Environmental Effects on the Elastic Moduli of Composite Materials

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ABSTRACT

The buckling moduli of Thornel 300/Fiberite 1034 graphite epoxy composites were measured at temperatures ranging from 105 K to 422 K and at moisture contents ranging from 0% (dry) to 1.5% (fully saturated). The measurements were made using 0°, 90° and $\pi/4$ laminates. A survey was also made of the existing data showing the effects of temperature and moisture content on the tensile modulus and the compressive modulus of different composite materials.

SCOPE

IN ORDER TO utilize the full potential of composite materials their performance during and after exposure to high temperature and high humidity environments must be known. One of the most important parameters in the design of composite elements and structures is the elastic modulus. The effects of temperature and moisture content on tensile (E_t) and compressive (E_c) moduli have been studied in the past. The objective of this investigation was to evaluate the changes in the buckling modulus (E_b) of composite materials exposed to air in which the temperature ranged from 195 K to 450 K and the moisture content from 0% (dry) to 1.5% (fully saturated). The changes in the buckling modulus were measured by performing buckling tests on Thornel 300/Fiberite 1034 graphite epoxy composites using 0°, $\pi/4$ and 90° lay-ups. A summary was also made of the existing data. This summary, together with the present results, was used to assess the influence of the temperature and the moisture content on the elastic moduli of composite materials.

CONCLUSIONS

On the basis of both the present data (for buckling modulus) and the existing data (for tensile and compressive moduli, Table 1) the following general conclusions may be drawn.

Table 1. Summary of Experimental Data on the Effects of Moisture and Temperature on the Elastic Modulus of Composite Materials

Composite	Reference	Laminate Lay-Up Orientation					
		0°		$\pi/4$		90°	
		Moist	Temp	Moist	Temp	Moist	Temp
BUCKLING TEST							
Thornel 300/Fiberite 1034	Shen & Springer 1977	N	N	N	N	S	S
TENSILE TEST							
Hercules AS-5/3501	Browning, et al 1976 [5]	L	N	L	N	S	S
	Verette 1975 [6]	N	N	N	-	S	S
	Kerr et al 1975 [7]	-	N	-	N	-	-
Thornel 300/Narmco 5208	Hofer et al 1975 [8]	N	N	N	N	N	N
	Husman 1976 [9]	-	-	-	-	S	S
Modmor II/Narmco 5206	Hofer et al 1974 [10]	N	N	N	N	S	S
Courtaulds HMS/Hercules 3002M	Hofer et al 1974 [10]	N	N	N	N	N	S
HT-S/ERLA-4617	Browning 1972 [11]	-	-	N	S	-	-
HT-S/Fiberite X-911	Browning 1972 [11]	-	-	N	N	-	-
HT-S/UCC X-2546	Browning 1972 [11]	-	-	N	L	-	-
PRD-49/ERLB-4617	Hanson 1972 [12]	-	S	-	-	-	-
HT-S/(8183/137-NDA-BF_3: MEA)	Hertz 1973 [13]	-	-	-	-	N	S
TENSILE TEST							
HT-S/Hysol ADX-516	Browning 1972 [11]	-	-	N	S	-	-
HT-S/710 Polyimide	Kerr et al 1975 [7]	-	N	-	N	-	-
HT-S/P13N Polyimide	Browning 1972 [11]	-	-	-	L	-	-
Boron/AVCO 5505	Hofer et al 1974 [10]	N	N	N	N	S	S
Boron/Narmco 5505	Browning 1972 [11]	-	-	N	N	-	-
COMPRESSIVE TEST							
Hercules AS-5/3501	Verette 1975 [6]	N	N	-	-	L	S
Thornel 300/Narmco 5208	Hofer et al 1975 [8]	L	N	N	N	L	N
Modmor II/Normco 5206	Hofer et al 1974 [10]	N	N	N	N	S	S
Courtaulds HMS/Hercules 3002M	Hofer et al 1974 [10]	N	N	N	N	S	S
Boron/AVCO 5505	Hofer et al 1974 [10]	N	N	N	N	S	S

a) N = Negligible effect

b) L = Little effect (<30%)

c) S = Strong effect (>30%)

1. **Temperature Effects**

(a) For 0° and $\pi/4$ laminates the temperature (in the range of 200 K to 450 K) has a negligible effect on the elastic moduli regardless of the moisture content of the material.

