Dabco	0.05	656.2	690.0	689.1	18275	672.5	707.1	708.6	17663
	0.10	606.2	644.9	--	17232	645.1	679.2	--	18491
	0.15	617.6	655.2	--	17706	660.6	697.7	699.0	18714
Sipene	0.05	656.7	687.5	687.4	18438	683.8	716.7	718.8	19659
	0.10	648.1	680.1	678.9	18427	681.5	715.5	715.9	19011
	0.15	659.7	692.6	691.9	17955	674.9	710.3	710.9	18331
Polycat-8	0.05	658.1	695.2	697.8	18521	649.7	695.8	697.3	17965
	0.10	629.2	660.0	--	18015	629.1	668.1	--	17641
	0.15	645.7	681.1	--	18360	685.2	722.3	--	19595
Polycat-13	0.50	671.6	700.4	703.0	18131	665.2	698.0	699.9	18066
	1.00	668.1	692.8	694.8	18220	681.9	710.0	713.8	18516
	2.00	667.2	697.2	695.9	18237	676.2	704.5	707.0	18240

Table 3. Normalized Compressive Strength of 6.5 lb/ft^3 Foam at 6 Percent Deflection

Catalyst (pbw)	Parallel to Rise		Perpendicular to Rise	
	Strength (psi)	Order*	Strength (psi)	Order*
No Catalyst	169.2	20	153.5	2
NMM				
0.05	180.7	9	153.2	3
0.15	188.8	7	156.7	1
0.25	200.3	3	144.1	5
0.35	205.2	1	135.4	17
0.45	191.6	6	139.6	9
0.50	193.5	5	136.3	14
TMBDA				
0.05	168.0	22	135.7	15
0.10	168.6	21	137.1	12
0.15	171.9	19	135.3	18
Dabco				
0.05	179.8	10	133.3	19
0.10	178.7	12	130.4	21
0.15	177.2	14	127.1	22
Sipene				
0.05	176.6	15	143.8	6
0.10	179.3	11	135.6	16
0.15	182.7	8	131.3	20
Polycat-8				
0.05	177.8	13	147.9	4
0.10	197.7	4	139.4	10
0.15	202.0	2	136.7	13
Polycat-13				
0.50	174.3	16	140.2	8
1.00	172.4	18	140.6	7
2.00	173.4	17	138.8	11

*Numbers in Order column are in order of decreasing strength-- 1 is highest; 22 is lowest.

Table 4. Normalized Compressive Strength of 6.5 lb/ft^3 Foam at 10 Percent Deflection

Catalyst (pbw)	Parallel to Rise		Perpendicular to Rise	
	Strength (psi)	Order*	Strength (psi)	Order*
No Catalyst	156.2	20	151.9	4
NMM				
0.05	165.9	10	158.6	1
0.15	168.3	7	156.8	2
0.25	175.8	5	145.9	7
0.35	183.5	1	140.1	13
0.45	174.0	6	141.2	12
0.50	180.1	3	138.4	15
TMBDA				
0.05	153.8	22	136.9	17
0.10	163.4	11	137.4	16
0.15	166.0	9	136.7	18
Dabco				
0.05	162.5	12	134.9	19
0.10	158.0	18	134.4	20
0.15	160.2	14	132.4	21
Sipene				
0.05	157.2	19	146.1	6
0.10	160.1	15	139.4	14
0.15	166.6	8	130.5	22
Polycat-8				
0.05	158.9	16	152.3	3
0.10	176.9	4	143.6	8
0.15	181.2	2	143.4	9
Polycat-13				
0.50	160.5	13	143.1	10
1.00	155.9	21	146.2	5
2.00	158.9	16	143.0	11

*Numbers in Order column are in order of decreasing strength-- 1 is highest; 22 is lowest.

