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Mechanical Properties of Laminated Plastics at −70°, 77°, and 200° F[1]

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Laminates of an unsaturated polyester reinforced with glass fabric and of phenolic resin reinforced with asbestos fabric, high-strength paper, cotton fabric, and rayon fabric were tested in impact, bending, tension, and compression at —70°, 77°, and 200° F. Special apparatus was constructed for conducting the tests at the extreme temperature conditions. The impact strength of the glass-fabric laminate increases at —70° and decreases at 200° F relative to 77° F; the impact strengths of cotton- and rayon-fabric laminates decrease at —70° and increase at 200° F; the paper and asbestos-fabric laminates have small changes in impact strength with temperature. The flexural, tensile, and compressive strengths and moduli of elasticity increase at —70° and decrease at 200° F relative to the 77° F values.

Tests made at room temperature after heating the materials at 200° F for 24 hr indicate that prolonged heating with consequent loss of moisture content and further cure of the resin may offset the effect of high temperature alone. In flexural tests made at 150° F and 90-percent relative humidity, two laminates showed considerable loss in strength.

I. Introduction

A knowledge of the effect of temperature on the strength properties of plastics is of considerable importance in application of the materials for aircraft purposes. Results obtained by various investigators [1, 2, 3] [2] on plastic materials indicate that considerable variation in mechanical properties with temperature may be expected.

Oberg, Schwartz, and Shinn [2] reported variations of 10 to 30 percent in the tensile and flexural properties of Grades C, L, and XX phenolic laminates for the range −38° to 78° F.

Norelli and Gard [3] reported data for tensile, compressive, and shear strengths and tensile moduli of elasticity for various phenolic laminates for temperatures ranging from −67° F to as high as 392° F in some instances. They concluded that the percentage change in strength for cellulose laminates is greater than for those made with mineral reinforcement.

Meyer and Erickson [4] determined the mechanical properties of high-strength-paper phenolic laminates for temperatures from −69° to 200° F. For this temperature range they found large variations in tensile, compressive, and flexural strengths and somewhat smaller variations in modulus of elasticity. The strength and modulus of elasticity values diminished with increasing temperature.

In investigations by the Naval Air Experimental Station [5] considerable data have been obtained at 77° and 160° F on the mechanical properties of a variety of plastic laminates. The ultimate strength and modulus of elasticity values were generally lower at the higher temperature, but the percentage changes varied greatly for the different materials.

Witt, Wolfe, and Rust [6] obtained tensile and compressive data at 160° F and flexural and impact data at −70° and 160° F on a large number of samples of Grades C and L laminates from various manufacturers. They reported decreases in flexural, tensile, and compressive strengths and moduli of elasticity at 160° F rang-

[1] The data presented in this paper are a summary of results reported in NACA Technical Notes 1054 and 1550.

[2] Figures in brackets indicate the literature references at the end of this paper.

TABLE 1. *Description of materials*

NBS Designation	Type of laminate [a]	Density	Thickness, average	Manufacturer	Resin: Type	Resin: Content by weight	Reinforcement: Type	Thread count: Warp	Thread count: Filling	Number of plies	Ply arrangement	Molding conditions: Pressure	Temp.[b]	Time of heating [b]	Time of cooling [b]
		g/cm³	*in.*			*Percent*						*lb/in²*	°F	*min*	*min*
L1 L2	Low-pressure cotton-fabric phenolic.	1.36 1.32	0.15 .60	Bakelite Corp.	Bakelite—BV-16887.	52	Enameled duck 8 oz/yd²	84	28	9 35	Cross	250	325	30	--------
V1 V2	Low-pressure Grade C phenolic.	1.27 1.29	.15 .55	Synthane Corp.	do	51	Army duck 10.4 oz/yd²	50	40	7 [c] 26	do	180	320	50	--------
W1 W2	High-pressure Grade C phenolic.	1.36 1.36	.14 .45	do	Bakelite—BV-1112.	47	do	50	40	7 25	do	1,800	320	50	--------
I2	Grade C phenolic	1.34	.53	do	do	48	Cotton fabric	50	40	27	Parallel	1,800	340±20	50	20
Z1 [d] Z2	Rayon-cotton-fabric phenolic.	1.37 1.37	.16 .48	Formica Insulation Co.	Ironsides Co.—Phenolic 91-L.	37 to 40	Fortisan WE-3975 3/1 twill, 12.5 oz/yd²	Rayon 75	Cotton 12	7 23	Cross	1,100	300	20	20
S1 S2	High-strength-paper phenolic.	1.42 1.42	.12 .50	Consolidated Water Power and Paper Co.	Bakelite—16526	30	High-strength Mitscherlich paper 32.5 lb/ream of 480 sheets, 24×36 in.	--------	--------	27/0.060-in. thickness.	do	250	310±10	12 30	-------- --------
K1 K2	Grade AA asbestos-fabric phenolic.	1.50 1.48	.15 .57	Synthane Corp.	Bakelite—2427	47	Asbestos fabric 18 oz/yd²	18	16	5 20	Parallel	1,800	340±20	50	20
AB1	Glass-fabric unsaturated-polyester.	1.82	.13	Army Air Forces Technical Service Command.	Plaskon—900	43	Fiberglas ECC-11-112	38	38	45	do	40	180 220	120 120	-------- --------
AB2	do	1.86	.49	do	do	43	do	38	38	166	do	40	160 180 200 220	120 120 120 120	-------- -------- -------- --------
U2	do	1.78	.60	Plaskon Div., Libbey-Owens-Ford Glass Co.	do	50	do	38	38	160	do	50	122 230	720 240	-------- --------

[a] Grade AA and Grade C refer to NEHA designations.

[b] If two or more temperature-time conditions are listed for one laminate, they were applied in succession to cure the laminates.

[c] Warp directions at right angles in the two face plies.

[d] The ⅛-in.-thick sample and the ½-in.-thick sample of the Z material used in the impact, flexural, and tensile tests were received at the same time. The ½-in.-thick sample used in the compressive tests was received 10 months later.

ing from 20 to 25 percent relative to the corresponding values at 77° F. The impact strength of these cotton-fabric phenolic laminates decreased about 40 percent at −70° F and increased about 25 percent at 160° F.

Izod-impact test data reported by Fuller [7] for Grades L and XX phenolic laminates and for a glass-cotton-fabric phenolic laminate indicate an increase in Izod-impact strength with temperature for the cellulose laminates and an opposite trend for the glass-cotton-fabric laminate for the range −67° to 158° F. Shinn [8] also found that the Izod-impact strength of paper and cotton-fabric phenolic laminates increased with temperature over the temperature range −67° to 158° F; a similar trend was observed for paper and cotton-fabric unsaturated-polyester laminates between −67° and 77° F.

The present investigation was undertaken to obtain the impact, flexural, tensile, and compressive properties of representative laminates in the temperature range −70° to 200° F. Since testing at these temperatures presents many problems not met in testing at room temperature, a major part of the project was concerned with the development of apparatus and techniques.

This investigation, conducted at the National Bureau of Standards, was sponsored by and conducted with financial assistance from the National Advisory Committee for Aeronautics.

II. Materials

The materials tested were a group of laminates, which at the beginning of the project (1943) were considered for possible application in structural members of aircraft. The samples were supplied in nominal ⅛-in. and ½-in. thicknesses in the form of sheets 3 ft square or larger. A detailed description of the samples is contained in table 1.

Five of these laminates were tested at the University of Illinois [9] and the Pennsylvania State College [10] in research investigations of the mechanical properties of the materials. Creep at room temperature and flexural fatigue at various temperatures were determined at the former laboratory; static and dynamic creep were investigated at the latter institution. Limited measurements of the tensile and compressive properties of the laminates were made at 77° F in both of these projects. Some of these materials were included in other investigations at this Bureau [11, 12], which were undertaken to determine (a) the tensile stress-strain characteristics of laminates and (b) the effect of simulated service conditions on laminates. Findley, Adams, and Worley [13] made creep tests on the low-pressure Grade C laminate and the rayon-cotton-fabric laminate at three temperatures and 50-percent relative humidity. In all instances except (a) the tests were made on different sheets of the samples of the laminates.

III. Apparatus and Test Procedures

1. Sampling Procedures and Statistical Considerations

Each sample consisted of only one sheet. Impact, flexural, and compression specimens were cut from the same sheet of ½-in.-thick laminate. Initially the sheets were cut into quarters. Impact and flexural specimens were cut from the four quarters of the sheet. A similar procedure was followed in cutting tensile and impact specimens from the ⅛-in.-thick samples. The compression specimens were cut from the same quarter of the sheet, from an area of less than 1 square foot.

Since only one sheet of each sample was tested, the standard error as given in this report measures only variations due to the precision of the test method and variation within a sheet, but does not include sheet-to-sheet variability.

In section II of this report it has been mentioned that five of these same materials were tested concurrently at two other laboratories [9, 10]. Both of these laboratories had one ½-in.-thick sheet of each of the five types of laminates. When the results of compressive strength tests made at 77° F at the three laboratories were compared, it was found that, except for the second sheet of ½-in.-thick rayon-fabric phenolic laminate received at the National Bureau of Standards, the three sheets of each type of laminate had the same compressive strength within 15 percent. Therefore, the sheets tested at this Bureau are considered typical of the manufacturer's product.

For Izod impact tests the average ratio of standard error to impact strength for the 153 values given in table 2 is 2.3 percent. This ratio increases with temperature, being 2.0, 2.1, 2.3, and 2.7 for tests at −70°, 0°, 77°, and 200° F, respectively. In general, this ratio was smaller for impact tests made edgewise than for tests made flatwise. For the other tests the relative values of the standard errors are summarized as follows:

Average ratio of standard error to individual mean value

Type of test	Number of mean values	Strength	Modulus of elasticity
		Percent	*Percent*
Flexure	108	1.5	1.7
Tension	40	2.0	2.8
Compression	24	1.5	1.3

2. Preparation of Specimens

The testing procedures outlined in Federal Specification L–P–406a [14] were followed as closely as possible. The specimens, however, were not polished with fine emery paper after machining. The flexure specimens of glass-fabric laminate U2 were cut with a diamond abrasive saw. All the specimens of glass-fabric laminate sample AB were machined with carbide-tipped tools. Specimens of all other samples were machined with high-speed steel tools, which gave a finish considered satisfactory. The tensile specimens (fig. 1) were milled with a machine having a cam-operated milling fixture for duplicating the desired contour (fig. 2). The ends of the compressive specimens were ground, while the latter were held in a fixture designed to give parallel, square ends.

Specimens tested at 77° F and 50-percent relative humidity were conditioned at least 96 hr prior to test. Specimens tested at other temperatures were first conditioned the same as the 77° F specimens and then were kept at the testing temperature for 24 ±2 hr prior to test.

3. Impact Tests

The impact tests were made according to Method 1071 in Federal Specification L–P–406a [14], using a Baldwin-Southwark pendulum-type Izod impact machine, which had ranges of 2, 8, and 16-ft-lb. The specimens were centered and the notch located properly with alinement jigs.

The tests were made at temperatures of −70°, 0°, 77°, and 200° F. The relative humidity was controlled at 50 percent in testing at 77° F and was not controlled at the other temperatures.

The samples in the ½-in. thickness were tested flatwise and edgewise for both the lengthwise and crosswise orientations. Since the Izod impact machine had a limited capacity (16 ft-lb), the specimens of the glass-fabric laminate sample tested flatwise were made only 0.25 to 0.30 in. wide. Edgewise tests were made on specimens of the ⅛-in.-thick sheets of some of the samples for both lengthwise and crosswise orientations.

4. Flexural Tests

The flexural tests were made according to Method 1031 of Federal Specification L–P–406a [14], using a 2,400-lb-capacity Baldwin-Southwark hydraulic universal testing machine that had ranges of 240, 1,200, and 2,400 lb. This machine was located in a room in which the atmosphere was controlled at 77° F and 50-percent relative humidity. Tests to obtain flexural strength and load-deflection graphs were made at −70°, 77°, and 200° F.

A variable-span flexure test jig with a deflection indicator [15] was used in all tests (figs. 3 and 4). The deflection of the specimen at the center of the span relative to the supports was indicated by an equal-arm lever actuating a gage. The gage, a Southwark-Peters Plastics Extensometer, was coupled to the recorder on the testing machine to obtain load-deflection records. Two models of the Plastics Extensometer were used with this apparatus: the Type PS–6, a high-magnification gage with a range of 0.23 in., and the Type PS–7, a low-magnification gage with a range of 1 in.

The span of the flexure test jig is adjustable from 1.6 to 9 in., and the screw is graduated to 0.002 in. The combination of recording gage and lever is accurate to about 5 percent in the measurement of deflections over 0.01 in. with the PS–6 gage and to about 3 percent for deflections over 0.1 in. with the PS–7 gage. The percentage error diminishes as the deflection increases. Calibrations were made only at 77° F. Additional errors due to thermal expansion would have a maximum value of 0.2 percent.

The flexural properties were determined only for the 0.5-in.-thick samples. Each sample was tested four ways, flatwise and edgewise for specimens cut both lengthwise and crosswise. At least five specimens were tested for each sample for all orientations. The only deviation from Method 1031 of Federal Specification L–P–406a was the

TABLE 2. *Izod impact strengths of laminates at various temperatures* [a]

Material designation	Orientation of specimen	Direction of load	Impact strength for tests made at [b]—			
			−70° F	0° F	77° F	200° F
½-IN.-THICK MATERIAL						
			ft-lb/in. of notch	*ft-lb/in. of notch*	*ft-lb/in. of notch*	*ft-lb/in. of notch*
L2, Low-pressure cotton-fabric phenolic	Lengthwise	Flatwise	3.30 ±0.04	4.17 ±0.06	5.98 ±0.08	6.09 ±0.05
	Crosswise	do	3.32 ± .05	4.12 ± .06	5.96 ± .06	5.82 ± .07
	Lengthwise	Edgewise	1.87 ± .02	2.32 ± .02	3.22 ± .03	3.28 ± .02
	Crosswise	do	1.85 ± .03	2.39 ± .02	3.09 ± .01	3.22 ± .05
V2, Low-pressure Grade C phenolic	Lengthwise	Flatwise	3.93 ± .07	5.40 ± .19	6.57 ± .14	6.64 ± .14
	Crosswise	do	3.79 ± .14	5.04 ± .11	6.26 ± .13	6.39 ± .20
	Lengthwise	Edgewise		2.51 ± .05	3.30 ± .08	3.35 ± .11
	Crosswise	do		2.59 ± .06	3.31 ± .06	3.57 ± .06
W2, High-pressure Grade C phenolic	Lengthwise	Flatwise	4.15 ± .07	5.12 ± .25	5.69 ± .29	5.80 ± .28
	Crosswise	do	3.87 ± .08	4.34 ± .15	5.27 ± .37	6.46 ± .60
	Lengthwise	Edgewise	2.12 ± .05	2.40 ± .11	2.75 ± .14	3.02 ± .14
	Crosswise	do	2.42 ± .02	2.46 ± .11	3.22 ± .17	3.87 ± .26
I2, Grade C phenolic	Lengthwise	Flatwise	2.81 ± .07	3.89 ± .10	5.06 ± .14	6.69 ± .07
	Crosswise	do	2.45 ± .06	3.13 ± .05	4.03 ± .05	5.25 ± .13
	Lengthwise	Edgewise	1.74 ± .02	2.26 ± .02	2.69 ± .03	3.85 ± .04
	Crosswise	do	1.46 ± .01	1.91 ± .02	2.34 ± .03	3.19 ± .04
Z2, Rayon-cotton-fabric phenolic	Lengthwise	Flatwise	17.0 ± .6	18.4 ± .6	17.6 ± .6	15.8 ± .4
	Crosswise	do	18.6 ± .9	19.1 ± .6	17.4 ± .7	16.4 ± .6
	Lengthwise	Edgewise	9.02 ± .32	7.96 ± .10	6.62 ± .09	5.94 ± .35
	Crosswise	do	7.70 ± .15	6.94 ± .21	5.91 ± .15	5.00 ± .28
S2, High-strength-paper phenolic	Lengthwise	Flatwise	4.07 ± .08	4.21 ± .09	4.18 ± .10	4.36 ± .24
	Crosswise	do	4.21 ± .11	4.18 ± .11	4.17 ± .14	4.53 ± .17
	Lengthwise	Edgewise	0.694± .005	0.726± .008	0.841± .012	0.688± .009
	Crosswise	do	.709± .007	.741± .010	.867± .008	.686± .005
K2, Asbestos-fabric phenolic	Lengthwise	Flatwise	4.13 ± .09	4.26 ± .04	4.58 ± .07	4.22 ± .08
	Crosswise	do	1.63 ± .06	1.99 ± .05	2.01 ± .14	1.75 ± .07
	Lengthwise	Edgewise	3.19 ± .08	3.40 ± .06	3.84 ± .03	3.46 ± .03
	Crosswise	do	1.33 ± .05	1.46 ± .02	1.60 ± .05	1.50 ± .04
AB2, Glass-fabric unsaturated-polyester	Lengthwise	Flatwise	46.1 ± .7	39.8 ± .9	31.5 ± .6	26.6 ± .5
	Crosswise	do			29.4 ± .8	
	Lengthwise	Edgewise			9.88 ± .05	
	Crosswise	do			9.03 ± .03	
⅛-IN.-THICK MATERIAL [c]						
V1, Low-pressure Grade C phenolic	Lengthwise	Edgewise	1.94 ±0.02	2.46 ±0.02	3.23 ±0.06	3.15 ±0.05
	Crosswise	do	1.86 ± .03	2.39 ± .02	2.94 ± .04	3.11 ± .05
W1, High-pressure Grade C phenolic	Lengthwise	do	1.84 ± .04	2.21 ± .05	2.72 ± .05	3.13 ± .09
	Crosswise	do	1.67 ± .03	2.16 ± .05	2.71 ± .03	2.96 ± .04
Z1, Rayon-cotton-fabric phenolic	Lengthwise	do	12.9 ± .3	13.0 ± .6	11.8 ± .2	12.2 ± .3
	Crosswise	do	8.74 ± .17	7.82 ± .14	7.13 ± .09	6.91 ± .16
S1, High-strength-paper phenolic	Lengthwise	do	0.612± .006	0.608± .005	0.640± .008	0.664± .007
	Crosswise	do	.622± .004	.638± .007	.629± .015	.623± .004
AB1, Glass-fabric unsaturated-polyester	Lengthwise	do	14.4 ± .2	12.0 ± .4	10.0 ± .3	9.58 ± .16
	Crosswise	do			10.9 ± .2	

[a] The tests were made in accordance with method 1071, Federal Specification L–P–406a.

[b] Mean value for 9 to 12 specimens for all materials except glass fabric laminate AB2, for which 20 to 25 specimens were tested. The accompanying plus or minus value is the standard error.