(b) For 90° laminates an increase in temperature causes a decrease in the elastic moduli. The decrease in the modulus depends upon both the temperature and the moisture content. For an increase in temperature from 300 K to 450 K the elastic modulus may decrease by as much as 50 to 90 percent.

2. **Moisture Effects**

(a) For 0° and $\pi/4$ laminates there appears to be very little change in the elastic moduli over the entire spectrum of moisture content from dry to fully saturated. This conclusion appears to be valid regardless of temperature in the range 200 K to 450 K.

(b) For 90° laminates the elastic moduli decrease considerably with increase in the moisture content. The decrease in the modulus depends both on the moisture content and on the temperature. The decrease in the value of the modulus may be as high as 50 to 90 percent.

(c) In the tests reported here the moisture distribution was nonuniform inside the specimens. For 0° and $\pi/4$ specimens the variations encountered in the moisture distribution do not appear to affect the results significantly. For 90° specimens the moisture distribution may influence the absolute value of the buckling moduli, but is unlikely to affect the trend in the data.

3. **Additional Considerations**

(a) The values of the elastic moduli obtained by tensile, compressive and buckling tests are usually different. However, the *changes* in the moduli caused by changes in temperature and moisture content are nearly the same for all three moduli. Therefore, the conclusions stated in points 1 and 2 above are valid for all three elastic moduli.

(b) The above conclusions depict the general trend in the data. The precise effects of the temperature and the moisture content on a particular composite material must be evaluated from the relevant data. A ±20 percent scatter in the data is quite common. This scatter must be borne in mind when applying the data.

EXPERIMENTAL

All buckling measurements in this study were made with 8 ply T300/1034 specimens of thickness $h = 0.9$ mm and width $b = 4.76$ mm. Different length specimens were used in the tests, the lengths ranging from 36 mm to 318 mm. The test specimens were cut from 0.66 m x 0.66 m autoclave cured panels which were fabricated from 30.5 cm (12 in) prepreg (Fiberite Corp.) using standard lay-up and vacuum bagging procedures. The cure cycle used in manufacturing the panels was described in [1].

Prior to the buckling tests all the specimens were completely dried at 366 K in a desiccator. The specimens were then placed in environmental chambers [2] in which the temperature and the relative humidity were kept constant at 366 K and 100%. The specimens were kept in the chambers until the moisture content (weight gain) reached the required level, i.e. until the specimen was fully saturated or until the moisture contents reached 1/3 or 2/3 of the fully saturated value. At 1/3 and 2/3 saturation the moisture distribution was nonuniform inside the specimen. The moisture distribution at these saturation levels was given by Shen and Springer [1].

The buckling moduli were determined using a 10,000 lb capacity Instron machine (Model TTCLM 1-4). At the start of each test the specimen was placed between two 15.3 cm diameter smooth metal discs attached to the Instron machine. The ends of the specimen were not restrained in any other way. The specimen was compressed along its length at a cross-head speed of 1.27 mm min^{-1} (0.05 in/min). The load was recorded continuously during the test. As the specimen was compressed the load increased to a peak. The load then decreased and levelled off, remaining nearly constant with displacement, as shown in Figure 1. The value of this constant load, designated as the critical load P_{cr}, is related to the buckling modulus by the expression [3]

$$P_{cr} = \frac{\pi^2 I E_b}{L^2} \tag{1}$$

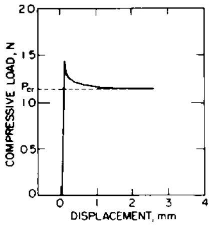

Figure 1. Graph of compressive load versus cross-head displacement in a typical buckling test. 90° specimen at 300 K and 0% moisture content.

where E_b is the buckling modulus, I is the moment of inertia of the cross sectional area ($I = bh^3/12$) and L is the length of the specimen.