Table 5. Normalized Compressive Strength of 6.5 lb/ft^3 Foam at Yield

Catalyst (pbw)	Parallel to Rise		Perpendicular to Rise	
	Yield (psi)	Order*	Yield (psi)	Order*
No Catalyst	169.8	22	157.8	3
NMM				
0.05	182.1	11	161.5	1
0.15	189.9	7	160.9	2
0.25	203.1	4	147.3	8
0.35	208.8	1	--	--
0.45	196.5	6	142.9	14
0.50	203.8	3	148.2	8
TMBDA				
0.05	170.5	21	138.4	18
0.10	183.3	9	141.1	16
0.15	186.0	8	143.3	13
Dabco				
0.05	180.8	13	142.2	15
0.10	179.2	15	135.8	21
0.15	181.9	12	136.0	19
Stipene				
0.05	177.2	17	148.8	5
0.10	179.8	14	141.1	17
0.15	182.6	10	135.9	20
Polycat-8				
0.05	178.4	16	154.6	4
0.10	198.8	5	145.3	12
0.15	208.1	2	146.5	10
Polycat-13				
0.50	175.9	19	147.1	9
1.00	172.8	20	148.5	6
2.00	176.2	18	145.4	11

*Numbers in the Order column are in the order of decreasing yield-- 1 is highest; 22 is lowest.

Table 6. Normalized Compressive Modulus of 6.5 lb/ft^3 Foam

Catalyst (pbw)	Parallel to Rise		Perpendicular to Rise	
	Modulus (psi)	Order*	Modulus (psi)	Order*
No Catalyst	4714.2	22	3782.2	2
NMM				
0.05	4980.3	21	3589.2	5
0.15	5387.8	13	3975.1	1
0.25	5893.1	5	3584.7	6
0.35	6302.4	2	3294.1	20
0.45	5730.6	10	3524.0	11
0.50	6160.3	3	3438.4	15
TMBDA				
0.05	5078.1	18	3472.9	14
0.10	5750.3	9	3543.8	9
0.15	5920.7	4	3534.3	10
Dabco				
0.05	5256.7	15	3382.5	18
0.10	5511.8	11	3294.3	19
0.15	5846.8	7	3173.9	21
Sipene				
0.05	5202.3	17	3640.0	4
0.10	5215.8	16	3399.2	17
0.15	5751.9	8	3104.7	22
Polycat-8				
0.05	5073.5	19	3484.6	13
0.10	5862.2	6	3689.6	3
0.15	6627.4	1	3514.5	12
Polycat-13				
0.50	5480.7	12	3559.7	8
1.00	5312.2	14	3582.4	7
2.00	5020.2	20	3437.7	16

*Numbers in the Order column are in order of decreasing modulus--1 is highest; 22 is lowest.

Table 7. Normalized Compressive Strength of 14.0 lb/ft^3 Foam at 6 Percent Deflection

Catalyst (pbw)	Parallel to Rise		Perpendicular to Rise	
	Strength (psi)	Order*	Strength (psi)	Order*
No Catalyst	656.4	13	673.4	11
NMM				
0.05	700.6	2	672.1	13
0.15	713.0	1	678.9	8
0.25	676.4	6	657.6	19
0.35	683.3	5	693.2	3
0.45	700.2	3	693.8	2
0.50	699.1	4	694.1	1
TMBDA				
0.05	652.2	15	669.0	14
0.10	626.0	19	663.2	17
0.15	586.8	22	665.8	15
Dabco				
0.05	656.2	14	672.5	12
0.10	606.2	21	645.1	21
0.15	617.6	20	660.6	18
Sipene				
0.05	656.7	12	683.8	5
0.10	648.1	16	681.5	7
0.15	659.7	10	674.9	10
Polycat-8				
0.05	658.1	11	649.7	20
0.10	629.2	18	629.1	22
0.15	645.7	17	685.2	4
Polycat-13				
0.50	671.6	7	665.2	16
1.00	667.2	9	681.9	6
2.00	668.1	8	676.9	9

*Numbers in the Order column are in order of decreasing strength--1 is highest; 22 is lowest.

Table 8. Normalized Compressive Strength of 14.0 lb/ft^3 Foam at 10 Percent Deflection

Catalyst (pbw)	Parallel to Rise		Perpendicular to Rise	
	Strength (psi)	Order*	Strength (psi)	Order*
No Catalyst	693.1	10	708.6	10
NMM				
0.05	716.2	5	696.8	17
0.15	740.1	1	711.3	7
0.25	713.9	6	695.9	19
0.35	718.4	4	730.5	2
0.45	734.3	2	740.7	1
0.50	729.1	3	729.7	3
TMBDA				
0.05	686.4	15	708.3	11
0.10	659.0	19	698.0	14
0.15	618.9	22	696.8	18
Dabco				
0.05	690.0	13	707.1	12
0.10	644.9	21	679.2	21
0.15	655.2	20	697.7	16
Sipene				
0.05	687.5	14	716.7	5
0.10	680.1	17	715.5	6
0.15	692.6	12	710.3	8
Polycat-8				
0.05	695.2	9	695.8	20
0.10	660.0	18	668.1	22
0.15	681.1	16	722.3	4
Polycat-13				
0.50	700.4	7	698.0	14
1.00	692.8	11	710.0	9
2.00	697.2	8	704.5	13

*Numbers in the Order column are in order of decreasing strength-- 1 is highest; 22 is lowest.