[c] The specimens were tested individually in the ⅛-in. thickness; composite specimens were not used.

use of a span-depth ratio of 8:1 instead of 16:1 in order to conserve materials. However, for comparative purposes flexure tests were made also at 77° F with a span-depth ratio of 16:1.

5. Tensile Tests

Tensile tests were made according to Method 1011 in Federal Specification L–P–406a [14], using the 1,200-lb range of a 2,400-lb capacity Baldwin-Southwark universal hydraulic testing machine and the 2,400- and 12,000-lb ranges of a 60,000-lb capacity Baldwin-Southwark universal hydraulic testing machine.

The Model PS–6 Southwark-Peters Plastics Extensometer, referred to previously was used. This instrument is a nonaveraging type with a 2-in. gage length, a strain magnification of 400, and a strain range of 10 percent. This gage sepa-

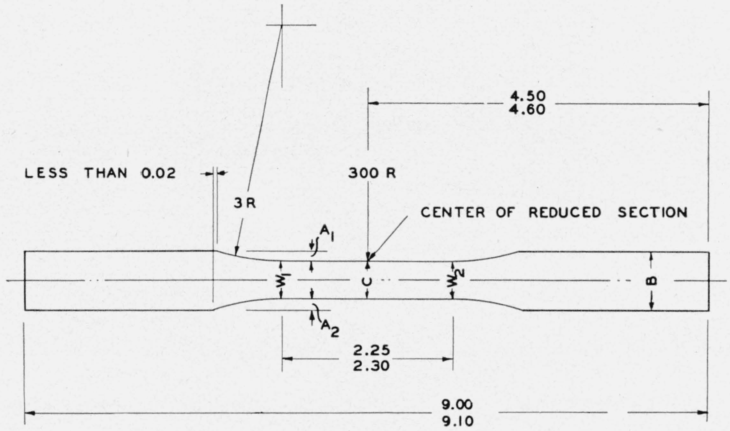

FIGURE 1. *Tensile specimen for plastic materials less than 0.25 in. thick.*

Notes on dimensions—All dimensions are in inches. Specimens shall besymmetrical about line-connecting centers of tab ends. W_1 W_2=0.505±0.002; W_1-W_2=less than 0.001; $C=W_1-0.004$; A_1-A_2=less than 0.004; B=0.750±0.002. Blanks, before machining reduced section, shall be parallel to within 0.002.

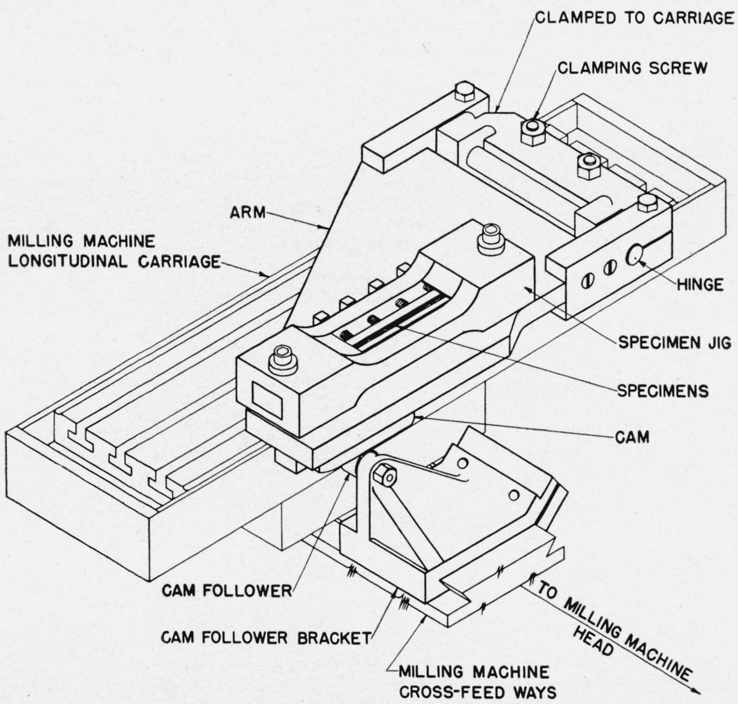

FIGURE 2. *Jig for milling tensile test specimen.*

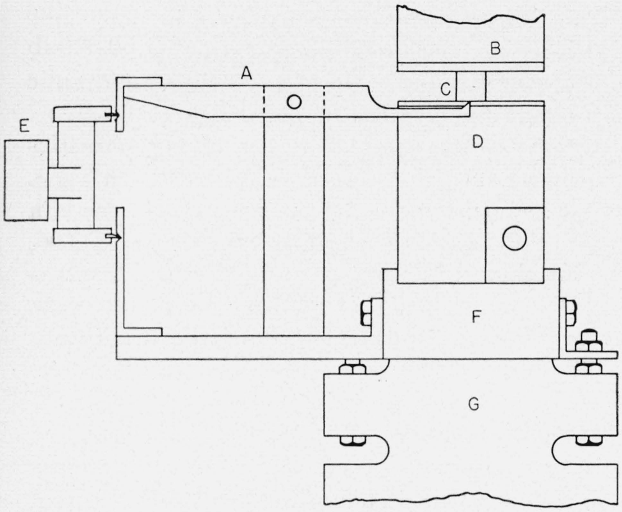

FIGURE 3. *Cross-sectional view of flexural test jig and deflection indicator.*

A, Equal-arm lever; *B*, loading head; *C*, specimen; *D*, specimen support; *E*, autographic tensile strain gage; *F*, base of flexural test jig; *G*, paper phenolic laminate support for flexural test jig. This support used at high and low temperatures.

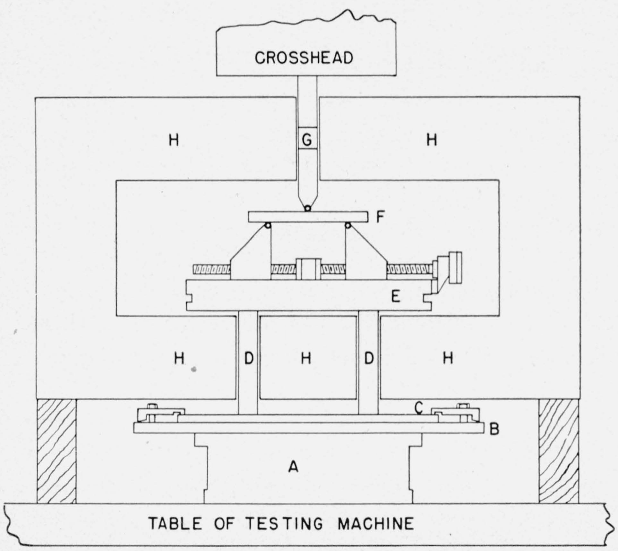

FIGURE 4. *Cross-sectional view of flexural test jig and insulated test cabinet.*

A, Magnetic chuck; *B*, flat steel plate screwed to magnetic chuck; *C*, flat steel plate; *D*, paper phenolic pieces, attached by screws to both *C* and *E*; *E*, base of flexural test jig; *F*, specimen; *G*, paper phenolic piece in loading head; *H*, insulation of test cabinet.

rates into two parts and hence was left on the specimen until failure. In all tests the relative rate of head motion was kept constant at 0.05 in./min until the specimen failed.

Tests to obtain tensile strength and load-elongation graphs were made at −70°, 77°, and 200° F. Tensile tests were made on nominal ⅛-in. thick samples. Both the lengthwise and crosswise directions of most of the samples were tested at the three temperatures. The 45°-diagonal direction was tested only at room temperature. The tensile specimens for a given sample were all taken from the same sheet and those for testing at the three temperatures sampled appropriately from the four quarters of the sheet.

6. Compressive Tests

The compressive tests were made according to Method No. 1021 in Federal Specification L-P-406a [14] on the 2,400-, 12,000-, and 60,000-lb ranges of a 60,000-lb capacity Baldwin-Southwark universal hydraulic testing machine.

The compression tool is shown in figure 5, together with the insulated loading and supporting pieces used in the high- and low-temperature testing. The compression tool incorporates several features of one designed by Aitchison and Miller [16].

(1) A spherical seat at the bottom of the plunger compensates for specimens that have ends that are nonparallel.

(2) The load is transmitted from the testing machine to the plunger by means of a steel push rod and a spherical bearing at the lower end of the push rod. The upper end of the push rod is a spherical surface concentric with the bearing, so that the line of application of the load remains, as nearly as possible, coaxial with the plunger during a lateral displacement of the heads of the testing machine relative to each other.

(3) The seat for the cylindrical lower bearing block was bored concentric with the plunger bushings. A jig, adjustable for specimens of slightly different thickness, was used to center the specimen on the lower bearing block to approximately 0.01 in. This made rapid centering of the specimen possible in the high-temperature and low-temperature tests.

An averaging type Southwark-Peters compressometer, model PC–4, with a gage length of 1 in., a strain magnification of 1,000, and a strain range of 4 percent was used in obtaining stress-strain data. In testing, the relative rate of head motion was 0.01 in./min until about 50 percent of the maximum load was attained. Then the strain gage was removed and the rate of loading increased to 0.03 in./min.

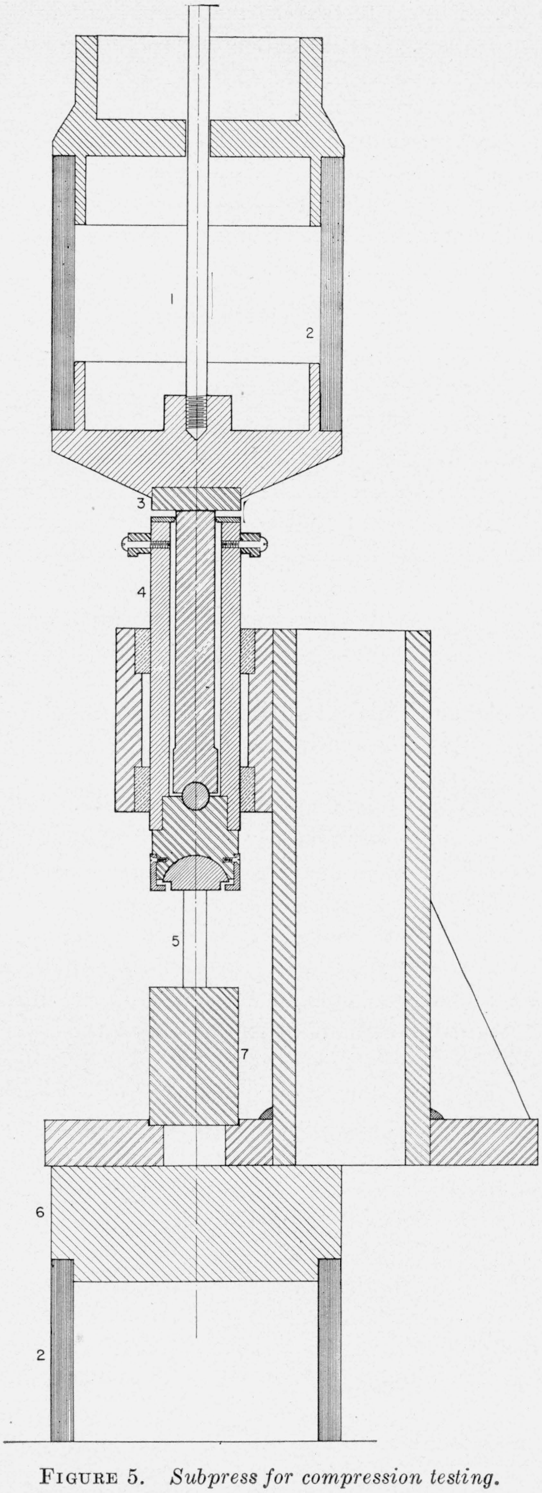

FIGURE 5. *Subpress for compression testing.*

(1), Rod, ½-in. diameter, 16 in. long, to hold loading head in lower crosshead of universal testing machine; (2), laminated paper phenolic tubing, 6½-in. outside diameter and ½-in. thickness; (3), hardened steel insert, 2-in. diameter and ½ in. thick, in loading head; (4), compression plunger; (5), specimen; (6), steel, 6½-in. outside diameter and 2½ in. thick; (7), case-hardened steel cylinder, 2-in. diameter and 3 in. high.

The compression specimen was 2 in. long and 0.50 in. wide; the thickness (0.45 to 0.60 in.) was that of the material (table 1). Compression tests were made for both the lengthwise and crosswise directions of the samples at 77° F, but only the lengthwise directions were tested at −70° and 200° F. For some of the samples, specimens oriented at 45° were tested at 77° F. The compression specimens for a given sample were all taken from the same section of the same sheet but were not otherwise sampled, since all the specimens were taken from a piece of the sheet less than 1 ft^2 in area.

An additional set of specimens was tested at 77° F to obtain the strain at failure. A Southwark-Peters deflectometer, model PD–1, was used to measure the motion of the plunger in the compression tool relative to the base of the tool. The deflectometer has low magnifications of 5, 10, and 20 with a range of 2 in. and high magnifications of 50, 100, and 200 with a range of 0.2 in.

7. High- and Low-Temperature Testing

In all tests at −77° and 200° F, the specimens were kept in a conditioning cabinet at the test temperature for about 20 hr and were then placed in the testing cabinet 1 to 4 hr prior to testing, resulting in a total conditioning period of 24 hr.

The impact tests at 0° and 77° F were made in rooms controlled at these temperatures. For the −70° and 200° F tests, the impact machine was housed in an insulated cabinet. The air in the cabinet was circulated by a fan except during the impact tests. Dry ice was used to cool the air; heating was done with electric heaters. In testing conducted in the insulated cabinet the operator kept his hands, which were protected with woolen gloves, inside the cabinet for periods of about 15 min at a time. This was sufficient for testing about 5 to 10 specimens.

For the low- and high-temperature flexural tests, the specimen, the flexural jig, and the deflection indicator were enclosed in a temperature-controlled cabinet equipped with a blower. The arrangement of the flexural apparatus for the low- and high-temperature tests is shown in figure 4.

For the low- and high-temperature tensile tests, the specimen, the grips, and the strain gage were enclosed in an insulated temperature-con-

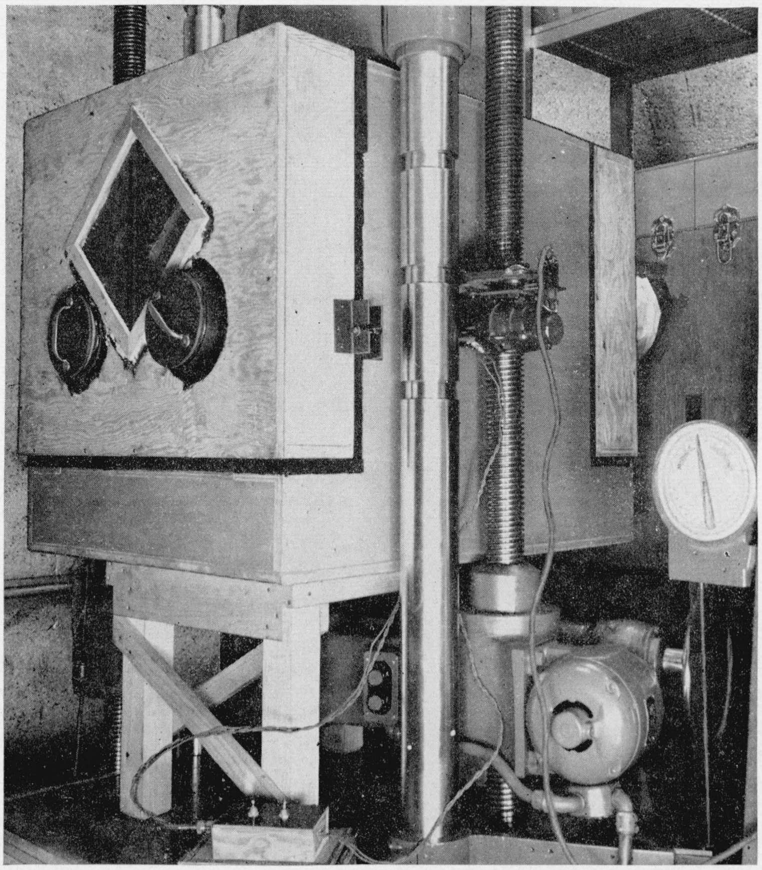

FIGURE 6. *Front view of tensile test enclosure in place in testing machine.*

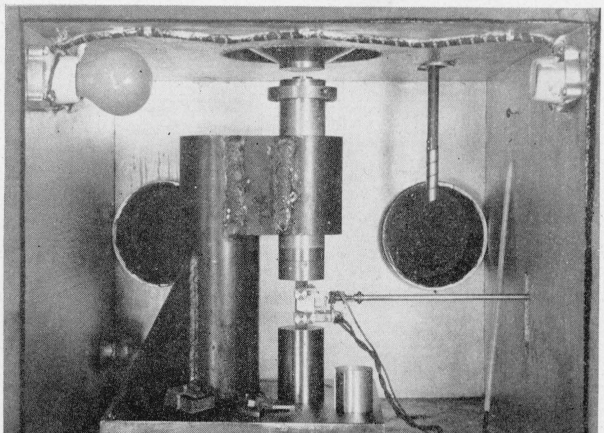

FIGURE 7. *Interior view of compression test enclosure with specimen in place in compression tool and compressometer attached to specimen.*

trolled cabinet (fig. 6). A triple-paned 12- by 12-in. window in the front, armholes, and interior lights enabled convenient handling of the specimens and equipment. Dry ice was used to cool the air; heating was done with electric heaters.

The arrangement for compression testing at low and high temperatures was similar to that for tensile testing. The specimen, compressometer, and compression tool were enclosed in an insulated temperature-controlled cabinet that was heated and cooled in the same way as the tensile test cabinet. Figure 7 shows the compression tool in the cabinet with the specimen and strain gage in position for testing. The method of supporting and loading the compression tool is indicated in figure 5. The steel supporting and loading blocks are insulated from the platen and cross-head, respectively, by tubular phenolic laminate pieces. The two holes shown in the rear of the box in figure 7 were used to circulate either hot or cold air from the conditioning unit shown in figure 6.

Little difficulty was encountered in the high-temperature testing with this equipment. At low temperature several problems were encountered, such as lubricants freezing, frost on the electrical contacts of the gage, and rusting of the gage and loading parts. The testing was carried out with no lubricant on the bearings of the pendulum impact machine, or on the flexural jig, or on the compression tool bushings. The bearings of the pendulum were oiled with heptane prior to warming up to room temperature. Frost on the electrical contacts of the strain gage was washed off with ethanol. Rusting of the strain gage, flexural jig, tensile grips, and compression tool plunger was avoided by immersing them in alcohol until they attained room temperature. They were then disassembled and dried thoroughly.

