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TENSILE (COMPRESSIVE) PROPERTIES OF GLASS-EPOXY COMPOSITES AS A FUNCTION OF VOLUME FRACTION

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13. ABSTRACT

The mechanical performance of unidirectionally reinforced glass epoxy composites was studied as volume fraction filler was varied over the range 30-70 percent. Experimentally determined quantitites included: longitudinal and transverse tensile strength, ultimate strain, modulus; and Poisson's ratio; and longitudinal and transverse compressive strength. Data analysis indicated that all properties varied linearly with volume fraction. Longitudinal properties and Poisson's ratio were interpreted in terms of the rule of mixtures.

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TENSILE (COMPRESSIVE) PROPERTIES OF GLASS-EPOXY COMPOSITES AS A FUNCTION OF VOLUME FRACTION

by

M. J. Michno, Jr. and F. J. Shea

December 1973

Monsanto/Washington University Association
High Performance Composites Program
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FOREWORD

The research reported herein was conducted by the staff of Monsanto/Washington University Association under the sponsorship of the Advanced Research Projects Agency, Department of Defense, through a contract with the Office of Naval Research, N00014-67-C-0218 (formerly N00014-66-C-0045), ARPA Order No. 876, ONR contract authority NR-356-484/4-13-66, entitled "Development of High Performance Composites."

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TENSILE (COMPRESSIVE) PROPERTIES OF GLASS-EPOXY COMPOSITES AS A FUNCTION OF VOLUME FRACTION

INTRODUCTION

Filament winding is a commonly employed viable technique for producing glass-reinforced plastic components. Processing variables which affect the mechanical performance of these components include widing tension, mandrel temperature, and winding speed [1]. Winding tension directly controls the volume fraction filler (v_f). Herein we consider the effect of variable v_f on the strength of glass-epoxy composites.

A general tensor polynomial strength criterion proposed by Tsai and Wu [2] appears to have wide applicability and for specially orthotropic material under plane biaxial stresses (in the absence of shear stress) assumes the form:

$$F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + 2F_{12}\sigma_1\sigma_2 = 1 \quad (1)$$

σ_1 = longitudinal stress

σ_2 = transverse stress

F_1, F_2 = 2nd rank strength tensors (contracted notation)

F_{11}, F_{22}, F_{12} = 4th rank strength tensors

The normal stress interaction tensor F_{12} can be determined only from tests under combined states of stress. However, the non-interacting components of the strength tensors can be experimentally determined from simple states of stress:

$$F_1 = \frac{1}{X} - \frac{1}{X'} \quad , \quad F_2 = \frac{1}{Y} - \frac{1}{Y'} \quad (2)$$

$$F_{11} = \frac{1}{XX'} \quad , \quad F_{22} = \frac{1}{YY'} \quad (3)$$

where X, X', Y, Y' are uniaxial tensile and compressive strengths along longitudinal and transverse directions respectively. Determination of X, X', Y, Y' as a function of v_f would allow calculation of F_1, F_2, F_{11}, and F_{22} as a function of v_f. If additional determinations of $F_{12}(v_f)$ were made the applicability of Eq. (1) for a range of v_f could be ascertained. Other commonly employed failure criteria such as maximum strain require knowledge of the ultimate strains at failure and the elastic constants. Hence, in addition to strength data we seek to determine as a function of v_f longitudinal and transverse moduli (E_{11}, E_{22}); longitudinal and transverse ultimate strains (ε_{11}^{ult}, ε_{22}^{ult}); and Poisson's ratio ν_{12}.

MATERIALS AND SPECIMENS

Composites were prepared using the same materials and filament winding techniques as reported in detail elsewhere [3]. The matrix resin was Epon 828 plus Shell Curing Agent Z(20 phr*). The filler was PPG 1062-T6** E glass roving. Unidirectional composites were prepared by filament winding on a rectangular mandrel with four 6 in. x 8 in. faces. After winding the mandrel was placed in a vacuum chamber for 45 min. to remove any entrapped air from the samples. The mandrel was then remounted on the filament winder and the final volume fraction was established by clamping steel plates to the mandrel faces, the final thickness of the sample being controlled by contact with preselected shims. Winding stresses in the glass were then relieved by cutting the glass tape across two corners of the mandrel. The composites were then B-staged while rotating on the mandrel under heat lamps. Final curing was at 100°C for 30 min. followed by 2 hours at 150°C.

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* Parts per hundred resin

** Manufactured by PPG Industries, Inc.

TENSILE SPECIMENS

Straight sided specimens 1/2 in. wide and 6 in. long were cut from the plates at 0° and 90° to the fiber direction. These were tabbed with glass fabric reinforced laminates to establish a gage length of 3 in.

Several hoop wound tubular samples at selected volume fractions were also tested in tension.

COMPRESSION SPECIMENS

Compression samples were prepared by adhesive bonding unidirectional composite sheets to either side of a 1/2 in. thick aluminum honeycomb. The resultant sandwich plate was then cut into strips 1 in. wide by 1 1/2 in. long with the fiber direction either parallel or perpendicular to the length. The honeycomb of the rectangular sandwiches was then machined away (slotted) at the midsection. The slotting produced an unsupported mid-length of approximately 0.3 in. Care was taken to eliminate adhesive from the composite faces along this unsupported length. As in the case of tensile samples, several hoop wound tubular samples at selected volume fractions were tested to determine transverse compressive strength.