By rewriting equation (1) in terms of the critical stress σ_{cr}, we obtain

$$\sigma_{cr} = \frac{P_{cr}}{bh} = \frac{\pi^2 h^2 E_b}{12L^2} \tag{2}$$

In order to evaluate E_b for a given environmental condition, a large number of buckling tests were performed using specimens of different lengths. For each environmental condition at least 12 buckling tests were performed using specimens of lengths 56, 89, and 172 mm. At room temperature (300 K, 0% moisture content) 25 specimens with lengths ranging between 36 mm and 318 mm were tested. The buckling modulus was then determined as follows.

The experimental error (ϵ) in the data is defined as

$$\epsilon = \sigma_{cr} - \frac{\pi^2 h^2 E_b}{12L^2} \tag{3}$$

For N number of tests, the sum of the squares of the errors S is

$$S = \sum_{i=1}^{N} (\epsilon_i)^2 \tag{4}$$

or

$$S = \sum_{i=1}^{N} \left(\sigma_{cr_i} - \frac{\pi^2 h^2 E_b}{12L_i^2} \right)^2 \tag{5}$$

The subscript i denotes the ith test. The value of E_b which makes S a minimum is taken as the buckling modulus. Differentiating equation (5) with respect to E_b yields

$$\frac{dS}{dE_b} = \sum_{i=1}^{N} 2 \left(\sigma_{cr_i} - \frac{\pi^2 h^2 E_b}{12L^2_i} \right) \left(-\frac{\pi^2 h^2}{12L^2_i} \right) \tag{6}$$

By equating equation (6) to zero and solving for the value of E_b, we obtain the required value of E_b

$$E_b = \frac{12}{\pi^2 h^2} \frac{\sum_{i=1}^{N} \frac{\sigma_{cr_i}}{L^2_i}}{\sum_{i=1}^{N} \frac{1}{L^4_i}} \tag{7}$$

It is noted that equation (2) may be written in the form

$$\log \sigma_{cr} = \log \frac{\pi^2 h^2 E_b}{12} - 2 \log L \tag{8}$$

According to this equation, on a log σ_{cr} versus log L plot, the data should fall on a straight line of slope-2. In order to check the accuracy of the present data, all the data were plotted on such a graph. For all test conditions, the data followed closely a straight line of slope-2. A typical set of results is shown in Figure 2.

During each buckling test the specimen was maintained at the desired temperature by an infrared heat lamp. The temperature of the specimen was measured by a copper-constantan thermocouple attached to the surface of the specimen. The moisture content of the environment was not controlled during the buckling test, and hence some drying of the outer layer of the specimen might have occurred during the test. The thickness of the layer affected by the drying and the amount of moisture lost during this drying was calculated, and was reported in reference [1].

RESULTS*

The effects of temperature and moisture content on the buckling modulus of T300/1034 were determined according to the test procedures described in the previous section. The results in Figure 3 show that for 0° and π/4 laminates the modulus is unaffected either by temperature or by moisture content. The slight decrease (~ 5%) in the buckling modulus for fully saturated specimens is within the range of the scatter of the data. For 90° laminates the buckling modulus seems to be insensitive to changes in temperature and moisture content as long as the temperature is in the range of 195 K – 300 K. However, in the temperature range 300 K – 450 K the buckling modulus is strongly influenced by both the temperature and the moisture content.

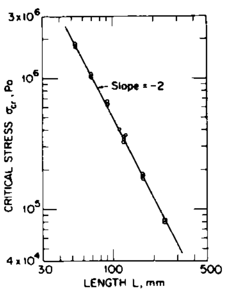

Figure 2. Graph of log σ_{cr} versus log L for 90° specimens at 300 K and 0% moisture content.

A survey was also made of all the existing data on the effects of temperature and moisture content on the tensile and compressive moduli of composite materials.

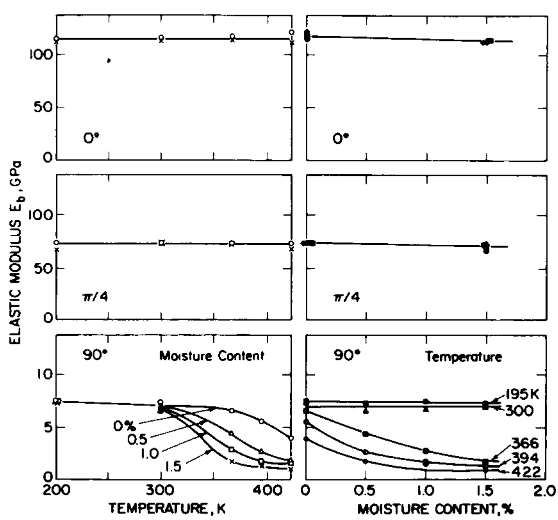

Figure 3. Buckling modulus of Thornel 300/Fiberite 1034 as a function of temperature and moisture content. Present data.