Table 9. Normalized Compressive Strength of 14.0 lb/ft^3 Foam at Yield

Catalyst (pbw)	Parallel to Rise		Perpendicular to Rise	
	Yield (psi)	Order*	Yield (psi)	Order*
No Catalyst	688.1	13	706.3	11
NMM				
0.05	723.8	5	702.3	12
0.15	741.2	1	713.8	4
0.25	714.2	6	697.8	16
0.35	726.3	4	--	--
0.45	736.0	3	745.0	1
0.50	737.0	2	--	--
TMBDA				
0.05	685.6	15	713.8	4
0.10	--	-	699.5	14
0.15	--	-	712.5	7
Dabco				
0.05	689.1	12	708.6	9
0.10	--	-	--	--
0.15	--	-	699.0	15
Sipene				
0.05	687.4	14	718.8	2
0.10	678.9	16	715.9	3
0.15	691.9	11	710.9	8
Polycat-8				
0.05	697.8	8	697.3	17
0.10	--	-	--	--
0.15	--	-	--	--
Polycat-13				
0.50	703.0	7	699.9	13
1.00	694.8	10	713.8	4
2.00	695.9	9	707.0	10

*Numbers in Order column are in order of decreasing yield.

Table 10. Normalized Compressive Modulus of 14.0 lb/ft^3 Foam

Catalyst (pbw)	Parallel to Rise		Perpendicular to Rise	
	Modulus (psi)	Order*	Modulus (psi)	Order*
No Catalyst	16,919	21	17,888	16
NMM				
0.05	19,331	3	17,844	18
0.15	19,137	4	17,817	19
0.25	18,841	6	17,644	21
0.35	18,870	5	18,876	6
0.45	19,469	2	19,548	4
0.50	20,025	1	19,734	1
TMBDA				
0.05	18,057	15	17,956	15
0.10	17,256	19	17,882	17
0.15	15,957	22	18,572	8
Dabco				
0.05	18,275	11	17,663	20
0.10	17,232	20	18,491	10
0.15	17,706	18	18,714	7
Sipene				
0.05	18,438	8	19,659	2
0.10	18,427	9	19,011	5
0.15	17,955	17	18,331	11
Polycat-8				
0.05	18,521	7	17,965	14
0.10	18,015	16	17,641	22
0.15	18,360	10	19,595	3
Polycat-13				
0.50	18,131	14	18,066	13
1.00	18,219	13	18,516	9
2.00	18,237	12	18,240	12

*Numbers in Order column are in order of decreasing modulus--
1 is highest; 22 is lowest.

Table 11. Effects of Catalyst Concentration on the Ratio of Perpendicular-to-Parallel Directional Compressive Strengths of 6.5 lb/ft^3 Foam at Yield

Catalyst	Concentration (pbw)	Ratio
NMM	0.05	0.887
	0.15	0.847
	0.25	0.725
	0.35	-- *
	0.45	0.727
	0.50	0.727
TMBDA	0.05	0.812
	0.10	0.770
	0.15	0.770
Dabco	0.05	0.787
	0.10	0.758
	0.15	0.748
Sipene	0.05	0.840
	0.10	0.785
	0.15	0.744
Polycat-8	0.05	0.867
	0.10	0.731
	0.15	0.704
Polycat-13	0.50	0.836
	1.00	0.859
	2.00	0.825

*No yield strength reported for this catalyst concentration in the perpendicular-to-rise test