EXPERIMENTAL DETAILS

The tensile specimens were tested in an Instron tester at a cross-head speed of 0.2 in/min. An extensometer was used to continuously record strains to complement the continuous load record. All tests were conducted at room temperature (75°F). Composite stress and modulus were calculated based upon the original cross sectional area and the recorded loads.

Compressive samples were also tested in an Instron tester at a crosshead rate of 0.2 in/min. Details of the testing followed those recommended in [4] and included the use of a lightly clamped lateral guide (outside the unsupported length). This method of testing resulted in the desired compressive failure mode within the unsupported length of the specimen and avoided end brooming or crushing and premature buckling failure. The ultimate load at failure was reduced to the ultimate stresses at failure based on the original cross sectional area of each face plate and the assumption that each face plate carried one half of the total load.

All tests on tubular samples were conducted on an MTS closed-loop servo control system. The tubes were instrumented with strain gages to determine ultimate strains and Poisson's ratio.

TEST RESULTS AND DISCUSSION

Stress-strain curves for both 0° and 90° composites were essentially linear to failure. The resulting graphs are shown in [3] and are not duplicated here.

Tabulated test results appear in the Appendix. Data gathered includes: longitudinal properties X, ε_{11}^{ult}, E_{11} (Table A1) and, X' (Table A2); transverse properties Y, ε_{22}^{ult}, E_{22} (Table A3) and Y', $-\varepsilon_{22}^{ult}$ (Table A4); Poisson's ratio ν_{21} (Table A5). Compressive moduli and ultimate strains were not determined for longitudinal samples. Compressive moduli for transverse samples were approximately equal to the transverse tensile moduli.

Data include the observed values of the various quantities and when appropriate the average values of several observations at a given v_f. Clearly scatter exists and a statistical treatment of the experimental data is in order.

In all cases a simple linear relationship was sought and data were fit to the best straight line employing the least square technique. The resulting relationships and associated standard deviations (SD) are:

$$X = 225.49v_f + 6.86;\ SD = 10.59\ (Ksi) \quad (4)$$

$$\varepsilon_{11}^{ult} = 0.97v_f + 1.62;\ SD = .24\ (\%) \quad (5)$$

$$E_{11} = 8.04v_f + 1.70;\ SD = .50\ (Msi) \quad (6)$$

$$X' = 41.81v_f + 68.86;\ SD = 7.28\ (Ksi) \quad (7)$$

$$Y = 5.64v_f + 4.13;\ SD = 0.95\ (Ksi) \quad (8)$$

$$\varepsilon_{22}^{ult} = -1.12v_f + 1.09;\ SD = .08\ (\%) \quad (9)$$

$$E_{22} = 6.09v_f - 1.44;\ SD = 0.26\ (Msi) \quad (10)$$

$$Y' = 15.74v_f + 13.71;\ SD = 1.64\ (Ksi) \quad (11)$$

These relationships are depicted graphically in Figure 1-8. The solid lines and shaded region represent the appropriate linear dependency upon volume fraction plus and minus one standard deviation. The open circles indicate a single experimental observation and an open circle with a scatter band represents the actual experimental scatter about the average value. In the case of ultimate longitudinal strain ε_{11}^{ult} (Fig. 2) an attempt was made to fit the best horizontal line i.e. ε_{11}^{ult} = const. however such a fit resulted in a standard deviation which exceeded the standard derivation of a linear relationship.

If one considers the longitudinal data (Figs. 1-3) the product of the ultimate strain and modulus for a given v_f accurately predict the ultimate tensile strength at that v_f i.e.

$$X\Big|_{v_f} = (\varepsilon_{11}^{ult}\ \varepsilon_{11})\Big|_{v_f} \qquad (12)$$

This result is to be expected in view of the fact that behavior was nearly linear to failure.

Examination of the transverse tensile data (Figs. 5-7) discloses the transverse modulus E_{22} (Fig. 7) increases with v_f at a greater rate than does the transverse tensile strength Y (Fig. 5). Hence, the transverse ultimate strain ε_{22}^{ult} (Fig. 6) must decrease with increasing v_f if for any given v_f strength and strain are to be nearly linearly related, i.e.

$$Y\Big|_{v_f} = (\varepsilon_{22}^{ult}\ E_{22})\ v_f \qquad (13)$$

A simple computation based on Eq. (8)-(10) verifies that Eq. 13 is essentially correct.

A point worth noting is that the transverse strength data Y (Fig. 5) and Y' (Fig. 8) include several test results from tubular samples (see Appendix 1). These results agree favorably with the results of tests on tensile strip or sandwich strip samples indicating that free edge and/or size effects were accounted for within observed scatter.

RULE OF MIXTURES

Longitudinal Properties

The linear form for longitudinal strength and moduli as a function of v_f indicates that interpretation in terms of the rule of mixture is possible. Consider longitudinal tensile strength X (Eq. 4). We wish to express this equation in the form:

$$X = X_f v_f + X_m (1 - v_f) \tag{14}$$

where,

X = composite strength

X_f = strength of the fiber

X_m = strength of the matrix at composite ultimate strain

v_f = volume fraction filler.