*Note: 1 GPa = 1.45 x 10^5 lbf/in^2.

The results of this survey are presented in Figures 4–25. In addition, in Table 1 a brief summary of all the data is given, including the type of material, the parameters varied, the general trend in the results, and the appropriate references. All those experiments known to the authors were included in the survey in which the

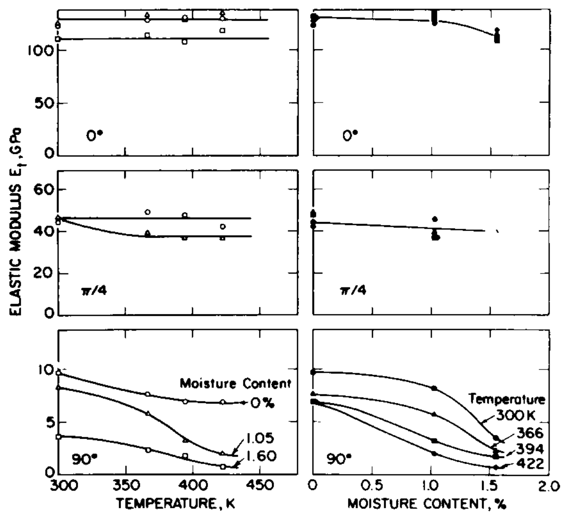

Figure 4. Tensile modulus of Hercules AS-5/3501 as a function of temperature and moisture content. Data of Browning et al, 1976 [5].

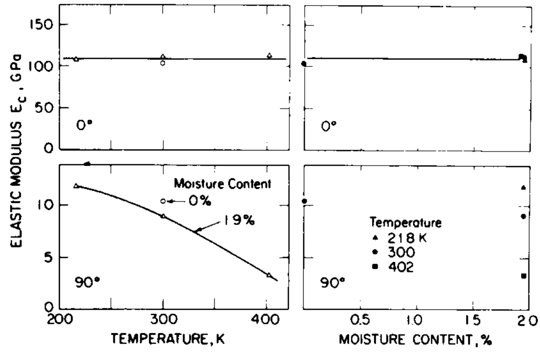

Figure 5. Tensile modulus of Hercules AS-5/3501 as a function of temperature and moisture content. Data of Verette, 1975, [6].

test conditions were either specified completely or could be assessed from the reports. Those test results where the environmental conditions were not completely identified were excluded. As can be seen from Figures 4–25 there is considerable scatter in the data. Furthermore, in certain cases only 2 or 3 data points were obtained. Nevertheless, the general trends in the behavior of previously obtained tensile and compressive moduli (Figures 4–25) are similar to the behavior of the buckling moduli obtained in the present study (Figure 3).

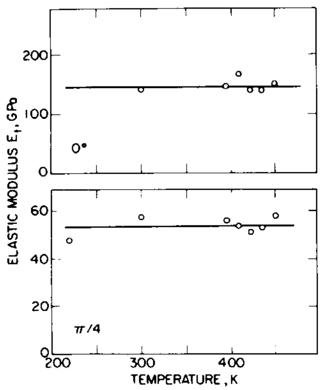

Figure 6. *Dry longitudinal and quasi-isotropic tensile moduli of Hercules AS-5/3501 as a function of temperature. Data of Kerr et al 1975 [7].*

Figures 3–25 may be used to evaluate the effects of temperature and moisture content on the tensile, compressive and buckling moduli of different composites. Figures 3–25 also indicate the conditions where data are lacking.

It is finally noted that the effects of temperature and moisture content on the three moduli (E_t, E_c, E_b) are very similar to those on the ultimate tensile strength [1].