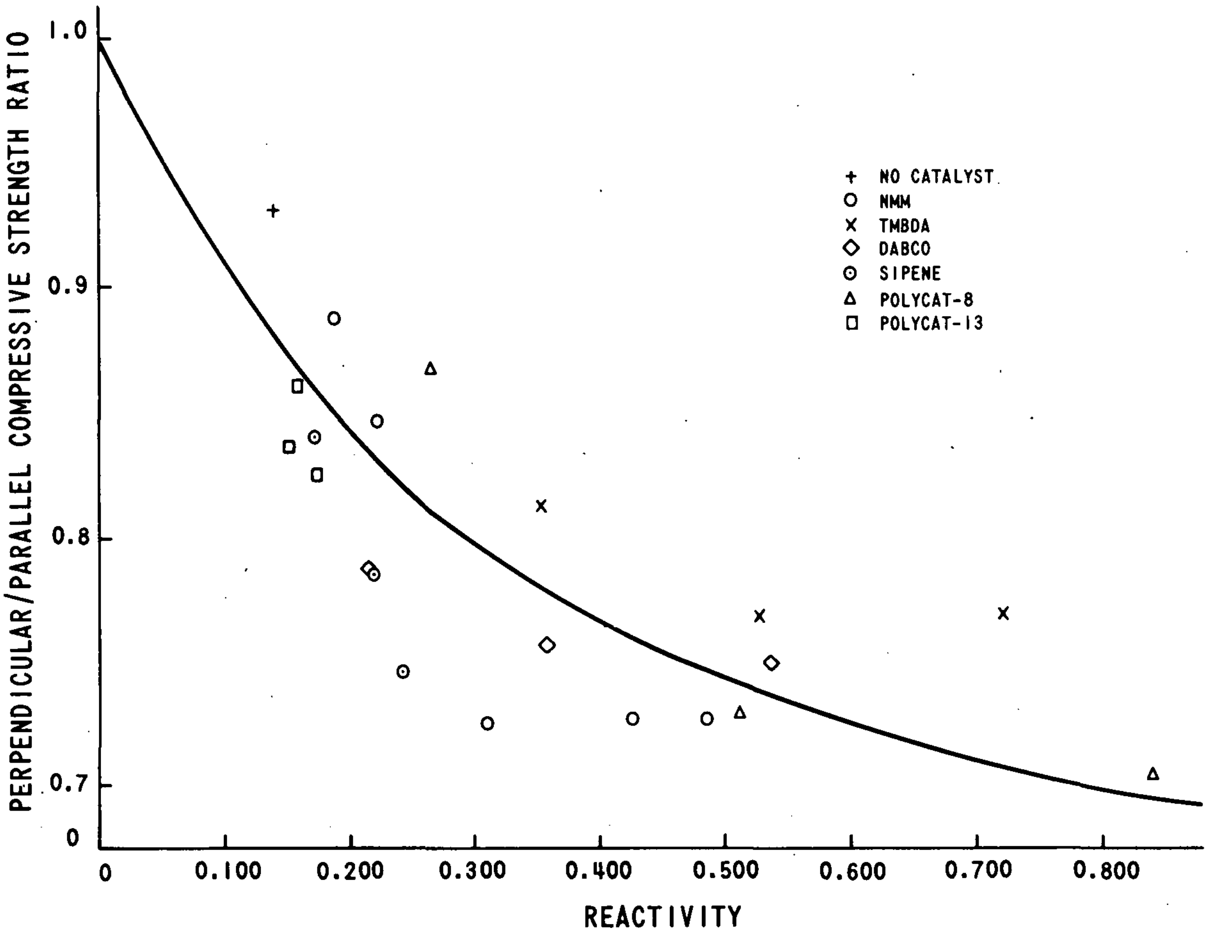

Figure 1. Effects of Catalyst Concentration Upon the Perpendicular-to-Parallel Compressive Strength Ratio

Section 4

DISCUSSION

A casual look at the data appears to indicate a correlation between the compressive properties of the foam and the type and concentration of the catalyst used, as reported by other researchers.[6] However, more detailed analysis tends to refute that impression.

Consider the factors that could cause apparent differences in the compressive properties of the foam.

- First, the accuracy of the data must be considered. Although the compressive properties of the various formulations have been listed as absolute numbers based on an average of six tests, the true compressive properties are unquestionably somewhat different from those listed. That error may have been caused by defects in the foam test specimens, inconsistencies in sample preparation, or inherent inaccuracies in the method of testing. The indicated catalyst orderings therefore may not be valid. The compressive strengths of individual test specimens taken from a single billet varied from the average values as much as 10 psi for the 6.5 lb/ft^3 foam, and as much as 20 psi for the 14.0 lb/ft^3 foam.