Using Eq. (5) and say $v_f = 0.50$ we determine $\varepsilon_{11}^{ult} = 2.11\%$. We know [3] that the modulus of the matrix is $E_m = 0.44$ Msi hence it follows the $X_m = 9.24$ Ksi. Composite strength at $v_f = .50$ is determined from Eq. (4) to be $X = 119.60$ Ksi. We can then incorporate Eq. (14) and back calculate X_f. The result is $X_f = 230$ Ksi and the rule of mixtures Eq. (14) can be written:

$$X = 230 v_f + 9.24(1 - v_f) \text{ Ksi} \tag{15}$$

X_f based upon the above calculation is a little lower than the value one would anticipate for virgin E-glass fibers; however, it may be representative of the strength of a typical fiber after filament winding.

A similar calculation for longitudinal compressive strength results in

$$X' = 170.3 v_f + 9.24 (1 - v_f) \text{ Ksi} \tag{16}$$

Of course, this computation assumes the tensile and compressive moduli and ultimate strains are equal, a fact not verified.

Rule of mixtures interpretation of the linear longitudinal modulus vs. v_f (Eq. 6) results in

$$E_{11} = 11.1 v_f + .44 (1 - v_f) \text{ (Msi)} \tag{17}$$

The back calculated $E_{11}^{f} = 11.1$ (Msi) agrees favorably with commonly accepted values of modulus for E-glass.

Poisson's Ratio

Poisson's ratio ν_{12} can also be closely approximated by a rule of mixture formulation [5]. The appropriate relationship is:

$$\nu_{12} = \nu_f v_f + \nu_m (1 - v_f) \qquad (18)$$

where

ν_f = Poisson's ratio of the fiber

ν_m = Poisson's ratio of the matrix

v_f = volume fraction fiber

Using the values of $\nu_f = .25$ and $\nu_m = .35$ reported in [6] the rule of mixture prediction for ν_{12} was calculated and is presented in Fig. 9. This figure also depicts the experimentally determined values ν_{21}. These values of ν_{21} were used along with knowledge of E_{22} to calculate $S_{12} = S_{21}$ (compliance coef.). The corresponding value of ν_{12} was then calculated from knowledge of E_{11} and the relationship $-\nu_{12} = S_{12}E_{11}$. Clearly a great deal of scatter exists but the rule of mixtures prediction appears to apply to the range $58\% \leq v_f \leq 75\%$

CONCLUSIONS

Longitudinal and transverse tensile strength, ultimate strain, and moduli data can be well correlated by linear relationships over a volume fraction range 30-70 percent. Longitudinal and transverse compressive strength data are also linearly related to v_f in this range. In particular 'rule of mixtures' models for longitudinal strength, and modulus are appropriate. Knowledge of $X(v_f)$, $X'(v_f)$, $Y(v_f)$, and $Y'(v_f)$ allows strength tensor components F_1, F_{11}, F_2, F_{22} to be determined as a function of v_f. Reported values of ultimate strains and Poisson's ratio would allow computation of the maximum strain failure criterion predictions as a function of v_f. Data available limit this prediction to $58\% \leq v_f \leq 75\%$ and to quadrants one and four of either principal strain or stress space.