IV. Results of Tests and Discussions

1. Impact Strength

The data for Izod impact strength of the various samples at temperatures of —70°, 0°, 77°, and 200° F are presented in table 2 and figures 8 to 10. The variation in impact strength with temperature is shown in figures 8 and 9 for lengthwise specimens of the 0.5-in.-thick samples tested flatwise.

The Izod impact strengths at 77° F for samples of the laminates tested flatwise are approximately as follows:

Type of laminate	Izod impact strength
	ft-lb/in. of notch
Grade C phenolic, high-pressure and low-pressure (L, V, W, I).	4 to 7
Rayon-cotton-fabric phenolic (Z)	17
High-strength-paper phenolic (S)	4
Asbestos-fabric phenolic (K)	2 to 4½
Glass-fabric unsaturated-polyester (AB)	30

All the cotton-fabric samples exhibited a steady decrease in impact strength as the temperature was reduced from 77° to —70° F (fig. 9). For samples I2, L2, and V2, the impact strength at —70° F was between 55 and 65 percent of the

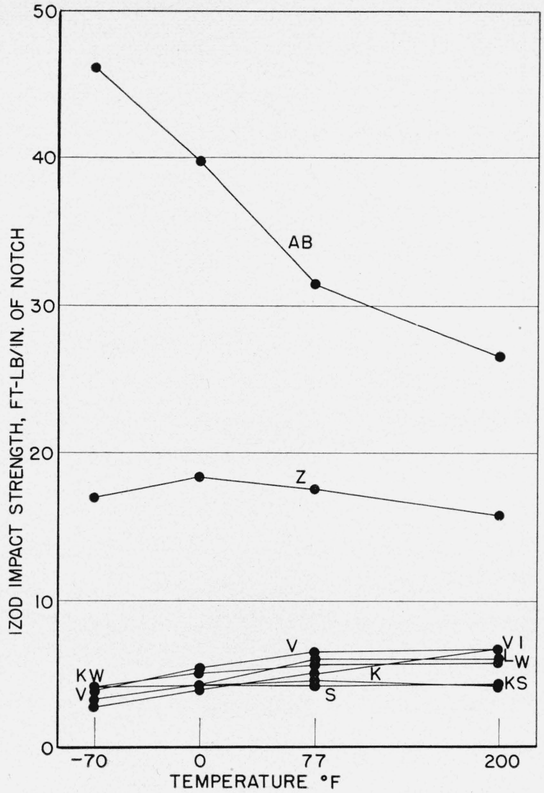

FIGURE 8. *Variation of Izod impact strength with temperature for ½-in.-thick laminates.*

Lengthwise specimens tested flatwise. *I*, Grade C phenolic; *K*, asbestos-fabric phenolic; *L*, low-pressure cotton-fabric phenolic; *S*, high-strength-paper phenolic; *V*, low-pressure Grade C phenolic; *W*, high-pressure Grade C phenolic; *Z*, rayon-cotton-fabric phenolic; AB, glass-fabric unsaturated-polyester.

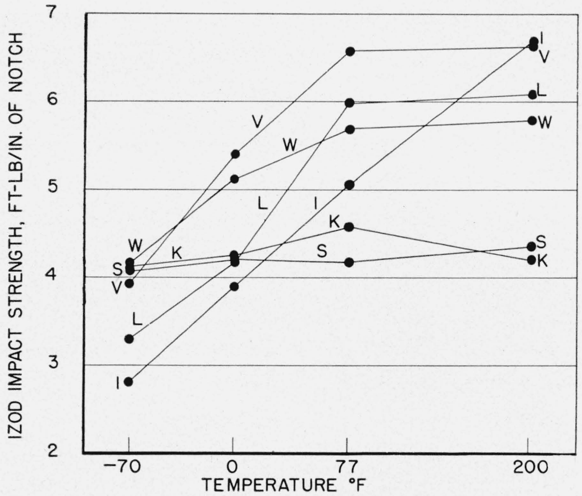

FIGURE 9. *Variation of Izod impact strength with temperature for ½-in.-thick laminates.*

Lengthwise specimens tested flatwise. *I*, Grade C phenolic; *K*, asbestos-fabric phenolic; *L*, low-pressure cotton-fabric phenolic; *S*, high-strength-paper phenolic; *V*, low-pressure Grade C phenolic; *W*, high-pressure Grade C phenolic.

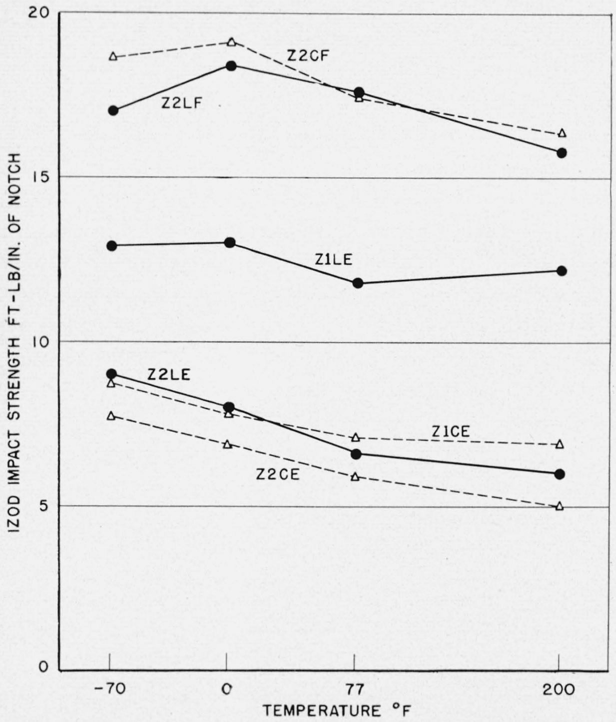

FIGURE 10. *Variation of Izod impact strength with temperature for rayon-cotton-fabric phenolic laminate.*

Z1, Sheet ⅛ in. thick; *Z2*, sheet ½ in. thick; *LF*, lengthwise specimens tested flatwise; *LE*, lengthwise specimens tested edgewise; *CF*, crosswise specimens tested flatwise; *CE*, crosswise specimens tested edgewise.

77° F value for all orientations of specimen and directions of load employed. The corresponding range for W2, a high-pressure grade C laminate sample, was 73 to 77 percent. Little change in impact strength at 200° F compared to 77° F was observed for the cotton-fabric laminates with the exception of the I2 sample. The latter showed a steady increase in impact strength with temperature up to 200° F. These results are in good agreement with values reported for Grade C laminates by Shinn [8], who found that in flatwise tests impact strengths at −67° and 158° F were 66 and 113 percent, respectively, of the value at 77° F.

The paper, S2, and asbestos, K2, laminate samples showed less than 25-percent variation in impact strength over the range of temperature and orientations of specimen and loading investigated (table 2). The variation in impact strength was less than 10 percent for the 0.5-in.-thick paper laminate sample tested flatwise.

The temperature-impact strength trend for the high-strength-paper laminate sample agrees quite well with Shinn's data [8] for flatwise tests where a very slight increase in strength with temperature was found for the range −67° to 158° F. Meyer and Erickson [4] reported that the impact strengths for "Papreg" at the extremes of temperature were slightly less than the normal temperature values, a trend found in this laboratory only for the 0.5-in. sheet tested edgewise. In their impact tests at 158° and 200° F, Meyer and Erickson stated that the specimen was "tested at room temperature within 15 to 30 sec after removal from the conditioning medium"; this test condition is believed to introduce some uncertainty into the results.

The rayon, Z, and glass-fabric, AB, laminate samples had much higher impact strengths than the other samples and also show different impact strength versus temperature trends (fig. 8). When tested edgewise, the rayon laminate sample in both the ⅛- and ½-in. thicknesses showed a slight but steady decrease in impact strength as the temperature was varied from −70° to 200° F (fig. 10). The glass-fabric laminate sample, AB2, showed a constant trend toward higher impact strength at low temperatures. This agrees with data on glass-fabric laminates given by both Field [1] and Fuller [7]. The values for the impact strength of the glass-fabric laminate sample in this paper agree very well with the 77° F data for the same combination of cloth and resin tested by C. D. Jones [17].

The increase in the impact strength of the glass-fabric laminate sample at low temperature is anomalous; it may be related to the interlaminar shear failure that occurs in impact testing of the glass fabric. Thus, if the shear strength increases at low temperature in proportion to the increase in tensile and compressive strengths at low temperature, the impact strength as measured by the Izod method should likewise increase.

The approximate values for the percentage changes in Izod impact strength at −70° and 200° F based on 77° F values are as follows:

Type of laminate	Change in Izod impact strength	
	−70° F	200° F
	Percent	*Percent*
Grade C phenolic, low-pressure (L, V)	−40	0 to +5
Grade C phenolic, high-pressure (W, I)	−25 to −40	+10 to +35
Rayon-fabric phenolic (Z)	0 to +35	0 to −10
High-strength-paper phenolic (S)	0 to −20	+5 to −20
Asbestos-fabric phenolic (K)	−15	−10
Glass-fabric unsaturated-polyester (AB)	+45	−5 to −15

In the tests at 200° F the specimens may have lost some moisture as compared to those tested at the lower temperatures and may have undergone further cure as a result of the heating. To obtain information relative to these effects, Izod impact specimens were tested at 77° F after being heated at 200° F for 24 hr and cooled to room temperature for 1 to 2 hr over calcium chloride in a desiccator. The results of these tests are shown in table 3. The low-pressure cotton-fabric phenolic samples, L2 and V2, were about 10 percent weaker and the glass-fabric laminate, sample AB2, about 10 percent stronger after the 200° F heating. A decrease of 10 percent in impact strength was noted for the rayon laminate, Z2. No definite effect of the heating on the strength of the other samples was noted.

TABLE 3. *Effect of heating at 200° F for 24 hr on Izod impact strengths of ½-in.-thick laminates* [a]

Material designation	Orientation of specimen	Direction of load	Impact strength [b]	
			No heating [c]	Heated at 200° F [d]
			ft-lb/in. of notch	*ft-lb/in. of notch*
L2, Low-pressure cotton-fabric phenolic	Lengthwise	Edgewise	3.22 ±0.03	2.88 ±0.04
	Crosswise	do	3.09 ± .01	2.85 ± .02
V2, Low-pressure Grade C phenolic	Lengthwise	Flatwise	6.57 ± .14	5.95 ± .21
	Crosswise	do	6.26 ± .13	5.55 ± .10
W2, High-pressure Grade C phenolic	Crosswise	Flatwise	5.27 ± .37	4.93 ± .12
I2, Grade C phenolic	Lengthwise	Flatwise	5.06 ± .14	5.13 ± .13
	Crosswise	do	4.03 ± .05	4.21 ± .07
Z2, Rayon-cotton-fabric phenolic	Lengthwise	Flatwise	17.6 ± .6	16.0 ± .4
	Crosswise	do	17.4 ± .7	15.8 ±1.0
S2, High-strength-paper phenolic	Lengthwise	Flatwise	4.18 ± .10	4.02 ±0.18
	Crosswise	do	4.17 ± .14	4.29 ± .20
K2, Asbestos-fabric phenolic	Lengthwise	Edgewise	3.84 ± .03	3.86 ± .06
	Crosswise	do	1.60 ± .05	1.48 ± .03
AB2, Glass-fabric unsaturated-polyester	Lengthwise	Flatwise	31.5 ± .6	35.5 ± .8

[a] The tests were made in accordance with method 1071, Federal Specification L–P–406a.

[b] Mean value for 9 to 12 specimens for all materials except glass-fabric laminate AB2, for which 20 to 25 specimens were tested. The accompanying plus or minus value is the standard error.

[c] Specimens conditioned and tested at 77° F and 50 % relative humidity. Data from table 2.

[d] Specimens tested at 77° F after being allowed to cool to room temperature for 1 to 2 hr in a desiccator containing calcium chloride.

2. Flexural Properties

The flexural properties of some of the laminates tested flatwise at 77° F were approximately as follows:

Type of laminate	Flexural strength	Initial flexural modulus of elasticity
	10^3 lb/in.²	*10^6 lb/in.²*
Grade C phenolic, low-pressure (L, V)	16	0. 80
Grade C phenolic, high-pressure (W, I)	18 to 22	1.0 to 1.1
Rayon-cotton-fabric phenolic (Z)	34	1.6
High-strength-paper phenolic (S)	33	2.4
Asbestos-fabric phenolic (K)	[a] 16 (L) 9 (C)	[a] 1.2 (L) 1.0 (C)
Glass-fabric unsaturated-polyester (U, AB)	55 (L) 45 (C)	2.5 to 2.9

[a] L=lengthwise; C=crosswise.

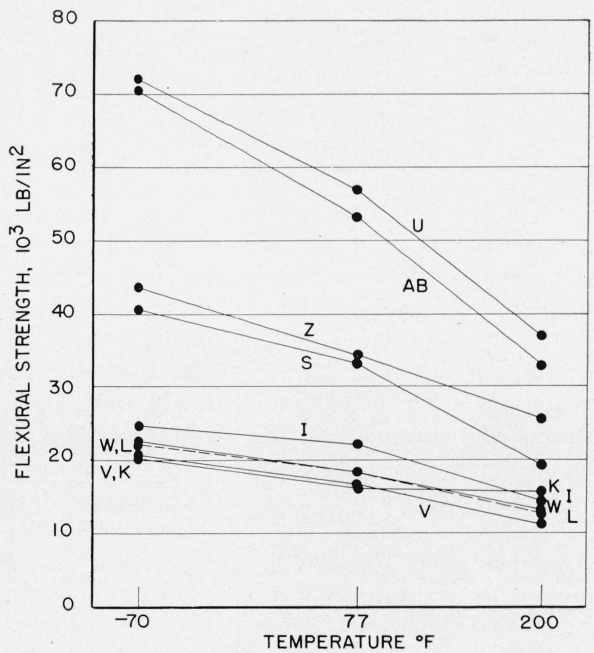

FIGURE 11. *Variation of flexural strength with temperature for ½-in.-thick laminates.*

Lengthwise specimens tested flatwise. Span-depth ratio 8:1. I, Grade C phenolic; *K*, asbestos-fabric phenolic; *L*, low-pressure cotton-fabric phenolic; *S*, high-strength-paper phenolic; *U*, glass-fabric unsaturated-polyester; *V*, low-pressure Grade C phenolic; *W*, high-pressure Grade C phenolic; *Z*, rayon-cotton-fabric phenolic; *AB*, glass-fabric unsaturated-polyester.

(a) Temperature Dependence

The variation of the flexural properties of the samples with temperature is shown graphically in figure 11 to 21.

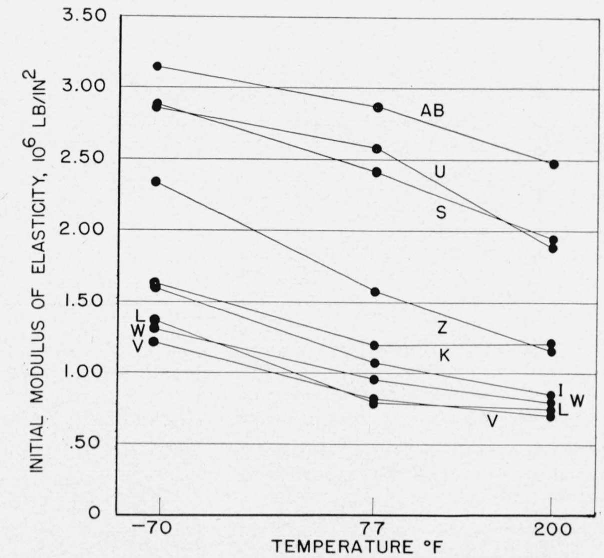

FIGURE 12. *Variation of initial flexural modulus of elasticity with temperature for ½-in.-thick laminates.*

Lengthwise specimens tested flatwise. Span-depth ratio 8:1. *I*, Grade C phenolic; *K*, asbestos-fabric phenolic; *L*, low-pressure cotton-fabric phenolic; *S*, high-strength-paper phenolic; *U*, glass-fabric unsaturated-polyester; *V*, low-pressure Grade C phenolic; *W*, high-pressure Grade C phenolic; *Z*, rayon-cotton-fabric phenolic; *AB*, glass-fabric unsaturated-polyester.

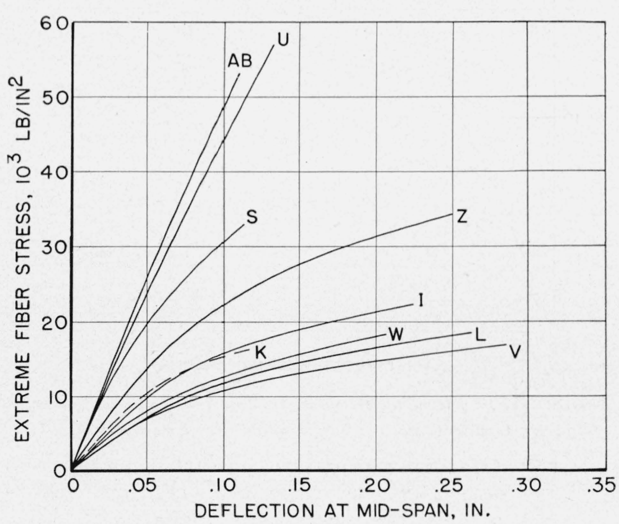

FIGURE 13. *Flexural stress-deflection curves for ½-in.-thick laminates at 77° F.*

Lengthwise specimens tested flatwise. Span-depth ratio 8:1. *I*, Grade C phenolic; *K*, asbestos-fabric phenolic; *L*, low-pressure cotton-fabric phenolic; *S*, high-strength-paper phenolic; *U*, glass-fabric unsaturated-polyester; *V*, low-pressure Grade C phenolic; *W*, high-pressure Grade C phenolic; *Z*, rayon-cotton-fabric phenolic; *AB*, glass-fabric unsaturated-polyester.