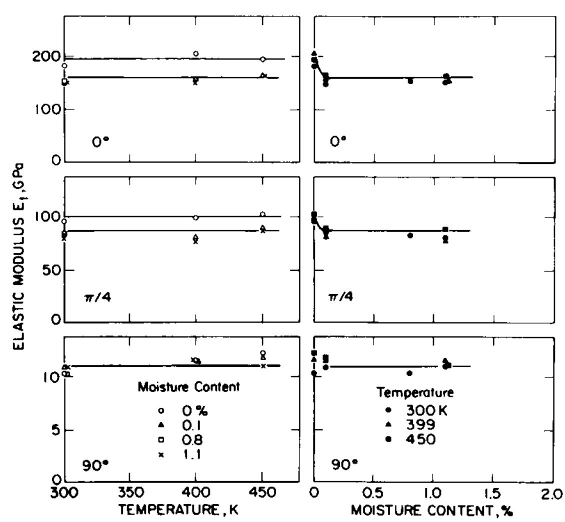

***Figure** 7. Tensile modulus of Thornel 300/Narmco 5208 as a function of temperature and moisture content. Data of Hofer et al, 1975 [8].*

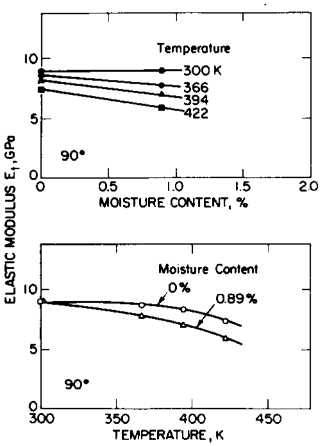

Figure 8. Transverse tensile modulus of Thornel 300/Narmco 5208 as a function of temperature and moisture content. Data of Husman, 1976 [9].

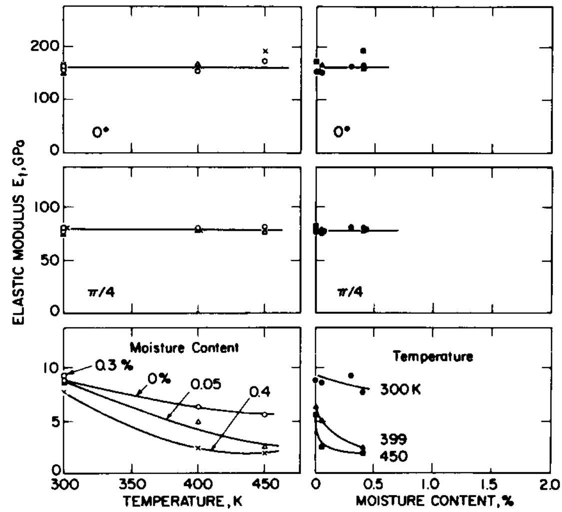

Figure 9. Tensile modulus of Modmor II/Narmco 5206 as a function of temperature and moisture content. Data of Hofer et al, 1974 [10].

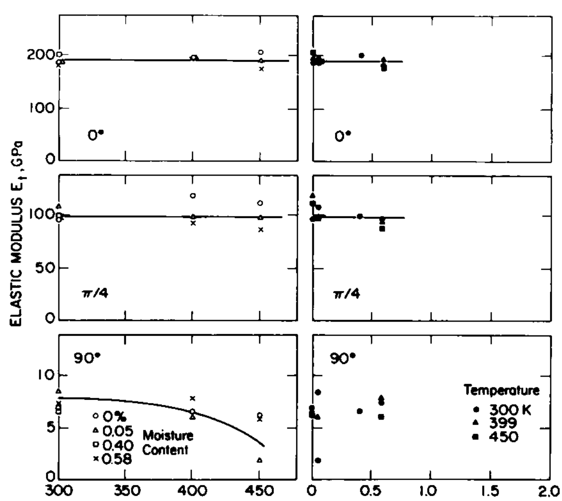

Figure 10. Tensile modulus of Courtaulds HMS/Hercules 3002M as a function of temperature and moisture content. Data of Hofer et al, 1974 [10].