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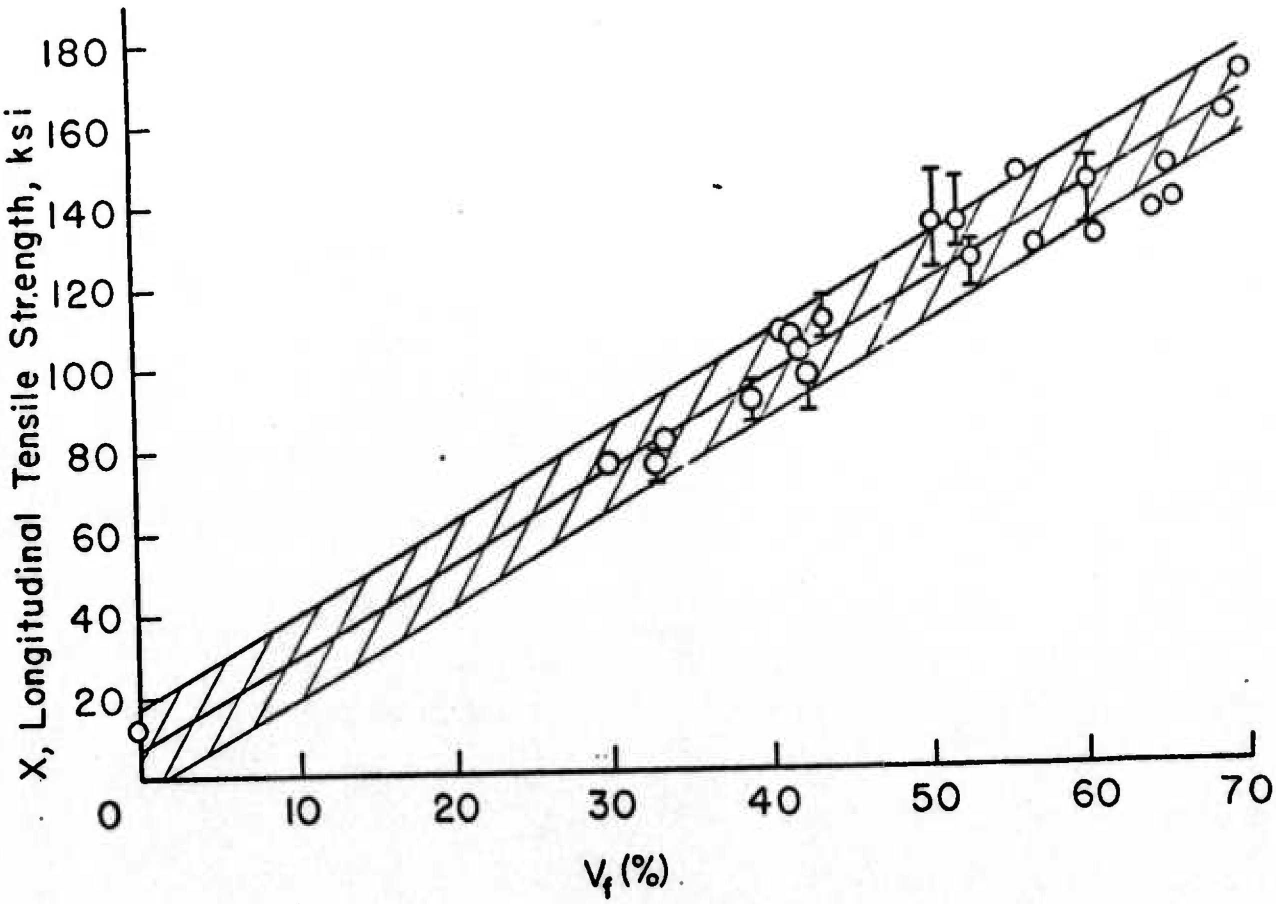