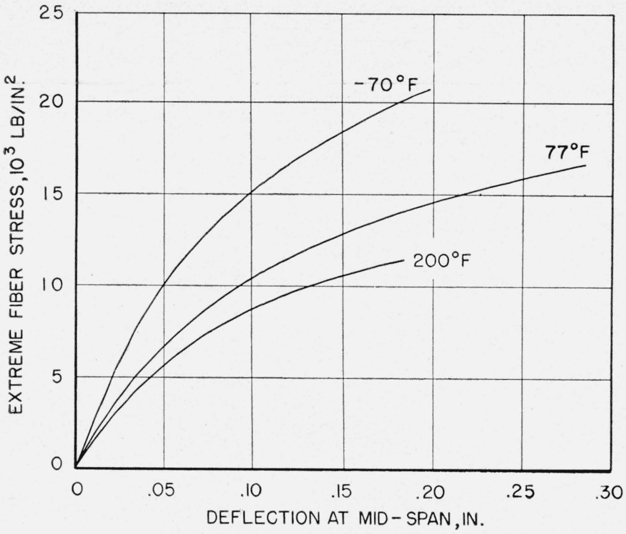

FIGURE 14. *Flexural stress-deflection curves for low-pressure Grade C cotton-fabric phenolic laminate, V2.*

Lengthwise specimens tested flatwise. Span-depth ratio 8:1. Initial modulus of elasticity: −70° F, 1,220,000 lb/in.^{2}; 77° F, 820,000 lb/in.^{2}; 200° F, 710,000 lb/in.^{2}

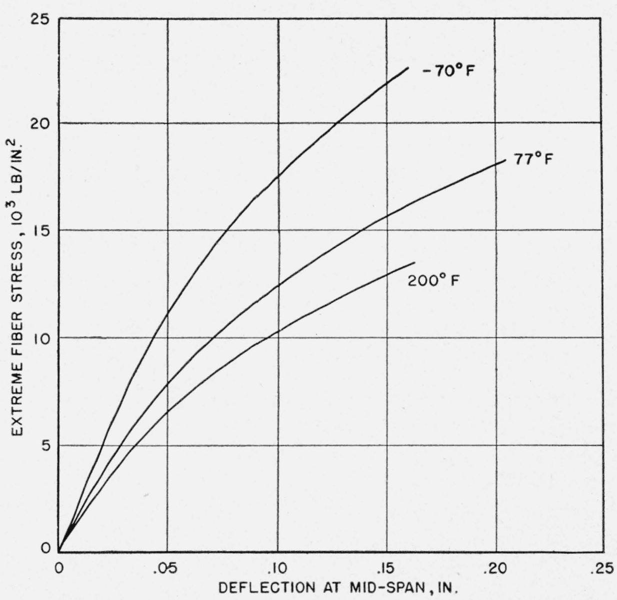

FIGURE 15. *Flexural stress-deflection curves for high-pressure Grade C cotton-fabric phenolic laminate, W2.*

Lengthwise specimens tested flatwise. Span-depth ration 8:1. Initial modulus of elasticity: −70° F, 1,310,000 lb/in.^{2}; 77° F, 960,000 lb/in.^{2}; 200° F, 800,000 lb/in.^{2}

The four samples of cotton-fabric phenolic laminates, I2, L2, V2, and W2, exhibited quite similar properties. The flexural strength of these cotton-fabric laminates increased about 10 to 30 percent at −70° F and decreased very nearly 30

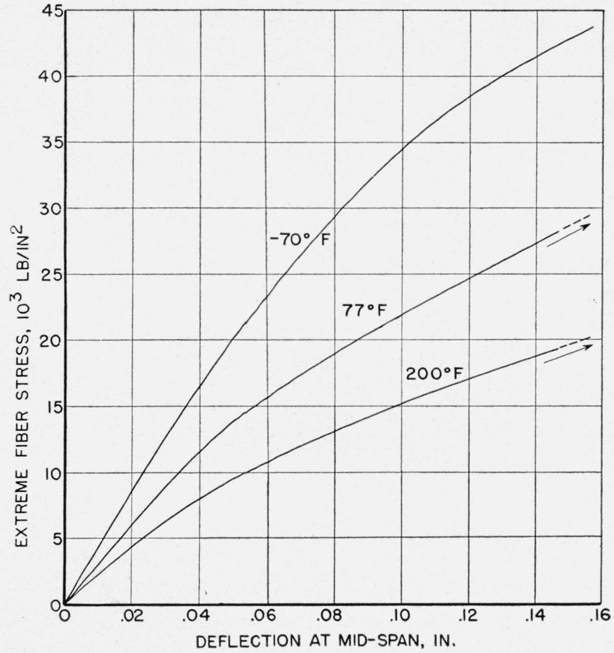

FIGURE 16. *Flexural stress-deflection curves for rayon-cotton-fabric phenolic laminate, Z2.*

Lengthwise specimens tested flatwise at three temperatures. Span-depth ration 8:1.

Temperature	Initial flexural modulus of elasticity	Flexural strength	Total deflection
°F	*lb/in.*^{2}	*lb/in.*^{2}	*in.*
−70	2, 340, 000	43, 700	0. 16
77	1, 580, 000	34, 400	. 25
200	1, 160, 000	25, 800	. 23

percent at 200° F, compared to the 77° F values (fig. 11). Corresponding changes for the initial modulus of elasticity (fig. 12) were increases of 40 to 80 percent at −70° F and moderate decreases up to about 25 percent at 200° F. The variations of secant modulus values with temperature were greater than for the initial modulus of elasticity.

These results are in fair agreement with data for grade C phenolic laminate given by Oberg, Schwartz, and Shinn [2]. They observed increases in flexural strength and flexural modulus of elasticity of about 17 percent at −38° F compared to values at 78° F and 40-percent relative humidity. Witt, Wolfe, and Rust [6] reported a 20-percent increase in flexural strength and 35-percent increase in modulus of elasticity at −70° F for eleven Grade C materials based on values at 77° F and 50-percent relative humidity.

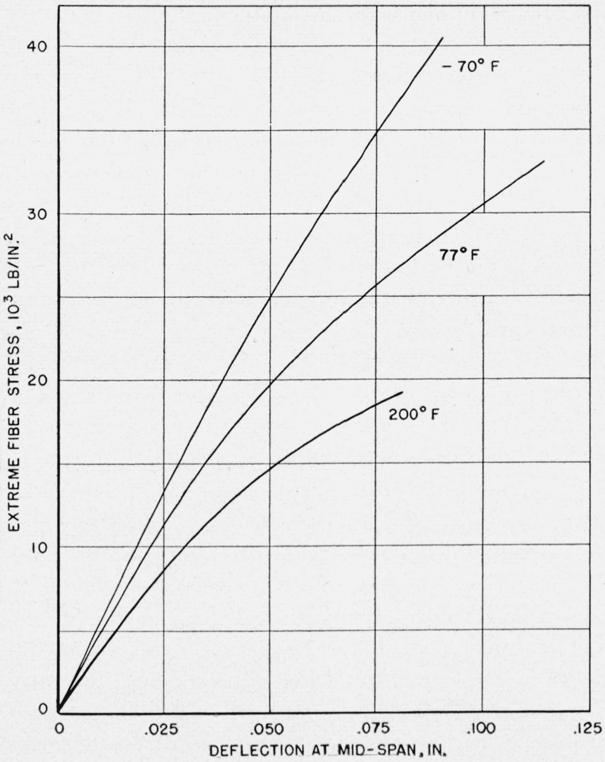

FIGURE 17. *Flexural stress-deflection curves for high-strength-paper phenolic laminate, S2.*

Lengthwise specimens tested flatwise. Span-depth ration 8:1. Initial modulus of elasticity: −70° F, 2,890,000 lb/in.^{2}; 77° F, 2,420,000 lb/in.^{2}; 200° F, 1,950,000 lb/in.^{2}

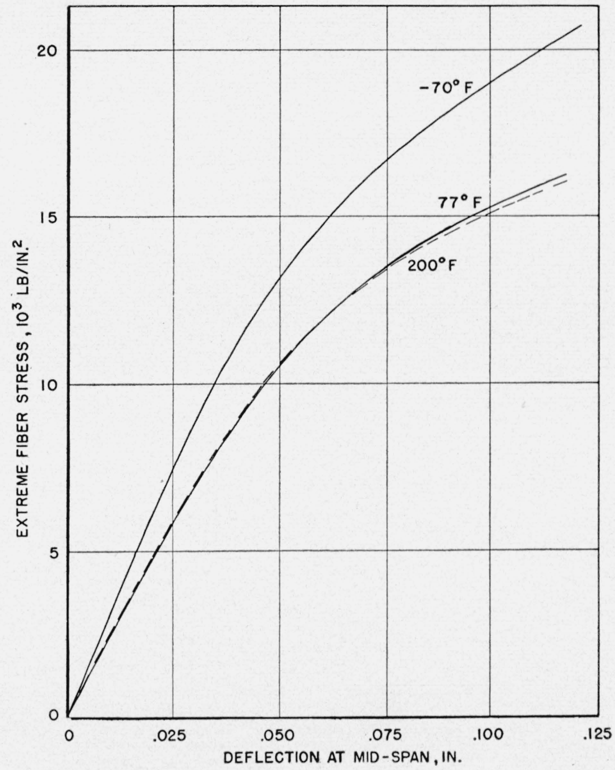

FIGURE 18. *Flexural stress-deflection curves for Grade AA asbestos-fabric phenolic laminate, K2.*

Lengthwise specimens tested flatwise. Span-depth ratio 8:1. Initial modulus of elasticity: −70° F, 1,640,000 lb/in.^{2}; 77° F, 1,200,000 lb/in.^{2}; 200° F, 1,220,000 lb/in.^{2}

The flexural strength and initial flexural modulus of elasticity of the paper phenolic laminate, S2, varied with temperature in a manner similar to the values for the cotton-fabric laminates, except that the initial modulus of elasticity increased only 20 percent between 77° and −70° F. Meyer and Erickson [4] reported that the flexural strength and flexural modulus of elasticity for high-strength-paper phenolic laminate decreased at elevated temperatures and increased at subnormal temperatures. The magnitudes of the changes that they recorded agree fairly well with the data given in this report. In tests at the Naval Air Experimental Station [5] on a phenolic material laminated with a spruce sulfite paper, probably of the high-strength type, it was noted that the flexural strength and flexural modulus of elasticity at 160° F were about a third less than at 77° F.

The variation of the flexural properties of the Grade AA asbestos-fabric-laminate, K2, with temperature was less than that of the cotton-fabric

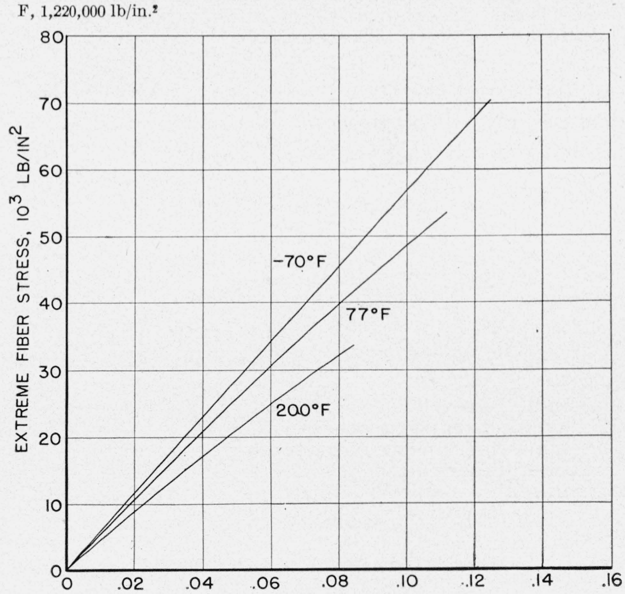

FIGURE 19. *Flexural stress-deflection curves for glass-fabric laminate, AB2.*

Lengthwise specimens tested flatwise. Span-depth ratio 8:1. Initial flexural modulus of elasticity: −70° F, 3,150,000 lb/in.^{2}; 77° F, 2,880,000 lb./in.^{2}; 200° F, 2,480,000 lb./in.^{2}

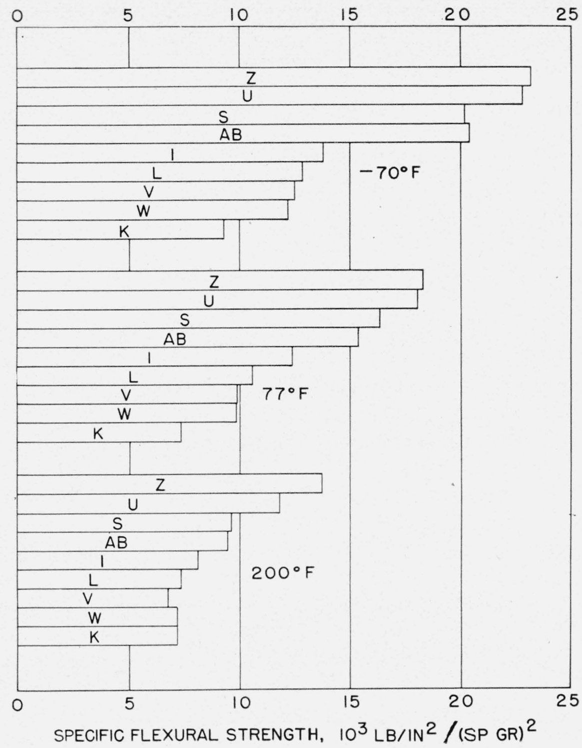

FIGURE 20. *Comparison of specific flexural strength of ½-in.-thick laminates at three temperatures.*

Lengthwise specimens tested flatwise. Span-depth ratio 8:1. *I*, Grade C phenolic; *K*, asbestos-fabric phenolic; L, low-pressure cotton-fabric phenolic; *S*, high-strength-paper phenolic; *U*, glass-fabric unsaturated-polyester; *V*, low-pressure Grade C phenolic; *W*, high-pressure Grade C phenolic; Z, rayon-cotton-fabric phenolic; *AB*, glass-fabric unsaturated-polyester.

laminates and the trend is different. Most of the change in flexural properties of the asbestos-fabric laminate occurred between 77° and −70° F; the flexural strength and initial modulus of elasticity increased roughly 20 and 35 percent of the 77° F values, respectively, at −70° F. The average change in flexural properties at 200° F was not over 5 percent. The stress-deflection curves for this material (fig. 18) indicate the similarity between the properties at 77° and 200° F.

The two glass-fabric laminates, U2 and AB2, showed the same trend in change of flexural strength and modulus of elasticity with temperature (figs. 11, 12, 19). The flexural strength increased about one-third at −70° F and decreased about one-third at 200° F. The flexural strengths of the two materials did not differ significantly. The AB2 sample was superior to the U2 sample in flexural modulus of elasticity, having greater values at all temperatures and for all directions of testing. The percentage decrease in modulus of elasticity at 200° F was less for the AB2 than for the U2 sample.

For both glass-fabric laminates the stress-deflection diagrams were less curved than for any other samples tested. In the lengthwise and crosswise directions the secant modulus of elasticity for the range 0 to 25,000 lb/in.[2] showed a decrease of less than 10 percent from the initial modulus of elasticity at all the temperatures.

The approximate values for the percentage changes in flexural strength and flexural modulus of elasticity at −70° and 200° F, based on 77° F values, for the lengthwise and crosswise directions of the laminates investigated may be summarized as follows:

Type of laminate	Change in flexural strength		Change in initial flexural modulus of elasticity	
	−70° F	200° F	−70° F	200° F
	Percent	*Percent*	*Percent*	*Percent*
Grade C phenolic (L, V, W, I)	10 to 30	−30	40 to 80	−8 to −25
Rayon-cotton-fabric phenolic (Z)	30	−25	40	−30
High-strength-paper phenolic (S)	25	−40	20	−18
Asbestos-fabric phenolic (K)	20	−5	35	0
Glass-fabric unsaturated-polyester (U, AB)	30	−30 to −35	10 to 15	−15 to −25

(b) Effects of Other Environmental Conditions

Flexural tests were also made at 77° F on specimens heated at 200° F for 24 hr to determine whether changes in the strength properties occurred in the 200° F tests. Such changes may be brought about by (a) additional cure of the resin, (b) loss of moisture, (c) deterioration of the filler if organic, or (d) a combination of these factors. The results of these tests and of tests on unheated specimens are shown in table 4. The flexural strength values showed an average decrease of about 8 to 13 percent for the cotton-fabric and

TABLE 4. *Effect of heating at 200° F for 24 hr on flexural properties of ½-in.-thick laminates* [a]

Material designation	Orientation of specimen	Direction of load	Flexural strength		Flexural modulus of elasticity			
					Initial		Secant	
			No heating [b]	Heated at 200° F [c]	No heating [b]	Heated at 200° F [c]	No heating [b]	Heated at 200° F [c]
			10^3 lb/in.^{2}	*10^3 lb/in.^{2}*	*10^6 lb/in.^{2}*	*10^6 lb/in.^{2}*	*10^6 lb/in.^{2}*	*10^6 lb/in.^{2}*
							0 to 10,000 LB/IN.^{2}	
L2, Low-pressure cotton-fabric phenolic	Crosswise	Flatwise	18.1±0.2	15.4±0.1	0.80±0.01	0.86±0.01	0.67±0.01	0.72±0.01
	do	Edgewise	17.5± .4	15.7± .1	.76± .02	.88± .01	.64± .01	.72± .01
V2, Low-pressure Grade C phenolic	Lengthwise	Flatwise	16.7± .3	14.7± .2	.82± .01	.79± .01	.58± .01	.56± .01
	Crosswise	do	16.3± .2	14.6± .2	.81± .02	.77± .01	.59± .02	.59± .01
	Lengthwise	Edgewise	16.3± .1	14.7± .1	.79± .01	.74± .01	.58± .01	.56± .01
	Crosswise	do	16.5± .2	14.5± .5	.79± .01	.74± .02	.60± .01	.59± .01
W2, High-pressure Grade C phenolic	Lengthwise	Flatwise	18.3± .4	16.9± .4	.96± .02	.89± .02	.76± .02	.76± .03
	Crosswise	do	18.4± .2	17.2± .2	.99± .02	.91± .03	.79± .02	.79± .03
	Lengthwise	Edgewise	17.9± .1	16.5± .2	1.00± .03	.91± .01	.78± .02	.78± .02
	Crosswise	do	18.0± .1	16.3± .2	1.03± .02	.94± .02	.81± .02	.81± .02
I2, Grade C phenolic	Crosswise	Flatwise	20.7± .3	18.8± .2	1.07± .07	1.07± .02	1.02± .04	.99± .02
	Lengthwise	Edgewise	21.2± .2	19.7± .3	1.14± .03	1.11± .03	1.09± .02	1.04± .01
							0 to 15,000 LB/IN.^{2}	
Z2, Rayon-cotton-fabric phenolic	Lengthwise	Flatwise	34.4± .5	31.0± .4	1.58± .02	1.71± .01	1.42±0.03	1.56±0.004
	Crosswise	do	32.7± .5	30.8± .7	1.40± .01	1.39± .02	1.25± .02	1.24± .02
S2, High-strength-paper phenolic	Lengthwise	Flatwise	33.2± .4	27.2± .6	2.42± .02	2.43± .02	2.28± .01	2.23± .01
	Crosswise	Edgewise	33.6± .4	30.4± .1	2.71± .06	2.88± .05	2.60± .06	2.64± .02
							0 to 7,500 LB/IN.^{2}	
K2, Asbestos-fabric phenolic	Crosswise	Flatwise	8.9± .2	9.6± .1	0.99± .01	1.11± .01	0.92±0.01	1.04±0.02
	do	Edgewise	9.4± .1	9.9± .2	.97± .02	1.07± .01	.90± .02	0.99± .02
							0 to 20,000 LB/IN.^{2}	
U2, Glass-fabric unsaturated-polyester	Crosswise	Flatwise	45.1± .7	53.0± .3	2.45± .01	2.55± .01	2.35±0.02	2.48±0.01
	do	Edgewise	48.6± .5	51.3± .5	2.43± .02	2.52± .03	2.37± .03	2.46± .03
AB2, Glass-fabric unsaturated-polyester	Lengthwise	Flatwise	53.2± .1	57.8± .7	2.88± .01	2.91± .04	2.80± .02	2.80± .02

[a] Tests were made in accordance with method 1031, Federal Specification L–P–406a, using an 8:1 span-depth ratio. Each value in the table represents the mean for five specimens. The accompanying plus or minus value is the standard error.