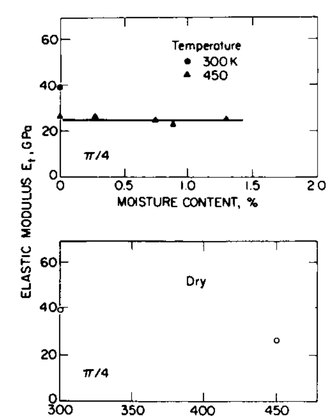

Figure 11. Quasi-isotropic tensile modulus of HT-S/ERLA-4617 as a function of temperature and moisture content. Data of Browning, 1972 [11].

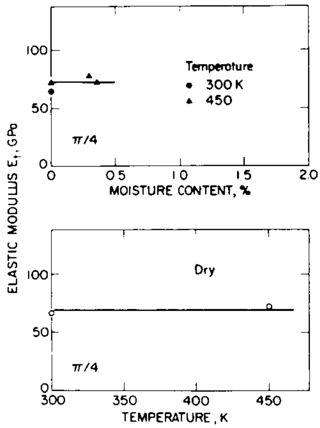

Figure 12. Quasi-isotropic tensile modulus of HT-S/Fiberite X-911 as a function of temperature and moisture content. Data of Browning, 1972 [11].

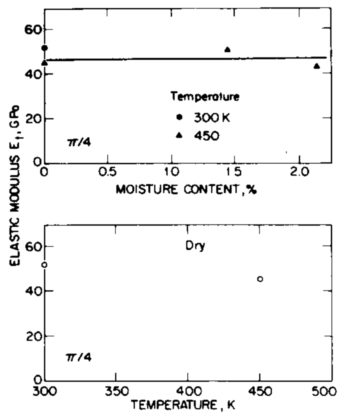

Figure 13. Quasi-isotropic tensile modulus of HT-S/UCC X-2546 as a function of temperature and moisture content. Data of Browning, 1972 [11].

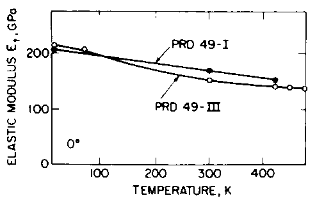

Figure 14. Dry longitudinal tensile modulus of PRD-49/ERLB-4617 as a function of temperature. Data of Hanson, 1972 [12].

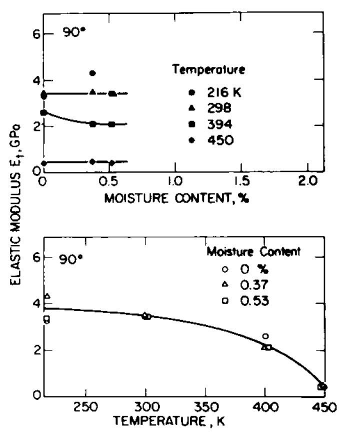

Figure 15. Transverse tensile modulus of HT-S/(8183/137-NDA-BF_3: MEA) as a function of temperature and moisture content. Data of Hertz, 1973 [13].

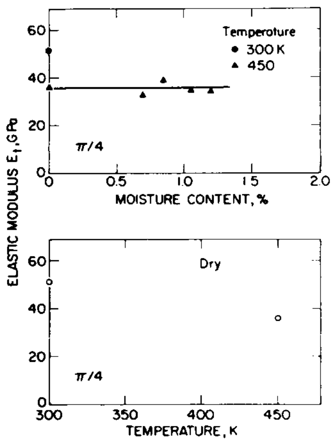

Figure 16. Quasi-isotropic tensile modulus of HT-S/Hysol ADX-516 as a function of temperature and moisture content. Data of Browning, 1972 [11].

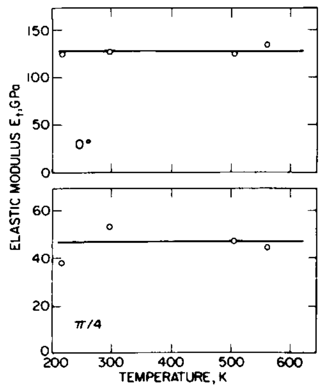

Figure 17. Dry longitudinal and quasi-isotropic tensile moduli of HT-S/710 Polyimide as a function of temperature. Data of Kerr et al, 1975 [7].