Fig. 1. Longitudinal Tensile Strength vs v_f

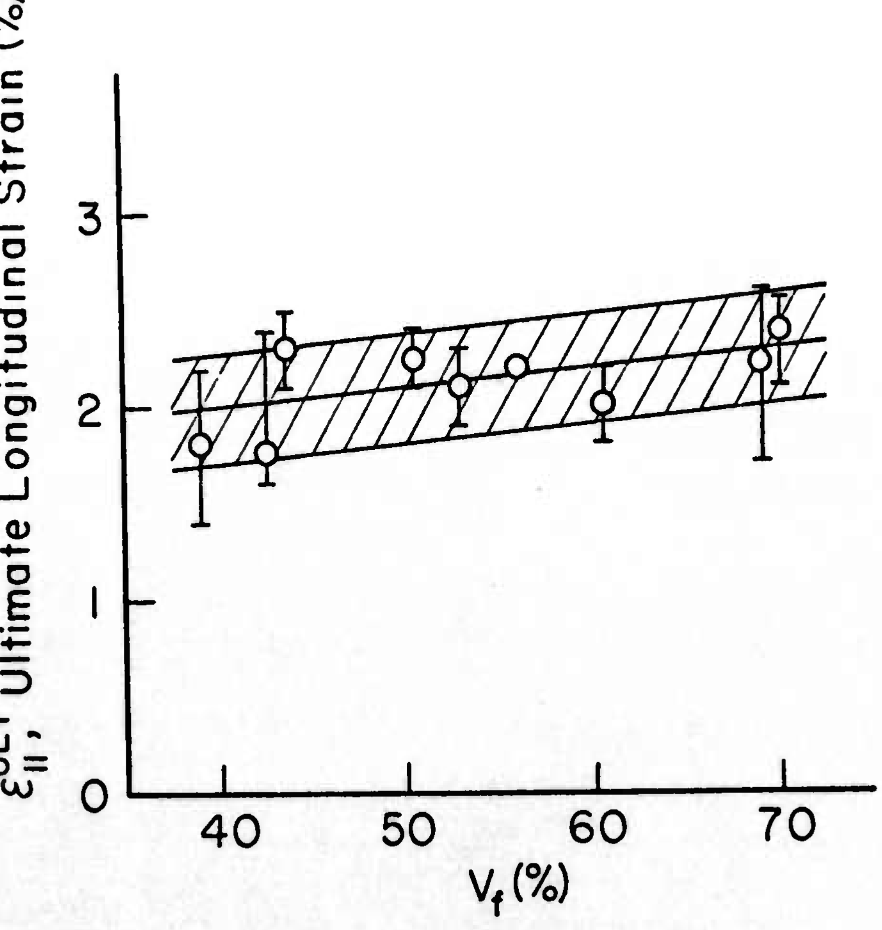

Fig. 2. Ultimate Longitudinal Strain vs v_f

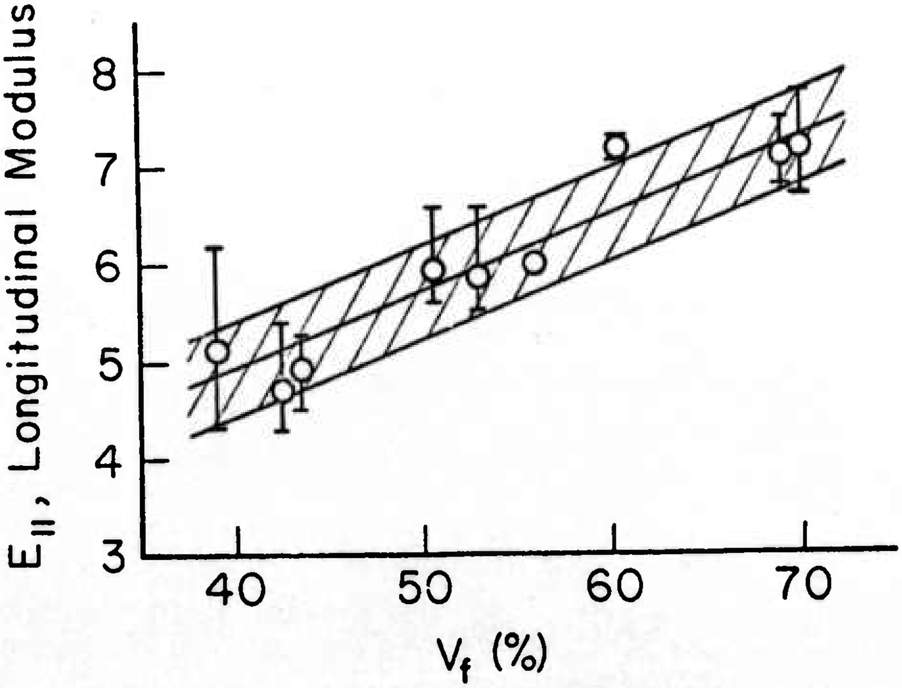