[b] Specimens conditioned and tested at 77° F and 50% relative humidity.

[c] Specimens tested at 77° F after being allowed to cool to room temperature for 1 to 2 hr in a desiccator containing calcium chloride.

paper laminates. The changes in the flexural moduli of elasticity were small and not consistent except for the low-pressure sample, L2, which exhibited increases of 10 percent after heating. The glass-fabric laminate, U2, exhibited average increases of 11 and 4 percent, respectively, in flexural strength and moduli of elasticity on heating. The asbestos-fabric laminate, K2, also exhibited higher flexural properties after heating, the increases in flexural strength and moduli of elasticity being about 7 and 12 percent, respectively.

It seems reasonable that the strength and modulus of elasticity values of these organic plastics should diminish with increase in temperature if no change in composition or structure takes place. If heating a laminate at 200° F for 24 hr causes an increase in the strength properties due to a change in composition or structure, then in the flexural tests at 200° F (table 4) the effects of prolonged heating and of an elevated test temperature may oppose one another. This may explain the very small differences between the flexural properties at 77° and 200° F (fig. 18) for the asbestos-fabric laminate, which had increased flexural properties at 77° F after heating (table 4). The effect of prolonged heating on the flexural strength of laminates was investigated by Hausmann, Parkinson, and Mains [18]. They found that the flexural strength of Grades C, X, and XXX phenolic laminates at 190° F increased with the length of time the specimens were at the test temperature (see table 1, [18]). For the Grade XXX laminate, the flexural strength values at 194° F after a month of heating were nearly equal to the 77° F values on unheated specimens.

Flexural strength tests were made on six samples at 150° F and 90-percent relative humidity after 24 hr of conditioning at the test temperature, combining the effects of elevated temperature and high relative humidity. The results of these tests are given in table 5, together with corresponding data for the 77° and 200° F tests.

The deleterious effect of these extreme conditions was most pronounced for the paper laminate,

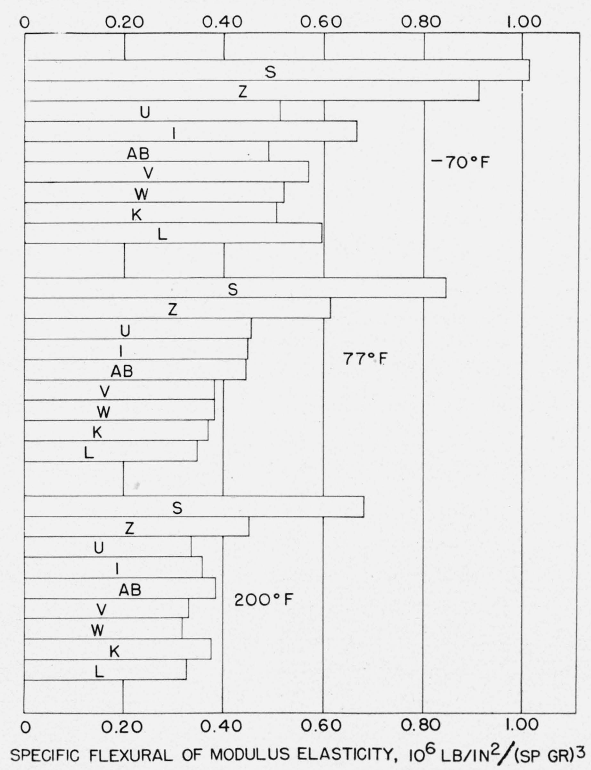

FIGURE 21. *Comparison of specific flexural modulus of elasticity of ½-in.-thick laminates at three temperatures.*

Lengthwise specimens tested flatwise. Span-depth ratio 8:1. *I*, Grade C phenolic; *K*, asbestos-fabric phenolic; *L*, low-pressure cotton-fabric phenolic; *S*, high-strength-paper phenolic; *U*, glass-fabric unsaturated-polyester; *V*, low-pressure Grade C phenolic; *W*, high-pressure Grade C phenolic; Z, rayon-cotton-fabric phenolic; *AB*, glass-fabric unsaturated-polyester.

TABLE 5. *Flexural strength of ½-in.-thick laminates at various temperatures and relative humidities* [a]

Material designation	Flexural strength at—		
	77° F, 50-percent relative humidity [b]	150° F, 90-percent relative humidity [c]	200° F, < 6-percent relative humidity [d]
	10^3 lb/in.^{2}	*10^3 lb/in.^{2}*	*10^3 lb/in.^{2}*
V2, Low-pressure Grade C phenolic	16.7 ±0.3	7.0 ±0.1	11.4 ±0.2
W2, High-pressure Grade C phenolic	18.3 ± .4	15.4 ± .3	13.3 ± .2
I2, Grade C phenolic	22.2 ± .3	19.8 ± .2	14.5 ± .1
Z2, Rayon-cotton-fabric phenolic	34.4 ± .5	26.0 ± .3	25.8 ± .5
S2, High-strength-paper phenolic	33.2 ± .4	13.2 ± .6	19.4 ± .2
AB2, Glass-fabric unsaturated-polyester	53.2 ± .1	34.7 ± .4	33.8 ± .8

[a] Lengthwise specimens tested flatwise. Tests were made in accordance with method 1031, Federal Specification L–P–406a, using an 8:1 span-depth ratio. Each value in the table represents the mean for 5 specimens. The accompanying plus or minus value is the standard error.

[b] Specimens conditioned and tested at 77° F and 50% relative humidity.

[c] Specimens tested at 150° F and 90% relative humidity after 24 hr at the test conditions.

[d] Specimens tested at 200° F and less than 6% relative humidity after 24 hr at the test conditions.

sample S2, and the low-pressure Grade C laminate, V2. The other four samples were not so greatly affected by these conditions as they were by 24 hr at 200° F and a low relative humidity. The effect of moisture content on the strength properties of high-strength-paper laminate was studied by Erickson and Mackin [19]. They tested specimens from a series of panels conditioned 100 days at 80° F at various relative humidities. They found decreases in ultimate strength in tension, compression, and flexure of 25 percent or more and decreases of about 35 percent in modulus of elasticity as the relative humidity was varied from 30 to 97 percent, corresponding to moisture contents ranging from 0.2 to 9.5 percent.

The above results and the results obtained in this laboratory indicate the necessity for studying the effect of relative humidity as well as temperature on the strength properties of laminates, especially those with cellulosic fillers.

(c) Strength-Density Considerations

When the density is considered in evaluating the flexural properties of these samples, the cellulose laminates, with lower densities than the mineral laminates, compare more favorably with the latter materials and are superior in some

TABLE 6. *Effect of span-depth ratio on flexural properties of ½-in.-thick laminates* [a]

Material designation	Orientation of specimen	Direction of load	Flexural strength at span-depth ratio: 8:1	Flexural strength at span-depth ratio: 16:1	Flexural modulus of elasticity — Initial modulus of elasticity at span-depth ratio: 8:1	Initial modulus of elasticity at span-depth ratio: 16:1	Secant modulus of elasticity at span-depth ratio: 8:1	Secant modulus of elasticity at span-depth ratio: 16:1
			10^3 lb/in.^{2}	*10^3 lb/in.^{2}*	*10^6 lb/in.^{2}*	*10^6 lb/in.^{2}*	*10^6 lb/in.^{2}*	*10^6 lb/in.^{2}*
							0 TO 10,000 LB/IN.^{2}	
L2, Low-pressure cotton-fabric phenolic	Lengthwise	Flatwise	18.4±0.2	----------	0.80±0.01	----------	0.67±0.01	----------
	Crosswise	do	18.1± .2	----------	.80± .01	----------	.67± .01	----------
	Lengthwise	Edgewise	17.5± .2	----------	.78± .01	----------	.65± .01	----------
	Crosswise	do	17.5± .4	16.5±0.2	.76± .02	0.87±0.01	.64± .01	0.64±0.01
V2, Low-pressure Grade C phenolic	Lengthwise	Flatwise	16.7± .3	15.3± .1	.82± .01	.84± .01	.58± .01	.56± .01
	Crosswise	do	16.3± .2	15.0± .2	.81± .02	.82± .01	.59± .02	.54± .02
	Lengthwise	Edgewise	16.3± .1	15.2± .2	.79± .01	.84± .02	.58± .01	.58± .01
	Crosswise	do	16.5± .2	14.8± .1	.79± .01	.80± .01	.60± .01	.54± .01
W2, High-pressure Grade C phenolic	Lengthwise	Flatwise	18.3± .4	17.1± .2	.96± .02	1.03± .03	.76± .02	.78± .04
	Crosswise	do	18.4± .2	17.4± .1	.99± .02	1.02± .05	.79± .02	.76± .06
	Lengthwise	Edgewise	17.9± .1	17.1± .1	1.00± .03	1.01± .02	.78± .02	.76± .04
	Crosswise	do	18.0± .1	16.6± .1	1.03± .02	1.00± .04	.81± .02	.74± .06
I2, Grade C phenolic	Lengthwise	Flatwise	22.2± .3	20.9± .1	1.08± .02	1.24± .02	1.07± .02	1.10± .02
	Crosswise	do	20.7± .3	19.7± .3	1.07± .07	1.22± .03	1.02± .04	1.08± .02
	Lengthwise	Edgewise	21.2± .2	19.8± .2	1.14± .03	1.30± .08	1.09± .02	1.09± .02
	Crosswise	do	21.4± .4	19.5± .1	1.11± .08	1.31± .04	1.04± .07	1.07± .03
							0 TO 15,000 LB/IN.^{2}	
Z2, Rayon-cotton-fabric phenolic	Lengthwise	Flatwise	34.4± .5	35.0± .4	1.58± .02	1.76± .03	1.42±0.03	1.58±0.03
	Crosswise	do	32.7± .5	30.4± .3	1.40± .01	1.42± .02	1.25± .02	1.20± .04
	Lengthwise	Edgewise	33.4± .5	31.9± .3	1.57± .03	1.66± .02	1.43± .03	1.47± .01
	Crosswise	do	31.7± .2	29.1± .4	1.50± .01	1.48± .04	1.37± .01	1.21± .04
							0 TO 20,000 LB/IN.^{2}	
S2, High-strength-paper phenolic	Lengthwise	Flatwise	33.2± .4	32.4± .2	2.42± .02	2.54± .02	2.10±0.01	2.15±0.03
	Crosswise	do	34.2± .6	32.4± .5	2.30± .02	2.52± .03	2.05± .01	2.12± .02
	Lengthwise	Edgewise	33.5± .5	32.6± .4	2.65± .03	2.57± .04	2.31± .01	2.17± .02
	Crosswise	do	33.6± .4	31.8± .5	2.71± .06	2.54± .03	2.35± .05	2.12± .04
							0 TO 5,000 LB/IN.^{2}	
K2, Asbestos-fabric phenolic	Lengthwise	Flatwise	16.3± .6	----------	1.20± .02	----------	1.20±0.02	----------
	Crosswise	do	8.9± .2	----------	.99± .01	----------	.99± .01	----------
	Lengthwise	Edgewise	16.4± .2	----------	1.15± .02	----------	1.15± .02	----------
	Crosswise	do	9.4± .1	9.0± .1	.97± .02	1.06± .02	.97± .02	1.02±0.02
							0 TO 20,000 LB/IN.^{2}	
U2, Glass-fabric unsaturated-polyester	Lengthwise	Flatwise	56.9± .1	55.7± .7	2.59± .02	2.82± .05	2.57±0.02	2.70±0.05
	Crosswise	do	45.1± .7	44.5± .4	2.45± .01	2.56± .02	2.35± .02	2.39± .02
	Lengthwise	Edgewise	54.8± .9	54.2± .5	2.70± .03	2.80± .02	2.67± .03	2.71± .02
	Crosswise	do	48.6± .5	45.1± .4	2.43± .03	2.57± .02	2.37± .03	2.40± .02
							0 TO 15,000 LB/IN.^{2}	
AB2, Glass-fabric unsaturated-polyester	Lengthwise	Flatwise	53.2± .1	52.1± .5	2.88± .01	3.14± .02	2.80±0.02	2.97±0.03
	Crosswise	do	46.0± .7	----------	2.84± .03	----------	2.61± .01	----------
	Lengthwise	Edgewise	60.8± .5	57.9± .8	2.89± .02	3.18± .04	2.87± .01	2.95± .03
	Crosswise	do	53.5± .7	----------	2.82± .02	----------	2.66± .01	----------

[a] Specimens were conditioned and tested at 77° F and 50% relative humidity in accordance with Method 1031, Federal Specifications L–P–406a. Each value in the table represents the mean for 5 to 10 specimens. The accompanying plus or minus value is the standard error.

instances. This may be seen by comparing figures 20 and 21 with figures 11 and 12. Figures 20 and 21 also show that there is no difference in specific strength properties between the low-pressure and high-pressure laminates, V2 and W2, made with the same Grade C fabric. When comparisons are based on density, the flexural strength and stiffness of the asbestos-fabric laminate, K2, are greater than those of the cotton-fabric laminates at 200° F.

(d) Effect of Span-Depth Ratio

The results of tests made at 77° F using span-depth ratios of 16:1 and 8:1 are given in table 6. The flexural strength obtained with a 16:1 span-depth ratio was slightly less for all samples, the decreases ranging from about 2 percent for the glass-fabric laminate, U2, to about 7 percent for the cotton-fabric phenolic laminates. The initial flexural modulus of elasticity values were usually a little greater for the tests with the larger span-depth ratio. The I2 material, a high-pressure phenolic Grade C laminate, showed significant changes in both flexural strength and initial modulus of elasticity with the change in span-depth ratio.

3. Tensile Properties

The results of the tensile tests of the plastic laminates at temperatures of −70°, 77°, and 200° F are shown in figures 22 to 30.

The tensile properties of representative laminates at 77° F are approximately as follows:

Type of laminate	Tensile strength	Tensile secant modulus of elasticity for lowest stress range in table 8
	10^3 *lb/in.*^{2}	10^6 *lb/in.*^{2}
Grade C phenolic, low-pressure (V)	9	0.8
Grade C phenolic, high-pressure (W)	10.5	1.0
Rayon-cotton-fabric phenolic (Z)	[a] 32 (L) 26 (C)	[a] 1.9 (L) 1.2 (C)
High-strength-paper phenolic (S)	30	2.6
Asbestos-fabric phenolic (K)	8 (L) 5 (C)	1.5 (L) 1.2 (C)
Glass-fabric unsaturated-polyester (AB)	43 (L) 33 (C)	3.0 (L) 2.6 (C)

[a] L=lengthwise; C=crosswise.

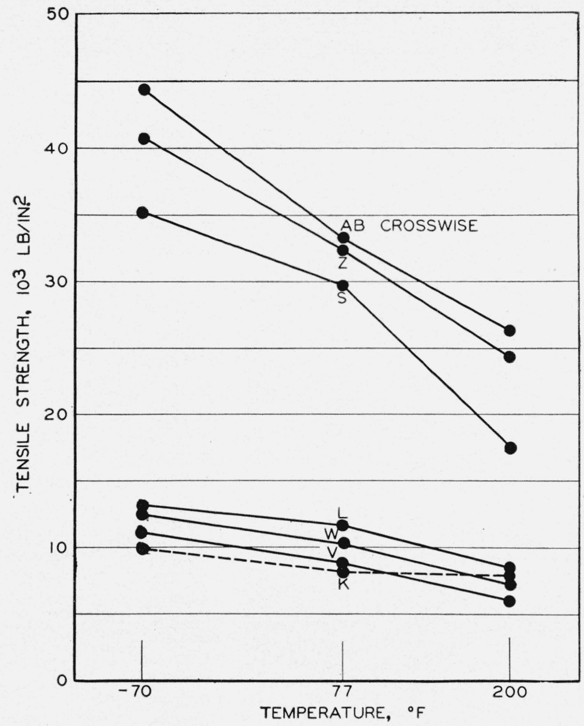

FIGURE 22. *Variation of tensile strength with temperature for ⅛-in.-thick laminates.*

Lengthwise specimens unless otherwise noted. Types of laminates shown are: *K,* asbestos-fabric phenolic; *L,* low-pressure cotton-fabric phenolic; *S,* high-strength-paper phenolic; *V,* low-pressure Grade C phenolic; *W,* high-pressure Grade C phenolic; *Z,* rayon-cotton-fabric phenolic; *AB,* glass-fabric unsaturated-polyester.

The tensile strengths and moduli of elasticity of all the samples increased at −70° F and decreased at 200° F relative to the 77° F values (figs. 22 and 23).

The three cotton-fabric phenolic laminates, L1, V1, and W1, exhibited similar changes in tensile strength properties with change in temperature. The tensile strengths of these samples increased 15 to 25 percent at −70° F and decreased 25 to 30 percent at 200° F compared to the 77° F values. Corresponding changes for the secant modulus of elasticity at 2,500 lb/in.^{2} were increases of about 40 to 50 percent at −70° F and decreases of about 20 to 30 percent at 200° F. Witt, Wolfe, and Rust [6], in tensile tests at 77° F and 160° F on a number of samples of Grade C phenolic laminates, found average decreases in strength and modulus of elasticity of about 18 and 22 percent, respectively.

The rayon-fabric phenolic laminate, Z1, showed the greatest percentage increase (55 crosswise and 70 lengthwise) in tensile modulus of elasticity at

−70° F. Other changes in the tensile properties of this laminate were similar to those for the three cotton-fabric phenolic laminates.

Of the samples tested, the high-strength-paper phenolic laminate, S1, showed the largest percentage decrease (40%) in tensile strength at 200° F. The percentage changes in modulus of elasticity at both −70° and 200° F were less for the paper (10 to 20%) than for the other four laminates with cellulosic reinforcement.