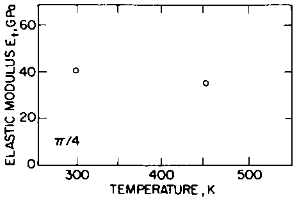

Figure 18. Dry quasi-isotropic tensile modulus of HT-S/P13N Polyimide as a function of temperature. Data of Browning, 1972 [11].

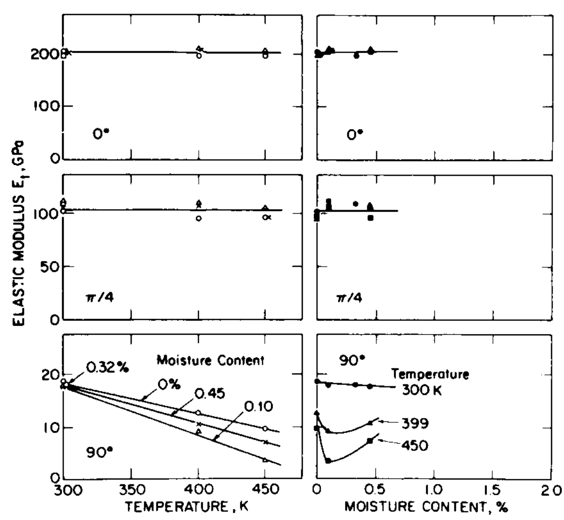

Figure 19. Tensile modulus of Boron/AVCO 5505 as a function of temperature and moisture content. Data of Hofer et al, 1974 [10].

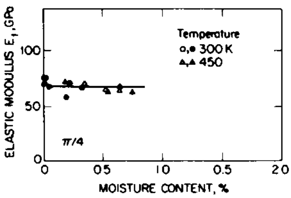

Figure 20. Quasi-isotropic tensile modulus of Boron/Narmco 5505 as a function of temperature and moisture content. Data of Browning, 1972 [11]. ○ Δ: post-cured specimen; ● ▲: not post-cured specimen.

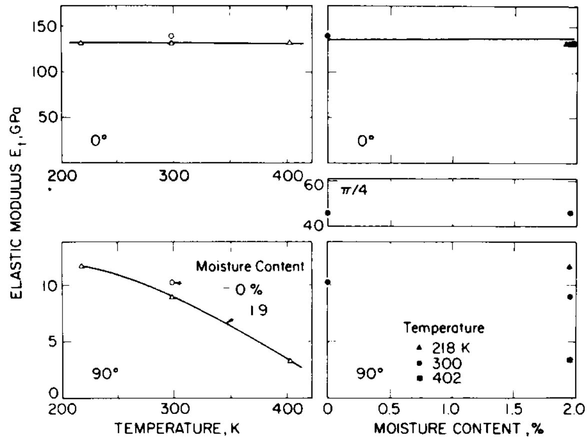

Figure 21. Longitudinal and transverse compressive moduli of Hercules HS-5/3501 as a function of temperature and moisture content. Data of Verette, 1975 [6].

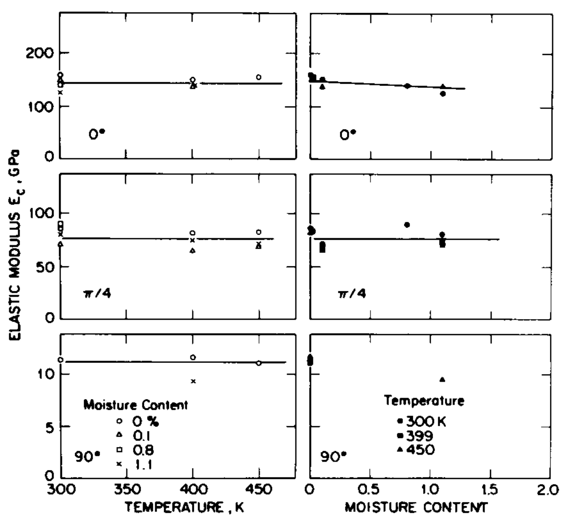

Figure 22. Compressive modulus of Thornel 300/Narmco 5208 as a function of temperature and moisture content. Data of Hofer et al, 1975 [8].