Fig. 3. Longitudinal Modulus vs v_f

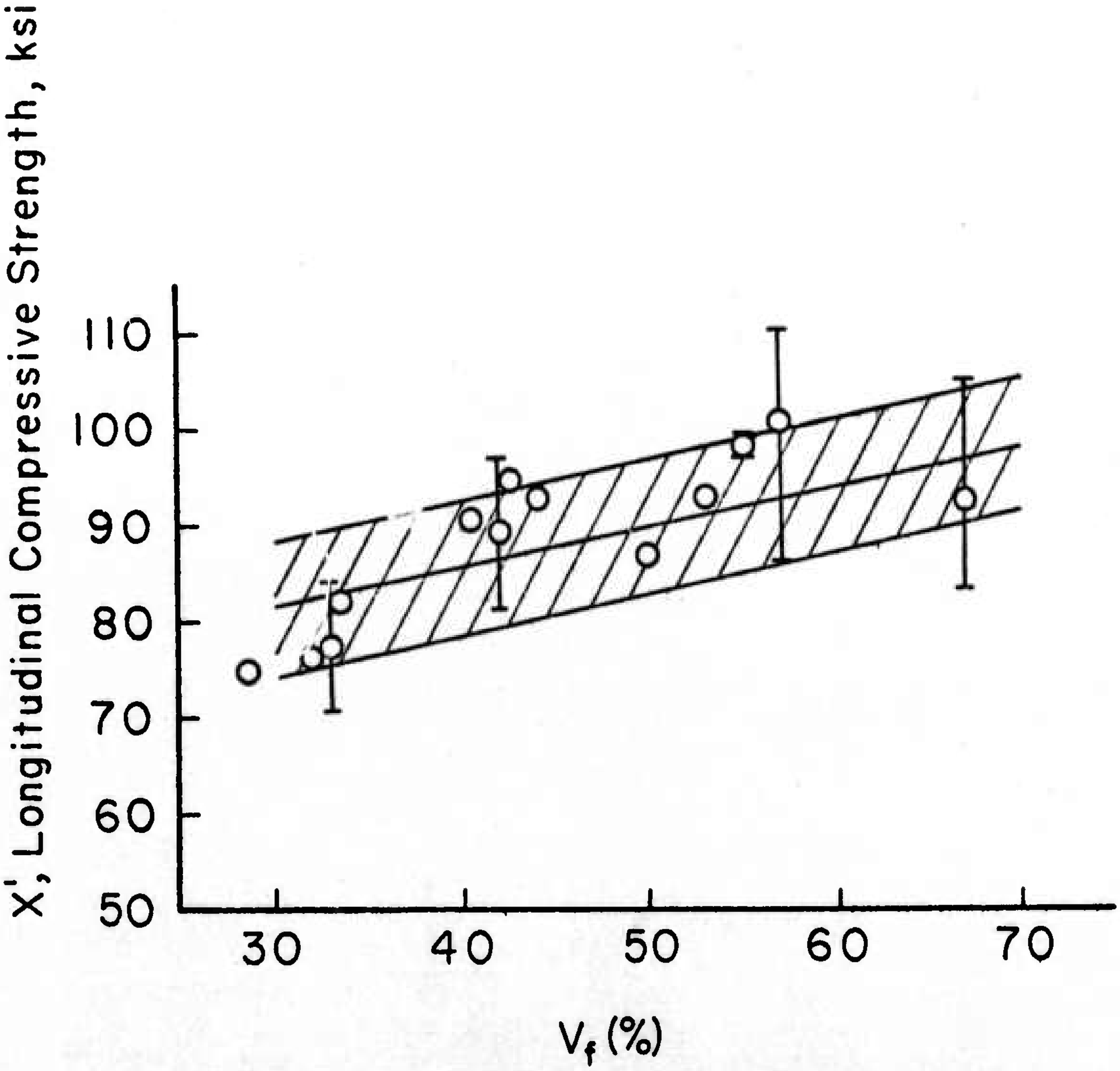

Fig. 4. Longitudinal Compressive Strength vs v_f