Meyer and Erickson [4] reported that the tensile strength and modulus of elasticity for high-strength-paper laminates decreased about 35 and 15 percent, respectively, at 200° F relative to 75° F; these values agree with the data in table 8. The changes found by them at subnormal temperatures were much less than those given in this report and included slightly negative values.[3]

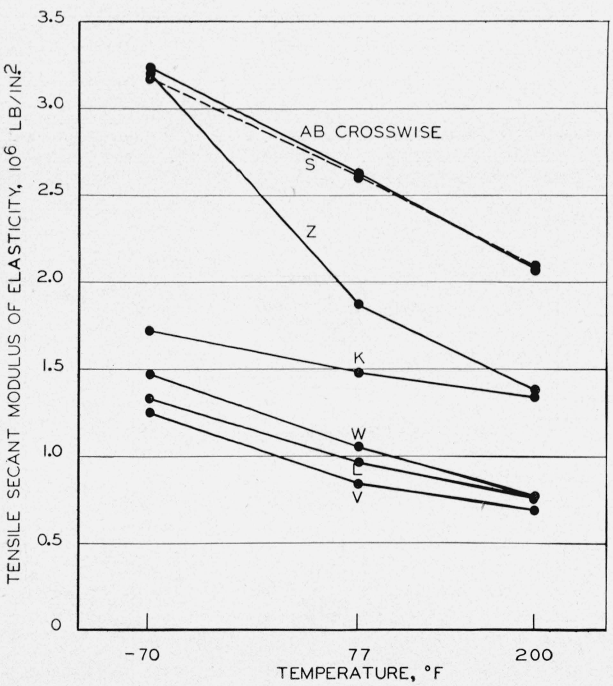

FIGURE 23. *Variation of tensile secant modulus of elasticity with temperature for 1/8-in.-thick laminates.*

Lengthwise specimens unless otherwise noted. Stress ranges: 0 to 5,000 lb/in.² for *AB, S, Z*; 0 to 2,500 lb/in.² for *K, W, L, V*. Types of laminates shown are: *K*, asbestos-fabric phenolic; *L*, low-pressure cotton-fabric phenolic; *S*, high-strength-paper phenolic; *V*, low-pressure Grade C phenolic; *W*, high-pressure Grade C phenolic; *Z*, rayon-cotton-fabric phenolic; *AB*, glass-fabric unsaturated-polyester.

[3] A possible reason for the small changes in both the tensile and compressive moduli of elasticity at −69° F reported by Meyer and Erickson is that their tests at the low temperature were made at a different laboratory and with different means of measuring the strain from those made at 75° F and higher temperatures. Hence the uncertainty in the changes they report for low temperatures may be somewhat greater than the uncertainty in corresponding changes obtained in this laboratory where all tests were made with the same equipment.

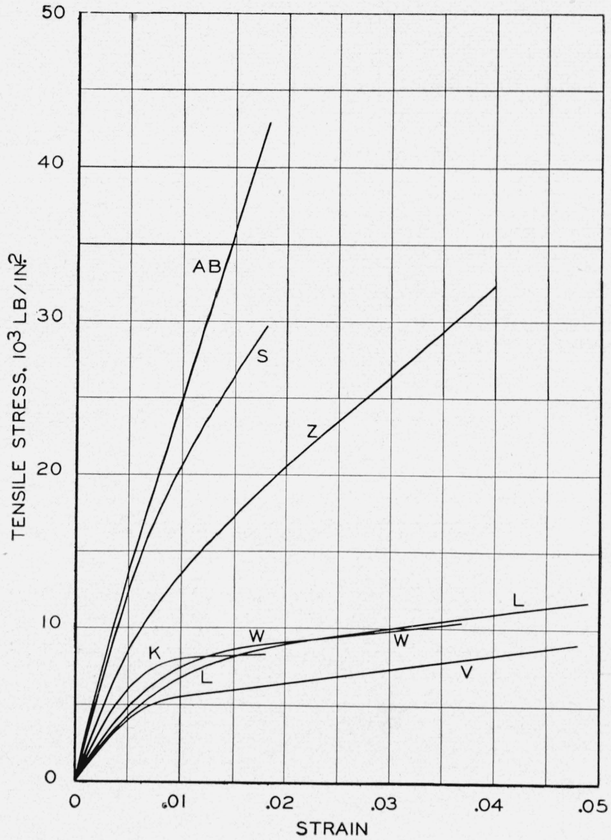

FIGURE 24. *Tensile stress-strain curves of 1/8-in.-thick laminates at 77° F.*

Lengthwise specimens. Types of laminates shown are: *AB*, glass-fabric unsaturated-polyester; *S*, high-strength-paper phenolic; *Z*, rayon-cotton-fabric phenolic; *K*, asbestos-fabric phenolic; *L*, low-pressure cotton fabric phenolic; *W*, high-pressure Grade C phenolic; *V*, low-pressure Grade C phenolic.

The material investigated by Meyer and Erickson was quite similar to that tested in this laboratory as regards resin, molding conditions, and paper base.

The asbestos-fabric laminate, K1, (fig. 33), with decreases in tensile properties of less than 10 percent at 200° F, exhibited the least change of all the samples. Witt and others [6] tested several Grade AA asbestos-fabric phenolic laminates in tension. They found that average decreases in strength and modulus of elasticity at 160° F relative to 77° F were 6 and 15 percent, respectively.

Next to the asbestos-fabric laminate, the glass-fabric laminate, AB1, (fig. 30) showed the smallest percentage loss (20%) in strength at 200° F. This change was approximately half that of the high-strength-paper laminate, S1. The glass-fabric laminate also had the highest percentage

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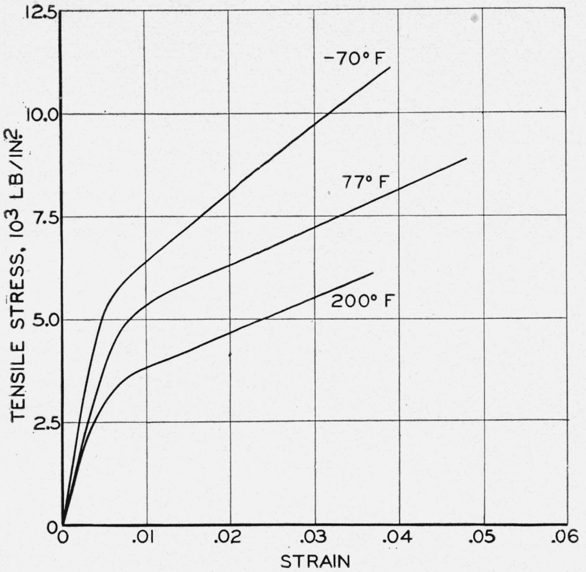

FIGURE 25. *Tensile stress-strain curves for low-pressure Grade C phenolic laminate, V1.*

Lengthwise specimens. Secant modulus of elasticity (0 to 2,500 lb/in.²): −70° F, 1,250,000 lb/in.²; 77° F, 840,000 lb/in.²; 200° F, 690,000 lb/in.²

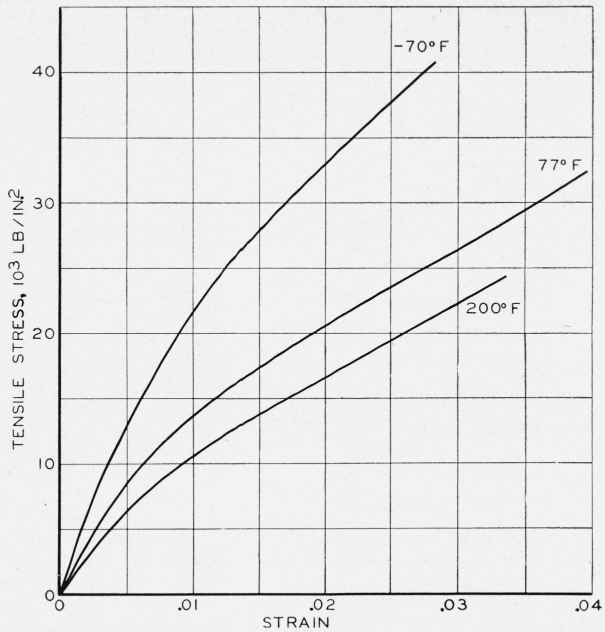

FIGURE 27. *Tensile stress-strain curves for rayon-cotton-fabric phenolic laminate, Z1.*

Lengthwise specimens. Secant modulus of elasticity (0 to 5,000 lb/in.²): −70° F, 3,200,000 lb/in.²; 77° F, 1,870,000 lb/in.²; 200° F, 1,380,000 lb/in.²

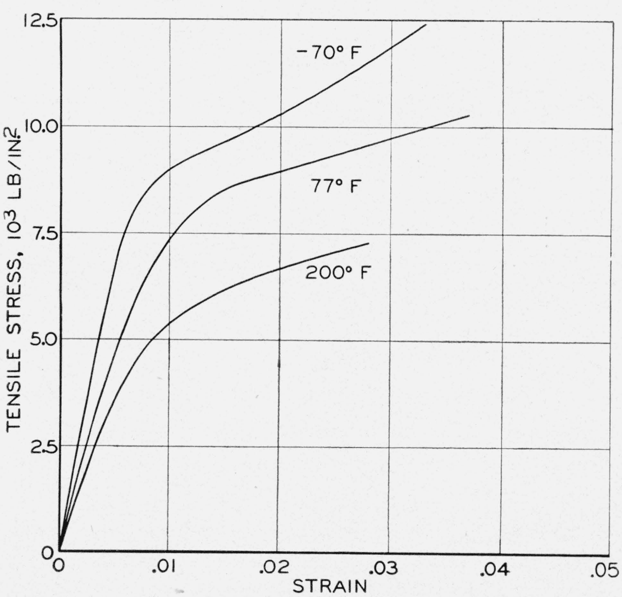

FIGURE 26. *Tensile stress-strain curves for high-pressure Grade C phenolic laminate, W1.*

Lengthwise specimens. Secant modulus of elasticity (0 to 2,500 lb/in.²): −70° F, 1,470,000 lb/in.²; 77° F, 1,050,000 lb/in.²; 200° F, 770,000 lb/in.²

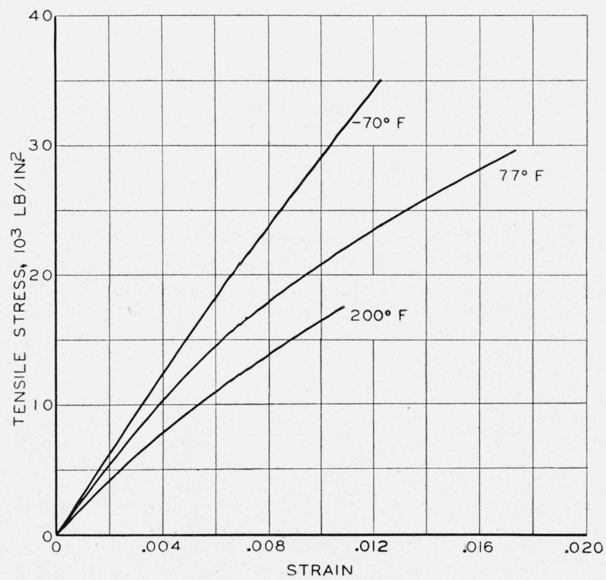

FIGURE 28. *Tensile stress-strain curves of high-strength-paper phenolic laminate, S1.*

Lengthwise specimens. Secant modulus of elasticity (0 to 5,000 lb/in.²): −70° F, 3,180,000 lb/in.²; 77° F, 2,610,000 lb/in.²; 200° F, 2,090,000 lb/in.²

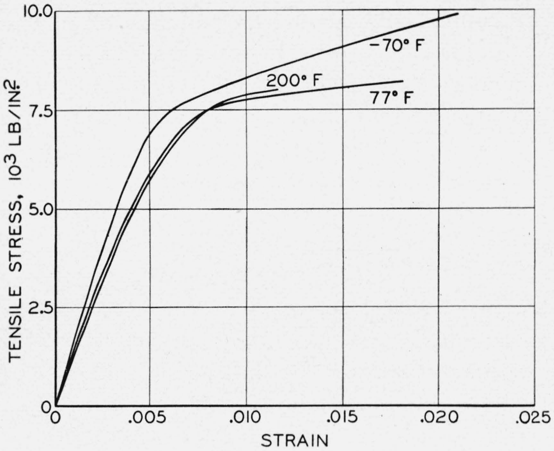

FIGURE 29. *Tensile stress-strain curves for Grade AA asbestos-fabric phenolic laminate, K1.*

Lengthwise specimens. Secant modulus of elasticity (0 to 2,500 lb/in.²): −70° F, 1,720,000 lb/in.²; 77° F, 1,480,000 lb/in.²; 200° F, 1,340,000 lb/in.²

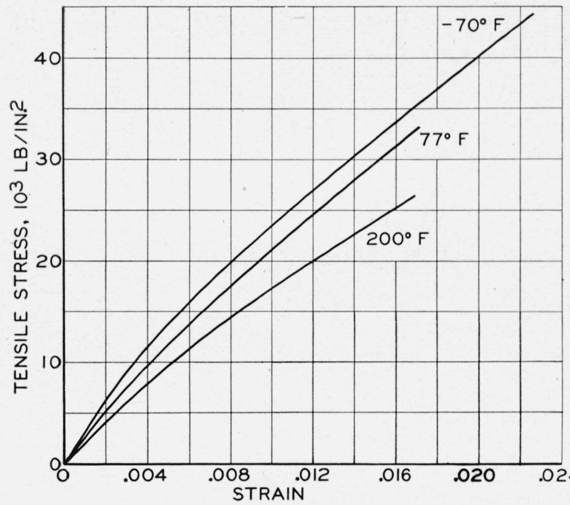

FIGURE 30. *Tensile stress-strain curves for glass-fabric unsaturated-polyester laminate, AB1.*

Crosswise specimens. Secant modulus of elasticity (0 to 5,000 lb/in.²): −70° F, 3,240,000 lb./in.²; 77° F, 2,630,000 lb/in.²; 200° F, 2,080,000 lb/in.²

increase (33%) in tensile strength at −70° F. The percentage change in the tensile modulus of elasticity of the glass-fabric laminate was about the same as for the high-strength-paper laminate at both the high and low temperatures.

The approximate values for the percentage changes in tensile strength and tensile secant modulus of elasticity at −70° and 200° F, relative to the value at 77° F for the laminates investigated, may be summarized as follows:

Type of laminate	Change in tensile strength		Change in tensile secant modulus of elasticity	
	−70° F	200° F	−70° F	200° F
	Percent	*Percent*	*Percent*	*Percent*
Grade C phenolic, low-pressure (V)	25	−30	47	−18
Grade C phenolic, high-pressure (W)	20	−30	45	−30
Rayon-cotton-fabric phenolic (Z)	25	−25	60	−30
High-strength-paper phenolic (S)	15	−40	23	−15
Asbestos-fabric phenolic (K)	15	−3	23	−10
Glass-fabric unsaturated-polyester (crosswise only) (AB)	33	−20	23	−20

The types of failure obtained in tension were similar to those shown by Findley and Worley (see fig. 49, [9]) and by Marin (see fig. 41, [10]) for the same laminates. The cotton-fabric phenolic laminates had a clean break, with the exception of the low-pressure molded laminate, V1, which also split on a central ply. The high-strength-paper laminate, S1, had a brittle and slightly jagged break. In the glass-fabric laminate AB1, the failure was very irregular and of the tongue and groove type, extending throughout the reduced section. The manner of failure in the rayon-fabric laminate, Z1, was between that of the glass-fabric and the cotton-fabric laminates.

4. Compressive Properties

The results of the compressive tests of the plastic laminates at temperatures of −70°, 77°, and 200° F are shown in figures 31 to 35.

The compressive properties of the laminates at 77° F are approximately as follows:

Type of laminate	Compressive strength	Compressive modulus of elasticity
	10^3 *lb/in.*^{2}	10^6 *lb/in.*^{2}
Grade C phenolic, low-pressure (V)	19	0.9
Grade C phenolic, high-pressure (W, I)	20 to 25	1.1 to 1.3
Rayon-cotton-fabric phenolic (Z)	24	[a] 2.0 (L) 1.9 (C)
High-strength-paper phenolic (S)	19	2.7
Asbestos-fabric phenolic (K)	21	1.5 (L) 1.2 (C)
Glass-fabric unsaturated-polyester (AB)	[a] 42 (L) 36 (C)	3.3 (L) 3.1 (C)

[a] L=lengthwise; C=crosswise.

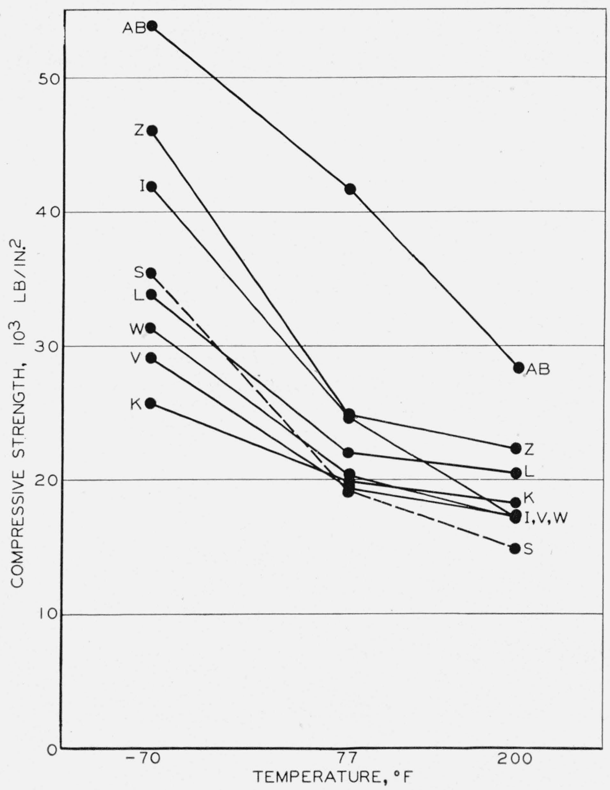

FIGURE 31. *Variation of compressive strength with temperature for ½-in.-thick laminates.*

Lengthwise specimens. Types of laminates shown are: *I*, Grade C phenolic; *K*, asbestos-fabric phenolic; *L*, low-pressure cotton-fabric phenolic; *S*, high-strength-paper phenolic; *V*, low-pressure Grade C phenolic; *W*, high-pressure Grade C phenolic; *Z*, rayon-cotton-fabric phenolic; *AB*, glass-fabric unsaturated-polyester.

The compressive strengths and moduli of elasticity of all the laminates increased at −70° F and decreased at 200° F, relative to the 77° F values (figs. 31 and 32).

The compressive strengths of the four cotton-fabric phenolic laminates increased 50 to 70 percent at −70° F and decreased 10 to 30 percent at 200° F. The compressive secant modulus of elasticity increased 30 to 60 percent at −70° F, with the greatest change in the low-pressure samples, and decreased 20 to 30 percent at 200° F. The two low-pressure cotton-fabric phenolic laminates, L2 and V2, made with the same resin, showed nearly identical variation in compressive properties with temperature. Witt, Wolfe, and Rust [6], who tested a large group of samples of Grade C phenolic laminate in compression at 77° and 160° F, found average decreases in compressive strength and modulus of elasticity of about 22 and 27 percent, respectively. Norelli and Gard [3], who tested a Grade C sample at various temperatures, indicated an increase in compressive strength of about 50 percent at −67° F and a decrease of 35 percent at 167° F, relative to 77° F.