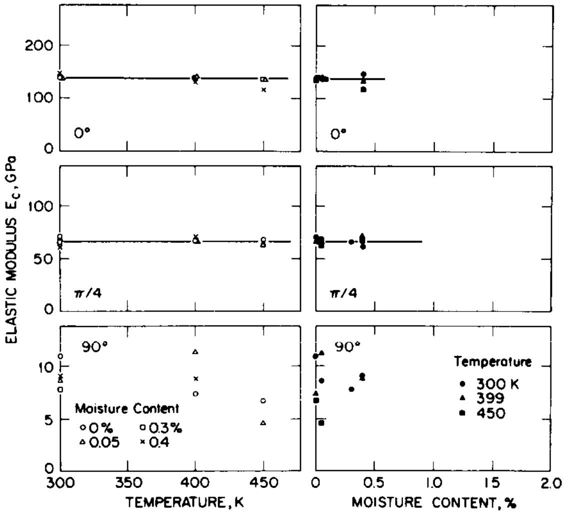

Figure 23. Compressive modulus of Modmor II/Narmco 5206 as a function of temperature and moisture content. Data of Hofer et al, 1974 [10].

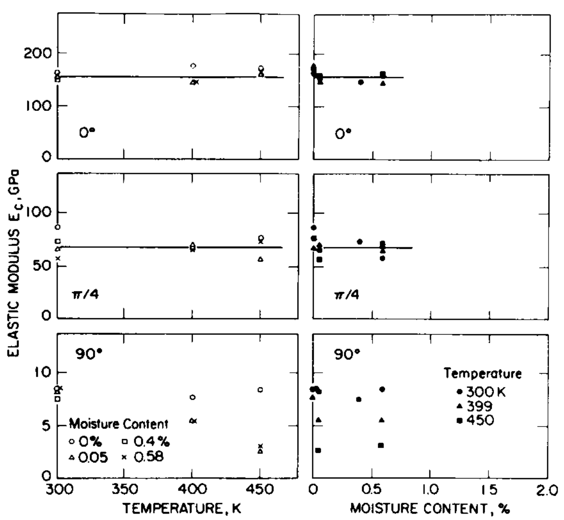

Figure 24. Compressive modulus of Courtaulds HMS/Hercules 3002M as a function of temperature and moisture content. Data of Hofer et al, 1974 [10].

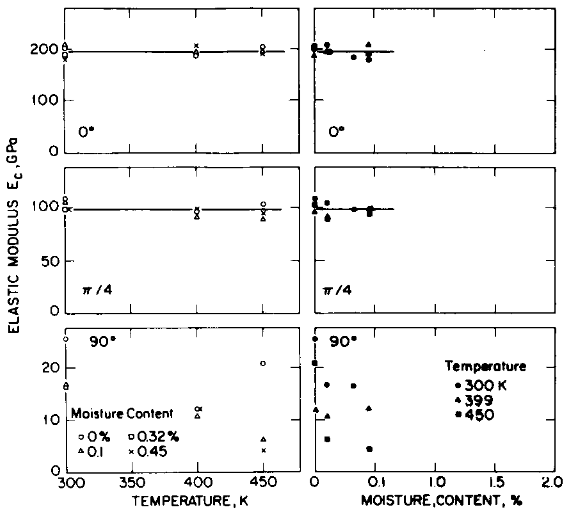

Figure 25. Compressive modulus of Boron/AVCO 5505 as a function of temperature and moisture content. Data of Hofer et al, 1974 [10].

It is emphasized again that the results presented illustrate the trend in the buckling moduli. In addition to temperature and humidity, other parameters such as cure cycle, temperature history (thermal spikes), and loading history may influence the absolute value of the buckling modulus.

ACKNOWLEDGMENTS

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NOMENCLATURE

b width of specimen (mm)
ϵ experimental error defined in equation (3) (Pa)
E_b buckling modulus (Pa)
E_c compressive modulus (Pa)
E_t tensile modulus (Pa)
h thickness of specimen (mm)
I moment of inertia of the cross sectional area (mm^4)
L length of specimen (mm)
N number of buckling tests (dimensionless)
P_{cr} critical buckling load (N)

S sum of the squares of the errors defined in equation (4) (Pa^2)
σ_{cr} critical buckling stress (Pa)

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