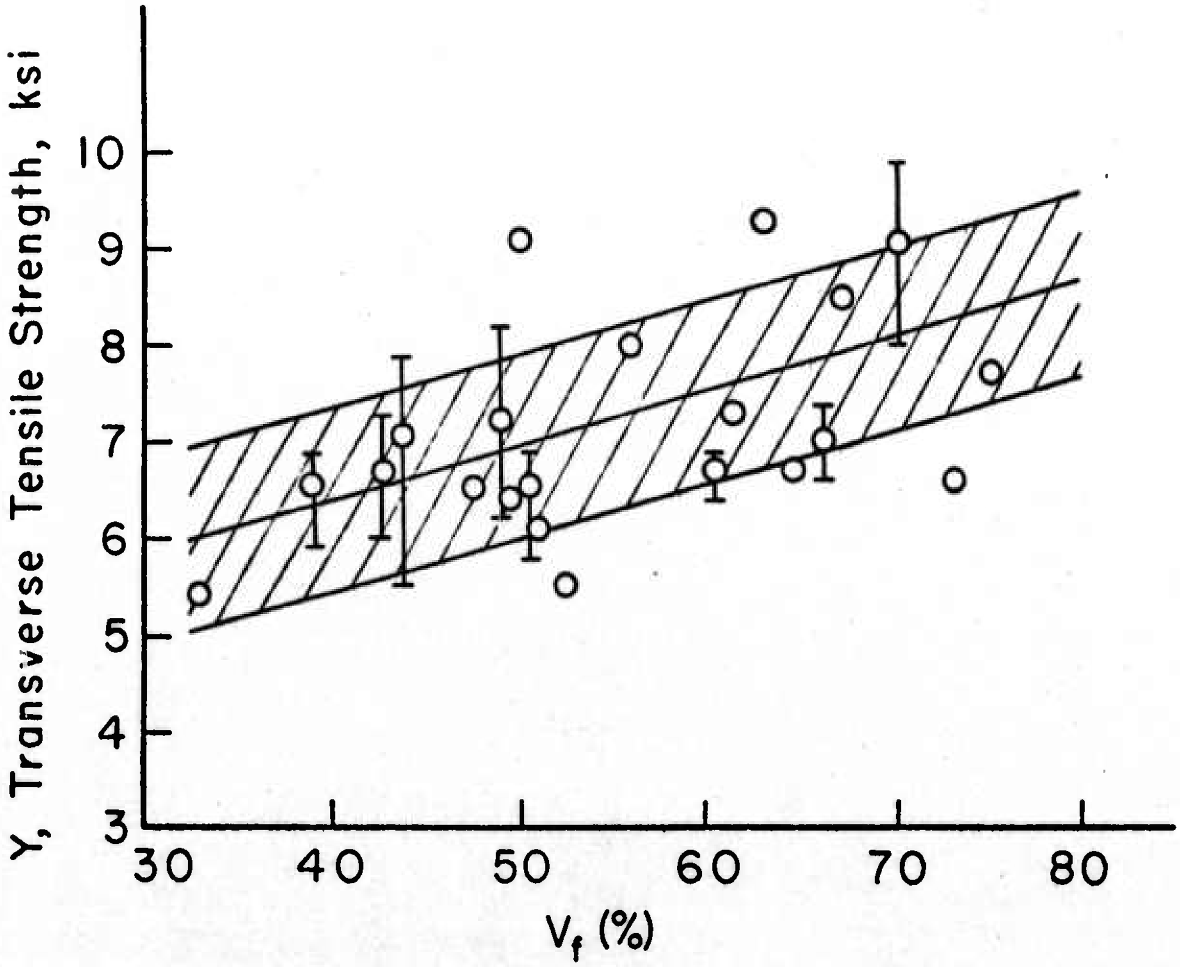

Fig. 5. Transverse Tensile Strength vs v_f

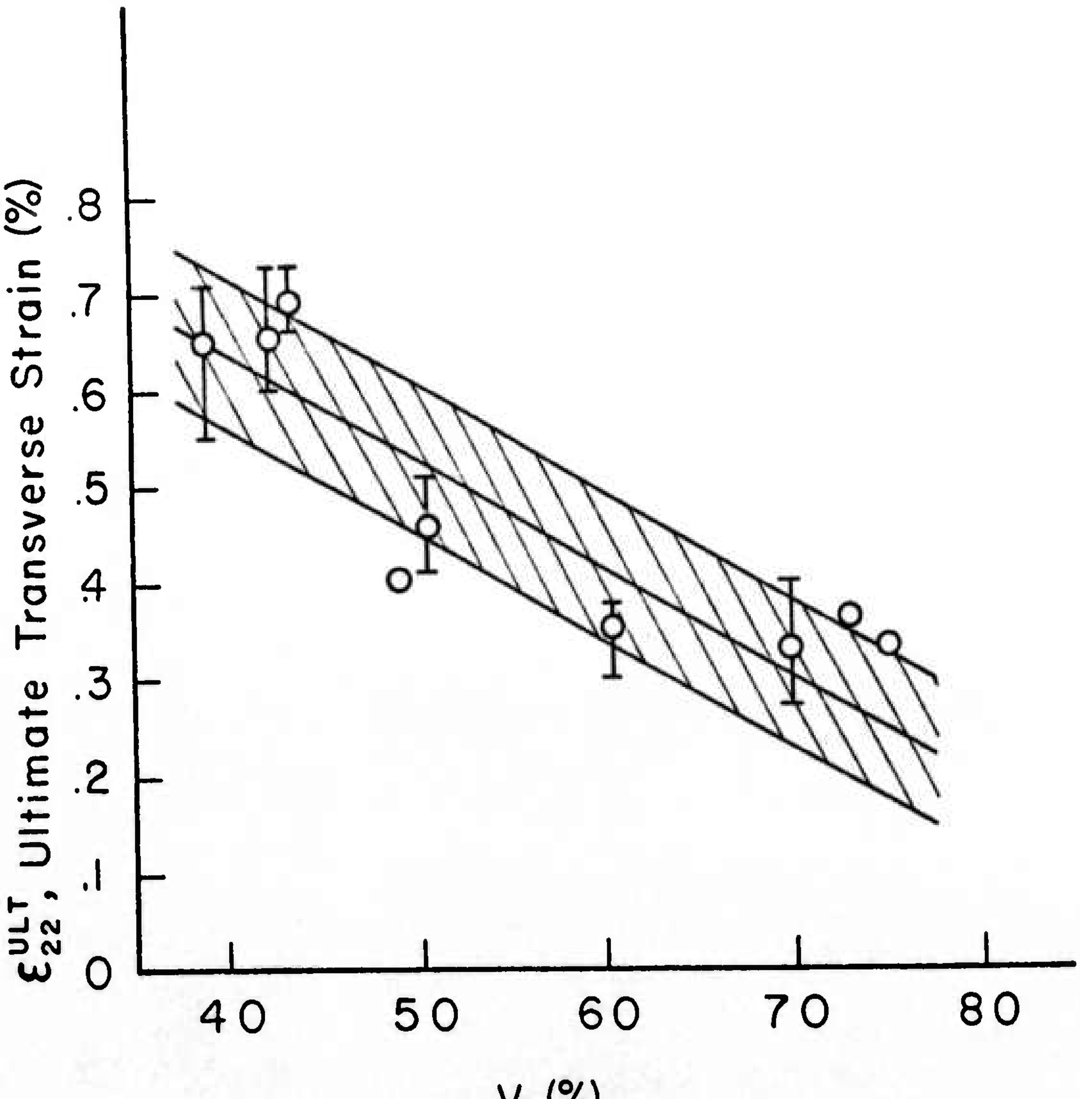

Fig. 6. Ultimate Transverse Strain vs v_f