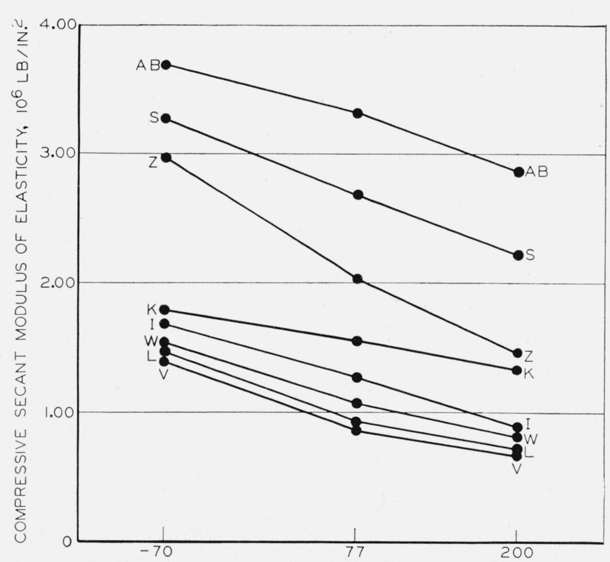

FIGURE 32. *Variation of compressive secant modulus of elasticity (0 to 2,500 lb/in.²) with temperature for ½-in.-thick laminates.*

Lengthwise specimens. Types of laminates shown are: *I*, Grade C phenolic; *K*, asbestos-fabric phenolic; *L*, low-pressure cotton-fabric phenolic; *S*, high-strength-paper phenolic; *V*, low-pressure Grade C phenolic; *W*, high-pressure Grade C phenolic; *Z*, rayon-cotton-fabric phenolic; *AB*, glass-fabric unsaturated-polyester.

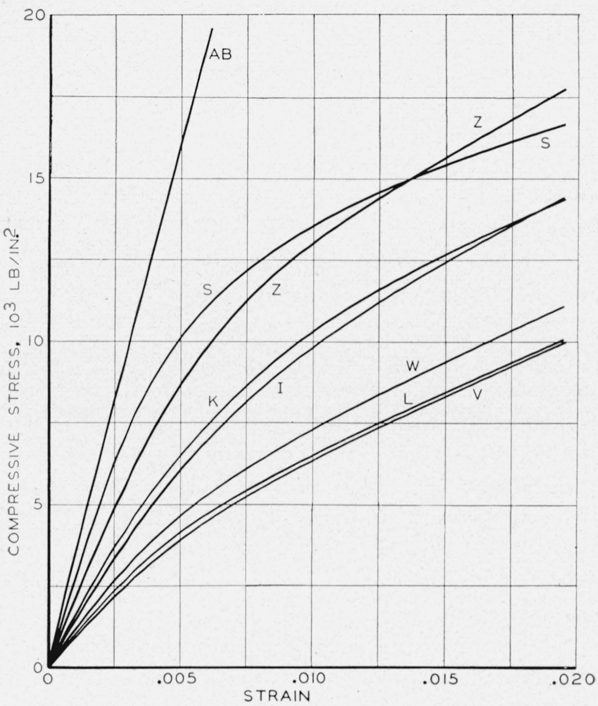

FIGURE 33. *Compressive stress-strain curves of laminates at 77° F.*

Lengthwise specimens. Types of laminates shown are: *I*, Grade C phenolic; *K*, asbestos-fabric phenolic; *L*, low-pressure cotton-fabric phenolic; *S*, high-strength-paper phenolic; *V*, low-pressure Grade C phenolic; *W*, high-pressure grade C phenolic; *Z*, rayon-cotton-fabric phenolic; *AB*, glass-fabric unsaturated polyester.

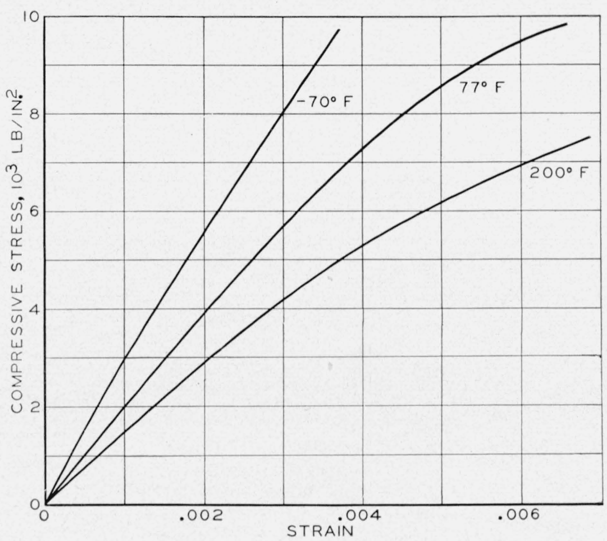

FIGURE 34. *Compressive stress-strain curves of rayon-cotton-fabric phenolic laminate, Z2.*

Lengthwise specimens.

Temperature	Secant modulus of elasticity, 0 to 2,500 lb/in.^{2}	Compressive strength
° *F*	*lb/in.*^{2}	*lb/in.*^{2}
−70	2, 970, 000	46, 100
77	2, 030, 000	24, 800
200	1, 460, 000	22, 300

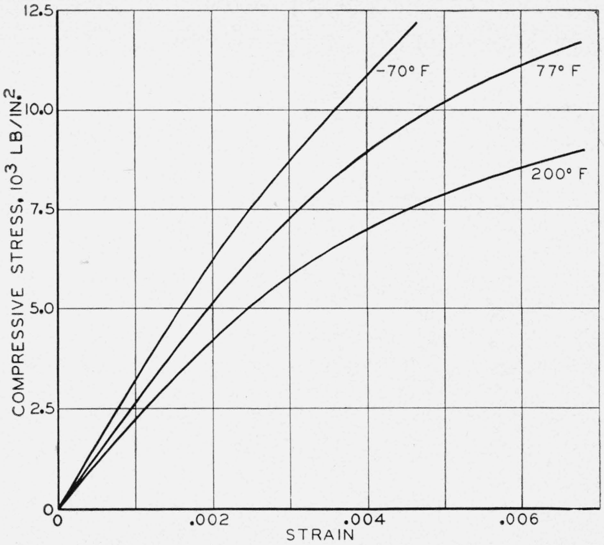

FIGURE 35. *Compressive stress-strain curves of high-strength-paper phenolic laminate, S2.*

Lengthwise specimens.

Temperature	Secant modulus of elasticity, 0 to 2,500 lb/in.²	Compressive strength
° *F*	*lb/in.²*	*lb/in.²*
−70	3, 270, 000	35, 400
77	2, 680, 000	19, 200
200	2, 220, 000	14, 900

The high-strength-paper, S2, and the rayon-fabric, Z2, phenolic laminates increased in compressive strength 85 percent at −70° F and decreased in compressive strength 10 to 20 percent at 200° F. The changes in compressive modulus of elasticity with temperature were less for the high-strength-paper laminate than for the other cellulose laminates, the increase at −70° F being 20 percent and the decrease at 200° F being 15 percent. The changes in compressive properties of a high-strength-paper phenolic laminate at −69° F and 200° F relative to 77° F, reported by Meyer and Erickson [4], are in good agreement with the results given in this report, except that they obtained much smaller increases in modulus of elasticity at −69° F.

The asbestos and glass laminates, K2 and AB2, in general, showed much smaller variations in compressive properties with temperature than the cellulose laminates. The changes in compressive strength and modulus of elasticity for the asbestos-fabric phenolic laminate were 30 and 15 percent, respectively, at −70° F, and −10 and −15 percent, respectively, at 200° F. The changes in the glass-fabric laminate were almost the same except for the 30-percent loss in compressive strength at 200° F.

The compressive-strength variation with temperature of the Grade AA asbestos-fabric laminate reported by Norelli and Gard [3] agrees in trend with, but differs in magnitude from, the data presented here. They obtained an increase of less than 10 percent at −67° F and a decrease of 25 percent at 167° F. No comparative data were found in the literature for a glass-fabric laminate similar to the sample, AB2.

The approximate values for the percentage changes in compressive strength and modulus of elasticity at −70° and 200° F, relative to the value at 77° F for lengthwise specimens, are as follows:

Type of laminate	Change in compressive strength		Change in compressive secant modulus of elasticity (0 to 2,500 lb/in.²)	
	−70° F	200° F	−70° F	200° F
	Percent	*Percent*	*Percent*	*Percent*
Grade C phenolic, low-pressure (L, V)	50	−10	60	−20
Grade C phenolic, high-pressure (W, I)	50 to 70	−15 to −30	30 to 45	−25 to −30
Rayon-cotton-fabric phenolic (Z)	85	−10	45	−30
High-strength-paper phenolic (S)	85	−20	20	−15
Asbestos-fabric phenolic (K)	30	−10	15	−15
Glass-fabric unsaturated-polyester (AB)	30	−30	10	−15

All of the cotton-fabric laminates, the asbestos-fabric and the rayon-cotton-fabric laminates failed in compression in the same manner. The break started at the top of the specimen at one edge and went downward across the machined face at an angle between 45° and 60° to the horizontal. A similar failure occurred in the low-pressure cotton-fabric laminate, except that there was splitting along a central ply. The line of failure in the high strength-paper laminate, S2, progressed from one corner to a diagonally opposite corner, partly on a 45° angle and partly by delamination. The glass-fabric laminate, AB2, failed explosively and delaminated at several places. Examples of broken compression specimens of similar laminates are shown by Findley and Worley (see fig. 50, [9]) and by Marin (see fig. 42, [10]).

5. Comparison of Temperature Dependence of Flexural, Tensile, and Compressive Properties

Figure 36 shows the percentage changes in strength and modulus of elasticity with temperature based on 77° F values for flexural, tensile, and compressive tests.

For the cellulose laminates, the percentage changes in tensile and flexural strengths with temperature for a given sample were about the same. These strength values increased 15 to 25 percent at −70° F and decreased 25 to 40 percent at 200° F. The compressive-strength behavior of the cellulose materials was different; the increases at −70° F were 50 to 85 percent, the decreases at 200° F were only 10 to 30 percent. For a given sample, the percentage increase in compressive strength at −70° F was at least double the percentage increase in flexural or tensile strength; at 200° F the percentage loss in compressive strength, in general, was half the percentage loss in flexural or tensile strength.

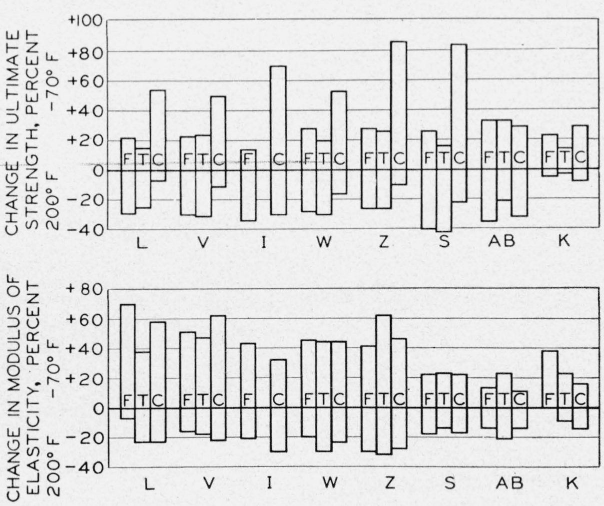

Figure 36. *Comparison of changes in flexural (F), tensile (T), and compressive (C) properties of laminates at −70° and 200° F based on values at 77° F.*

Types of laminates shown are: *L*, low-pressure cotton-fabric phenolic; *V*, low-pressure Grade C phenolic; *I*, Grade C phenolic; *W*, high-pressure Grade C phenolic; *Z*, rayon-cotton-fabric phenolic; *S*, high-strength-paper phenolic; *AB*, glass-fabric unsaturated-polyester; *K*, asbestos-fabric phenolic.

The increases in the three moduli of elasticity of the five cellulose-fabric laminates at −70° F were about 40 to 60 percent, and the decreases in moduli of elasticity at 200° F were from 15 to 30 percent. The high-strength-paper laminate, for which the three moduli change very similarly (fig. 36), showed smaller changes in moduli at −70° F than the other cellulose laminates.

The percentage changes in strength with temperature of the laminates with mineral reinforcement did not vary much with the type of test, in contrast to the cellulose laminates, for which the variation in compressive strength with temperature was much different from the percentage changes in flexural and tensile strength. The percentage changes in flexural, tensile, and compressive strengths of the asbestos-fabric laminate were increases of 15 to 30 percent at −70° F and decreases of about −5 percent at 200° F. The percentage changes in the three strength values for the glass-fabric laminate, AB, were nearly alike, particularly at −70° F. The respective increases in the flexural, tensile, and compressive moduli of the glass-fabric laminates at −70° F were almost equal to the decreases at 200° F. The changes in flexural and compressive moduli were about 12 percent; the tensile modulus changes were 22 percent. The over-all changes in the moduli of elasticity of the asbestos-fabric laminate for the temperature range −70° to 200° F were approximately 30 percent; there was no regularity in these changes.

6. Variation of Strength Properties of Laminates With Orientation of Specimen

Four of the nine samples tested, the two glass-fabric laminates, the asbestos-fabric laminate, and the Grade C laminate, I2, were of parallel-ply construction (table 1). The most pronounced difference in strength properties between specimens taken from the principal directions of the sheet was observed in the asbestos-fabric laminate, K2. The other three parallel-ply samples showed differences in strength with direction of testing, but not for all types of tests as did the asbestos-fabric laminate.

In the impact tests, directional properties were observed for the parallel-ply laminates, I2 and K2. The asbestos-fabric sample, K2, for which the effect was greatest, exhibited an impact strength in the crosswise direction less than half of the corresponding value in the lengthwise direction.

For all samples the impact strength for specimens struck edgewise was lower than that of specimens of the same sample tested flatwise. For a given orientation of specimens in the sheet, the ratio of edgewise to the flatwise impact strength was very nearly constant for a given material over the range of temperature employed. These ratios are given in table 7. The mean value of this ratio was 0.5 to 0.6 for the cotton-fabric laminates, 0.2 for the paper laminate, 0.8 for the asbestos-fabric laminate, and about 0.4 for the rayon-fabric laminate. The data of Meyer and Erickson [4] for cross-ply high-strength-paper laminate give a value of 0.19 for this ratio at the various test temperatures.

The following ratios have been calculated from impact data reported by Witt, Wolfe, and Rust [6]:

Material designation	Average ratio of edgewise impact strength to flatwise impact strength
Grade C, high-pressure (11 samples)	0. 57
Grade C, low-pressure (6 samples)	. 53
Grade AA (5 samples)	. 84
Grade L (10 samples)	. 47

Each of these phenolic laminates was tested at three temperatures, −70°, 77°, and 160° F, in both the lengthwise and crosswise directions. These data agree with the data given in table 7.

The effect of orientation on the flexural stress-deflection curves is shown in figures 37 to 39 for samples that have pronounced directional behavior. The asbestos-fabric sample, K2, had a flexural strength crosswise that was of the order of 55 percent of that lengthwise (fig. 37). The two glass-fabric laminates had flexural strengths crosswise about 85 percent of those lengthwise. All of the other samples, both parallel-ply and cross-ply, had flexural strengths in the crosswise direction almost

TABLE 7. *Ratio of edgewise impact strength to flatwise impact strength for ½-in.-thick laminates at various temperatures* [a]

Material designation	Orientation of specimen	Ratio at test temperature of— −70° F	0° F	77° F	200° F	Mean ratio, all temperatures
L2, Low-pressure cotton-fabric phenolic	Lengthwise	0. 57	0. 56	0. 54	0. 54	0. 55
	Crosswise	. 56	. 58	. 52	. 55	------
V2, Low-pressure Grade C phenolic	Lengthwise	------	. 46	. 50	. 50	. 51
	Crosswise	------	. 51	. 53	. 56	------
W2, High-pressure Grade C phenolic	Lengthwise	. 51	. 47	. 48	. 52	. 55
	Crosswise	. 63	. 57	. 61	. 60	------
I2, Grade C phenolic	Lengthwise	. 62	. 58	. 53	. 58	. 59
	Crosswise	. 60	. 61	. 58	. 61	------
Z2, Rayon-cotton-fabric phenolic	Lengthwise	. 53	. 43	. 38	. 38	. 39
	Crosswise	. 41	. 36	. 34	. 30	------
S2, High-strength-paper phenolic	Lengthwise	. 17	. 17	. 20	. 16	. 18
	Crosswise	. 17	. 18	. 21	. 15	------
K2, Asbestos-fabric phenolic	Lengthwise	. 77	. 80	. 84	. 82	. 80
	Crosswise	. 82	. 73	. 80	. 85	------
AB2, Glass-fabric unsaturated-polyester	Lengthwise	------	------	. 32	------	------
	Crosswise	------	------	. 32	------	------

[a] This table was computed from data in table 2.

equal to those in the lengthwise direction. The flexural properties of the Z2 rayon-fabric and AB2 glass-fabric laminates were greatly reduced for the 45° direction, as is evident from figures 38 and 39. The ratio of edgewise to flatwise flexural strength was nearly 1.0 for all of the samples except the glass-fabric laminate, AB2, for which the edgewise flexural strength was greater. The flexural modulus of elasticity of the high-strength-paper laminate, S2, was about 10 to 15 percent greater edgewise than flatwise, but in all the other samples there was little difference between the edgewise and flatwise flexural moduli of elasticity.

The variations of tensile and compressive strengths and secant moduli of elasticity for the various materials in the lengthwise, crosswise, and 45° diagonal directions are shown in figures 40 to 43. In general, the tensile strength and the tensile and compressive secant moduli of elasticity of the cotton-fabric and the high-strength-paper laminates showed small variations with the direction of test. The diagonal values were about 10 to 20 percent lower than the other values.