- Second, in the free-rise 6.5 lb/ft^3 foam, the compressive properties of the material are anisotropic, with the greatest strength along the axis parallel to the direction of foam rise. As the foam is strengthened in the parallel direction, it is weakened in the perpendicular direction. This is a result of the mechanical effect of cell elongation in the direction of rise. A comparison of the parallel and perpendicular compressive strengths confirms that statement. Table 11 and Figure 1 indicate the effect of catalyst concentration on the perpendicular/parallel-to-rise compressive strength ratio. The measure of reactivity in Figure 1 is the rise-rate constant[7] and is directly related to the maximum instaneous velocity of the foam.[3] As more catalyst is added, the foam-system reactivity is increased, thereby causing greater cell elongation. As a result, the parallel-to-rise compressive strength of the material is increased and the perpendicular-to-rise compressive strength is decreased.

Since compacting of the material in the mold tends to minimize cell elongation, the compressive properties of the 14.0 lb/ft^3 molded foam are isotropic. In fact, the test results indicate that the perpendicular-to-rise compressive strength is even greater than that in the direction of foam rise. Although the differences are small (a yield strength average of 5.0 psi), they appear to be consistent for all catalyst types and concentrations. However, the strength differences in the molded foam are not due to cell shape, but are likely caused by density gradients across the specimens. To confirm that opinion, the difference in density from top to bottom of each specimen along the rise axis was determined. That difference averaged 0.12 lb/ft^3. Therefore, when testing perpendicular to foam rise, the apparent density of the specimen is equal to the actual density of the material being tested. Since the compressive strength of the specimen is dependent upon the weakest (lowest density) portion of the material, the apparent density of the specimen tested parallel-to-rise is 0.060 lb/ft^3 greater than the actual density of the foam. When adjustment for that difference in density is made in Equation 2, the average parallel-to-rise yield strength increases 5.0 psi, precisely the amount required to equalize the strengths in both directions.

When the density compensation described above is considered, complete analysis of the test data does not show significant differences between the compressive strengths obtained with various catalyst types or concentrations. Since the compressive properties of the 6.5 lb/ft^3 nominal density material are anisotropic, the above conclusion is most easily verified by evaluating the compressive strength of the 14.0 lb/ft^3 molded foam. For example, refer to Table 8: Note that there is no pattern for either the type or the concentration of the catalysts in the data for foam tested perpendicular to the rise axis. Instead, the data are scattered randomly, with the no-catalyst material being near the center of the strength values. The parallel-to-rise compressive strengths of the NMM catalyst formulations are consistently higher than the others. That, however, can be misleading. If the type of amine catalyst can affect the compressive properties of the foam, it appears that the concentration of the catalyst would have a similar effect. Although there must be some threshold limit above which additional catalyst would produce no further effect, it is unlikely that such a concentration could have been exceeded in all of the formulations tested. Although the NMM-specimens appear to be the strongest, there is no definite ordering within that group (there is no consistent increase or decrease in strength as the catalyst concentration is increased). That same condition is true of all of the catalyst types and concentrations tested.

Section 5

CONCLUSIONS

Amine catalysts were shown to affect the compressive strength and modulus of low-density (6.5 lb/ft^3) free-rise foam. Increases in strength in the direction parallel to foam rise were evidently caused by greater cell elongation in that direction. Higher catalyst concentrations produce greater foam system reactivity, thereby increasing the elongation of the cells in the direction of rise. Increases in parallel-to-rise strength were accompanied by decreases in perpendicular-direction strength. However, the perpendicular-strength decrease was not proportional to the parallel-strength increase.

Neither the type nor the concentration of the catalyst affected the compressive properties of the 14.0 lb/ft^3 molded foam to a significant degree. The lesser extent of the strength variation in that material evidently was due to the limitation which the mold imposed upon cell elongation.

Since the specimens for this series of tests were prepared under closely controlled conditions, including critical measurement of catalyst content, there were no identifiable process variables other than the type of catalyst and the catalyst concentration. Because of possible sources of error discussed in the text, however, it is probable that many of the strength values shown in the tables are not absolute.

In spite of the limitations described, the writers believe that the work of this investigation supports the following conclusions.

- Both type and concentration of the catalyst have some influence upon the directional compressive strength properties of the low-density, free-rise foams;

- Neither the type nor the concentration of the catalyst has any significant effect upon the compressive strength properties of the molded foams; and

- The principal function of the catalyst in high-density, molded urethane foams is to control the reactivity of the foam to improve processability and optimize the molding process.

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