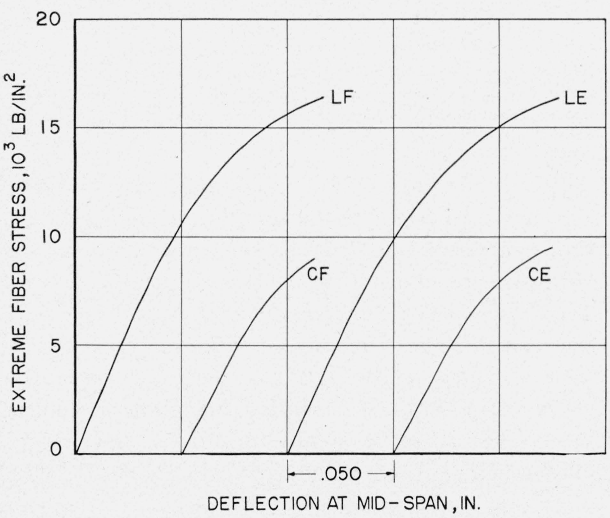

FIGURE 37. *Flexural stress-deflection curves for asbestos-fabric phenolic laminate, K2, at 77° F.*

Span-depth ratio 8:1. *LF*, Lengthwise specimens tested flatwise; *LE*, lengthwise specimens tested edgewise; *CF*, crosswise specimens tested flatwise; *CE*, crosswise specimens tested edgewise.

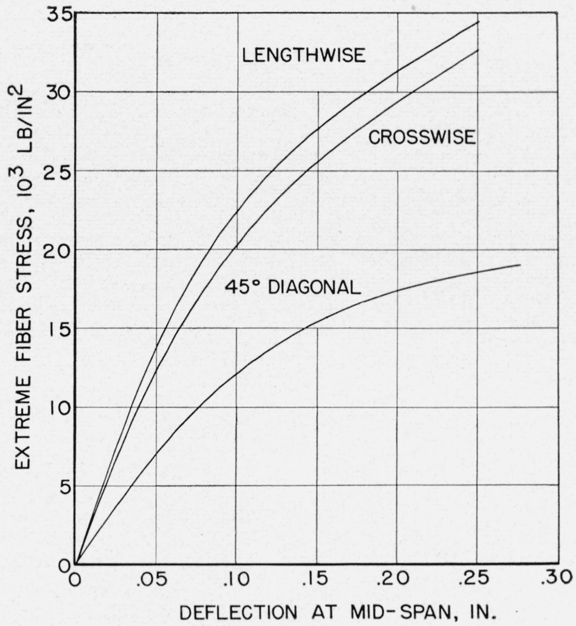

FIGURE 38. *Flexural stress-deflection curves for rayon-cotton-fabric phenolic laminate, Z2, tested flatwise at 77° F.*

Span-depth ratio 8:1. Initial flexural modulus of elasticity: lengthwise, 1,580,000 lb/in.²; crosswise, 1,400,000 lb/in.²; 45° diagonal, 760,000 lb/in.²

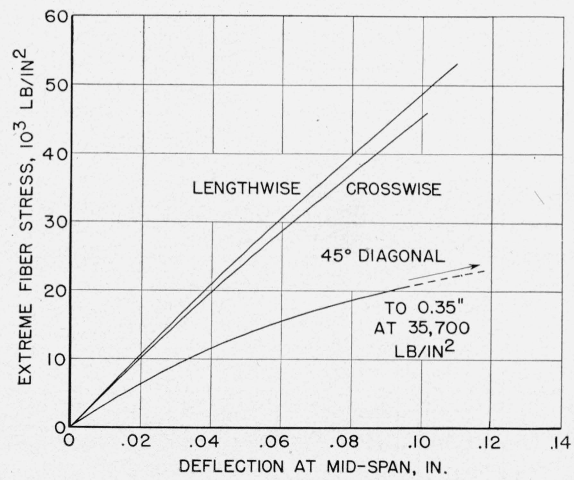

FIGURE 39. *Flexural stress-deflection curves for glass-fabric unsaturated-polyester laminate, AB2, tested flatwise at 77° F.*

Span-depth ratio 8:1. Initial flexural modulus of elasticity: lengthwise, 2,880,000 lb/in.²; crosswise, 2,840,000 lb/in.²; 45° diagonal, 1,810,000 lb/in.²

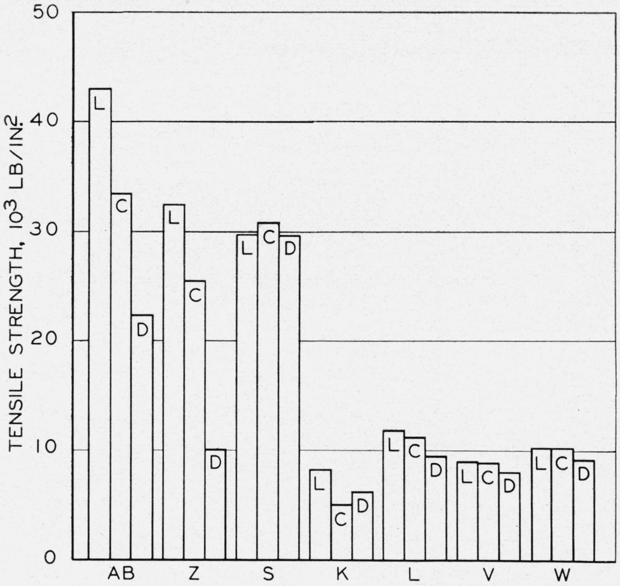

FIGURE 40. *Tensile strengths for the lengthwise (L), crosswise (C), and 45° diagonal (D) directions of ⅛-in.-thick laminates.*

Types of laminates are: *AB*, glass-fabric unsaturated-polyester; *Z*, rayon-cotton-fabric phenolic; *S*, high-strength-paper phenolic; *K*, asbestos-fabric phenolic; *L*, low-pressure cotton-fabric phenolic; *V*, low-pressure Grade C phenolic; *W*, high-pressure Grade C phenolic.

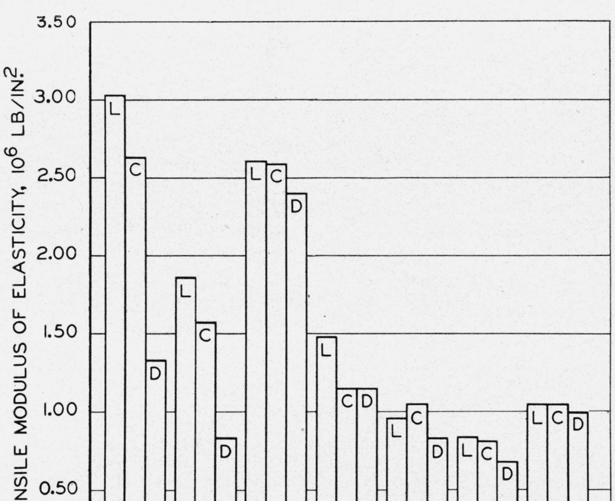

FIGURE 41. *Tensile secant moduli of elasticity for lengthwise (L), crosswise (C), and 45° diagonal (D) directions of ⅛-in.-thick laminates.*

Stress ranges: 0 to 5,000 lb/in.^{2} for *AB*, *Z*, *S*; 0 to 2,500 lb/in.^{2} for *K*, *L*, *V*, *W*. Types of laminates shown are: *AB*, glass-fabric unsaturated-polyester; *Z*, rayon-cotton-fabric phenolic; *S*, high-strength-paper phenolic; *K*, asbestos-fabric phenolic; *L*, low-pressure cotton-fabric phenolic; *V*, low-pressure Grade C phenolic; *W*, high-pressure Grade C phenolic.

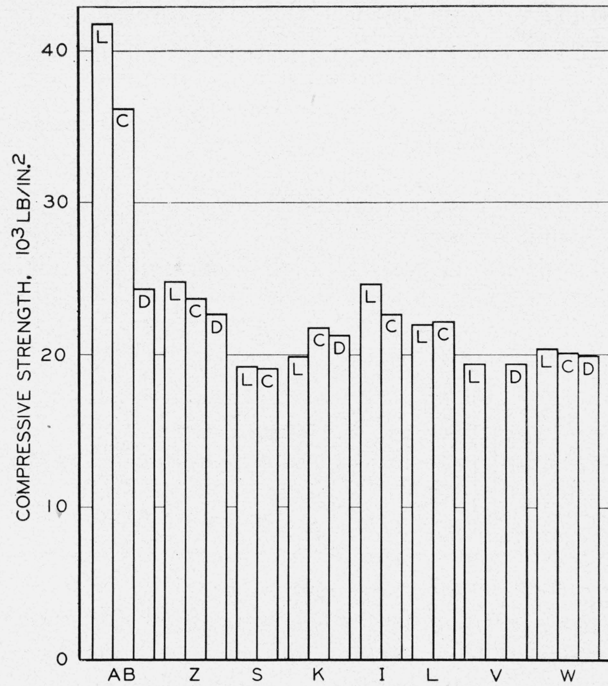

FIGURE 42. *Compressive strengths for lengthwise (L), crosswise (C), and 45° diagonal (D) directions of ½-in.-thick laminates.*

Types of laminates shown are: *AB*, glass-fabric unsaturated-polyester; *Z*, rayon-cotton-fabric phenolic; *S*, high-strength-paper phenolic; *K*, asbestos-fabric phenolic; *I*, Grade C phenolic; *L*, low-pressure cotton-fabric phenolic; *V*, low-pressure Grade C phenolic; *W*, high-pressure Grade C phenolic.

The rayon-fabric and the glass-fabric laminates, similarly to their behavior in flexure, showed large variations in tensile strength and tensile and compressive moduli with the direction of test. The diagonal values were as low as 30 to 50 percent of the lengthwise values. The rayon-fabric sample, although a crossed-ply laminate, showed the greatest variation between the lengthwise and crosswise values of tensile modulus of elasticity.[4]

In the asbestos-fabric sample, a parallel-ply laminate, the tensile strength and the tensile and compressive moduli were greatest in the lengthwise, least in the crosswise, and intermediate in the diagonal directions (fig. 40).

[4] This may be explained as follows: The rayon fabric, of higher strength and modulus of elasticity than the resin, was practically unidirectional in strength. In the ⅛-in. thickness there were four plies lengthwise to three crosswise. If the modulus of elasticity of the resin, small compared to the fabric, is neglected, the ratio of lengthwise to crosswise tensile modulus of elasticity should be 1.33; the measured ratio was 1.18. Application of the same idea to the compressive moduli, where the specimen has 12 lengthwise and 11 crosswise plies, indicates a corresponding ratio of 1.09; the measured ratio was 1.07.

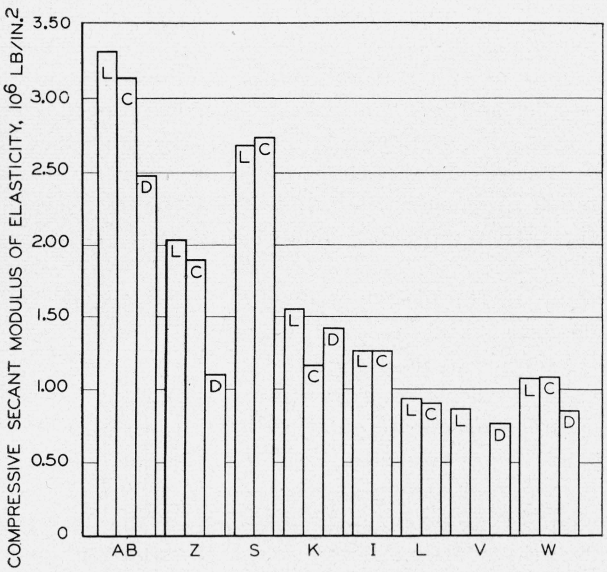

FIGURE 43. *Compressive secant moduli of elasticity (0 to 2,500 lb/in.²) for lengthwise (L), crosswise (C), and 45° diagonal (D) directions of ½-in.-thick laminates.*

Types of laminates shown are: *AB*, glass-fabric unsaturated-polyester; *Z*, rayon-cotton-fabric phenolic; *S*, high-strength-paper phenolic; *K*, asbestos-fabric phenolic; *I*, Grade C phenolic; *L*, low-pressure cotton-fabric phenolic; *V*, low-pressure Grade C phenolic; *W*, high-pressure Grade C phenolic.

In all samples, the compressive strength varied less with direction than the tensile strength. For a given sample, the compressive strengths for the three directions of test differed by 10 percent or less. The only exception was the glass-fabric laminate whose compressive strength in the 45°-diagonal direction was only 60 percent of that in the lengthwise direction. Moreover, except for the glass-fabric laminate, the compressive strengths of the laminates were within 10 percent of 21,000 lb/in.²; the tensile strengths of these same laminates (excluding the glass-fabric laminate) ranged from 5,000 to 32,000 lb/in.²

The relative constancy of compressive strength with variation of direction and reinforcement indicates that the strength of the resin is the major factor in determining the compressive strength of fabric and paper laminates. This conclusion was reached by Erickson and Mackin (see p. 268 and tables 1 and 2, [19]) in regard to a parallel-ply high-strength-paper laminate. Witt, Wolfe, and Rust [6] showed that, although the average lengthwise tensile strength for ten Grade L laminates was 50 percent greater than the average crosswise tensile strength, and for eleven Grade C laminates 15 percent greater, the difference in compressive strengths of the different directions of the two materials was less than 3 percent.

7. Strain at Failure

Except for the asbestos-fabric laminates, the elongation at failure in tension (table 8) was the same for the lengthwise and crosswise directions and greatest for the 45°-diagonal direction. The greatest elongations in tension were those of the two low-pressure cotton-fabric laminates, L1 and V1, and the glass-fabric laminate in the 45°-diagonal direction.

Table 8 also shows that, in compression, the maximum strain at failure occurred in the 45°-diagonal direction. In general, the strain at failure in compression was greater than in tension for the same sample and orientation of specimen.

The elongation in tension for the cellulose

TABLE 8. *Strain at failure in tension and compression tests* [a]

Material designation	Orientation of specimen	Total strain of failure: Tension −70° F	Tension 77° F	Tension 200° F	Compression at 77° F
		Percent	*Percent*	*Percent*	*Percent*
L, Low-pressure cotton-fabric phenolic, cross ply.	Lengthwise	2.9	4.9	4.2	12.2
	Crosswise	3.3	4.8	3.2	11.6
	45° diagonal	----	8.7	----	----
V, Low-pressure Grade C phenolic, cross ply.	Lengthwise	3.9	4.8	3.7	10.5
	Crosswise	3.9	5.0	3.6	----
	45° diagonal	----	8.5	----	14.7
W, High-pressure Grade C phenolic, cross ply.	Lengthwise	3.3	3.7	2.8	8.6
	Crosswise	3.0	4.8	2.5	8.2
	45° diagonal	----	4.7	----	11.8
I, Grade C phenolic, parallel ply.	Lengthwise	----	----	----	12.0
Z, Rayon-cotton-fabric phenolic, cross ply.	Lengthwise	2.8	4.0	3.4	5.7
	Crosswise	3.0	3.9	3.4	5.8
	45° diagonal	----	4.9	----	8.6
S, High-strength-paper phenolic, cross ply.	Lengthwise	1.2	1.7	1.1	4.5
	Crosswise	1.3	1.7	1.1	----
	45° diagonal	----	2.0	----	----
K, Asbestos-fabric phenolic, parallel ply.	Lengthwise	2.1	1.8	1.2	5.1
	Crosswise	0.5	0.6	0.5	6.3
	45° diagonal	----	.6	----	5.4
AB, Glass-fabric unsaturated polyester, parallel ply.	Lengthwise	----	1.8	----	1.5
	Crosswise	2.2	1.7	1.7	1.5
	45° diagonal	----	8.2	----	2.5

[a] The tension tests were made on ⅛-in.-thick samples, and the compression tests were made on ½-in.-thick samples.

laminates was greater at 77° F than at either −70° or 200° F. The deflection at failure in flexural testing was greater at 77° F than at either −70° or 200° F for the six cellulose laminates (figs. 14 to 17). Meyer and Erickson [4] have shown that the elongation at failure in tension of a high-strength-paper laminate increases directly with the moisture content of the laminate. Therefore, part of the increase in brittleness of the cellulose laminates at 200° F may be due to the decrease in moisture content of the laminates caused by 24-hr conditioning at 200° F.

V. Conclusions

The Izod impact strength-temperature trend of the laminated plastics is different for the various types of reinforcement. The glass-fabric laminates decrease steadily in impact strength with increasing temperature, the value of 200° F being about 70 percent of the −70° value. The asbestos-fabric, rayon-fabric, and high-strength-paper laminates show little variation in impact strength between −70° and 200° F. The cotton-fabric laminates exhibit increasing impact strength with temperature, roughly doubling their impact strength between −70° and 200° F.

The Izod impact-strength values for the rayon-fabric and the glass-fabric laminates are much greater than for the other materials.

An increase in flexural properties occurs for all the samples at low temperature, and at high temperature, a decrease occurs for all the samples except the asbestos fabric laminate, which shows no change.

The high-strength-paper and two glass-fabric laminates are outstanding in flexural properties. When the samples are compared on the basis of specific strength values, the paper and rayon-fabric laminates are superior to the others.

The low-pressure Grade C phenolic laminate, V2, compares favorably in flexural strength properties with the high-pressure laminate, W2, made with the same reinforcement, especially when the comparison is made in terms of specific strength properties.

The tensile and compressive strengths and moduli of elasticity of all laminates increase at low temperature and decrease at high temperature relative to the values at 77° F.

For all laminates, except the asbestos-fabric product, the tensile and compressive strengths at 200° F are approximately half of the corresponding values at −70° F. The changes in the strength values of the asbestos-fabric product are much smaller and less than for any other laminate.

For the cellulose laminates, the increase in compressive strength at the low temperature is much greater in magnitude than the decrease at the high temperature; the tensile strength variation, however, is less at the low temperature than at the high temperature. The tensile and flexural strengths of these samples exhibit similar temperature changes.

The tensile and compressive moduli of all samples increase more at the low temperature than they decrease at the high temperature. Except for the high-strength-paper laminate, the over-all changes are greater for the cellulose than for the mineral-type laminates. The high-strength-paper, asbestos-fabric, and glass-fabric laminates show about the same over-all variation of tensile and compressive moduli with temperature.

The tensile strengths of the high-strength-paper, rayon-fabric, and glass-fabric laminates are about three times greater than those of the cotton-fabric and asbestos-fabric phenolics.

The glass-fabric laminate is outstanding in compressive strength; at 77° F its strength is 36,000 and 42,000 lb/in.^{2}, respectively, in the crosswise and lengthwise directions. The compressive strength of the other laminates is 21,000 lb/in.^{2} within about 10 percent.

The tensile and compressive moduli of elasticity of the glass-fabric and high-strength-paper laminates are greater than for the other materials at all temperatures and are in the range 2,600,000 to 3,300,000 lb/in.^{2}

The flexural properties of plastic laminates at high temperature are not a function of temperature alone, but may be affected by further cure of the resin and loss of moisture content. The effect of high humidity in addition to an elevated temperature may be much different from the effect of the elevated temperature alone. A severe loss in strength was noted for the high-strength-paper and one low-pressure cotton-fabric laminate at 150° F and 90-percent relative humidity.

The ratio of edgewise to flatwise impact strength for the ½-in.-thick phenolic laminates tested is nearly constant over the range of temperatures, −70° to 200° F.

VI. References

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