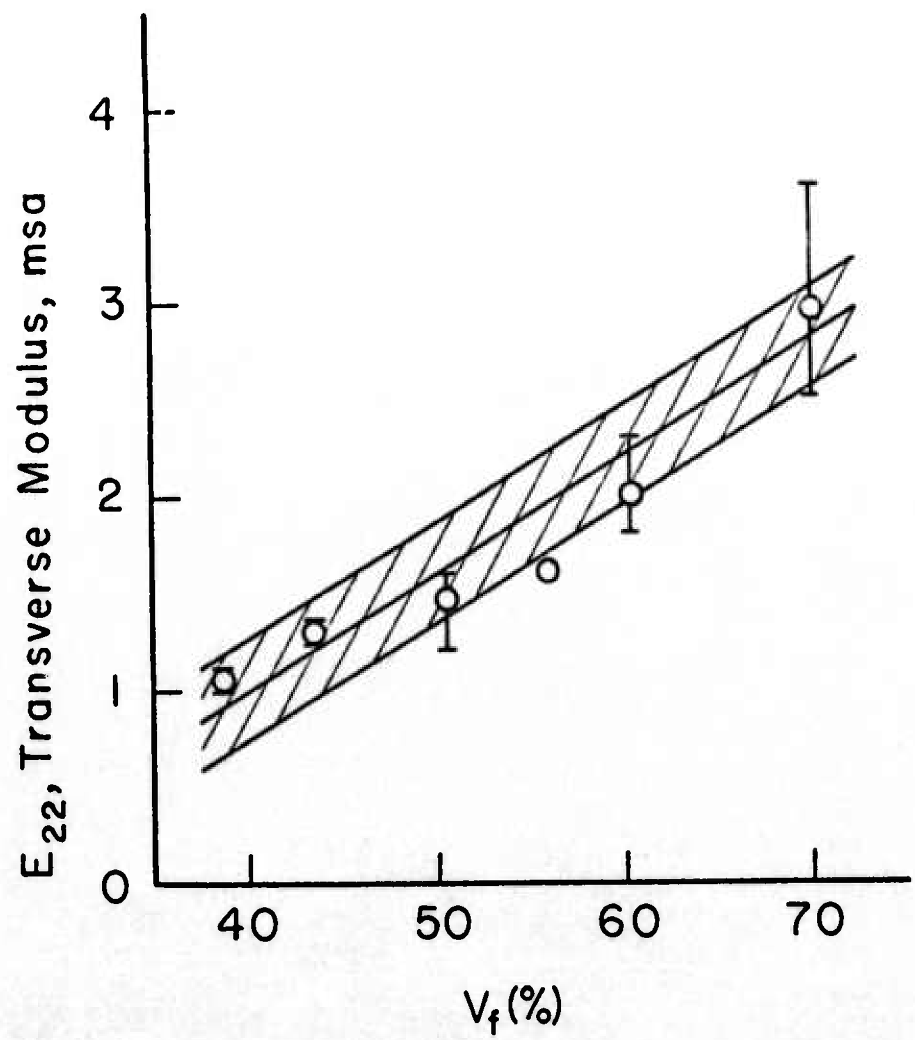

Fig. 7. Transverse Modulus vs v_f

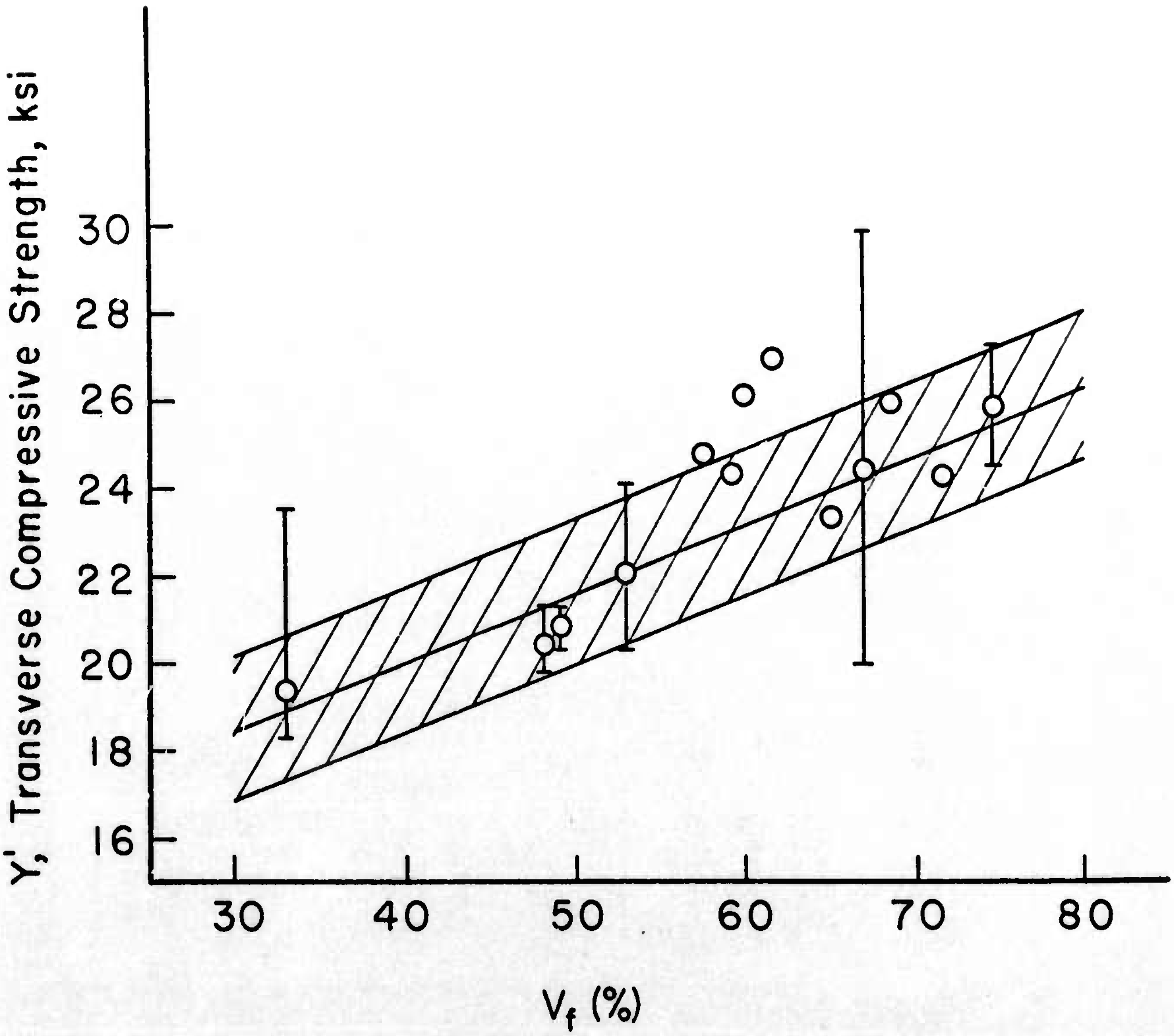

Fig. 8. Transverse Compressive Strength vs v_f

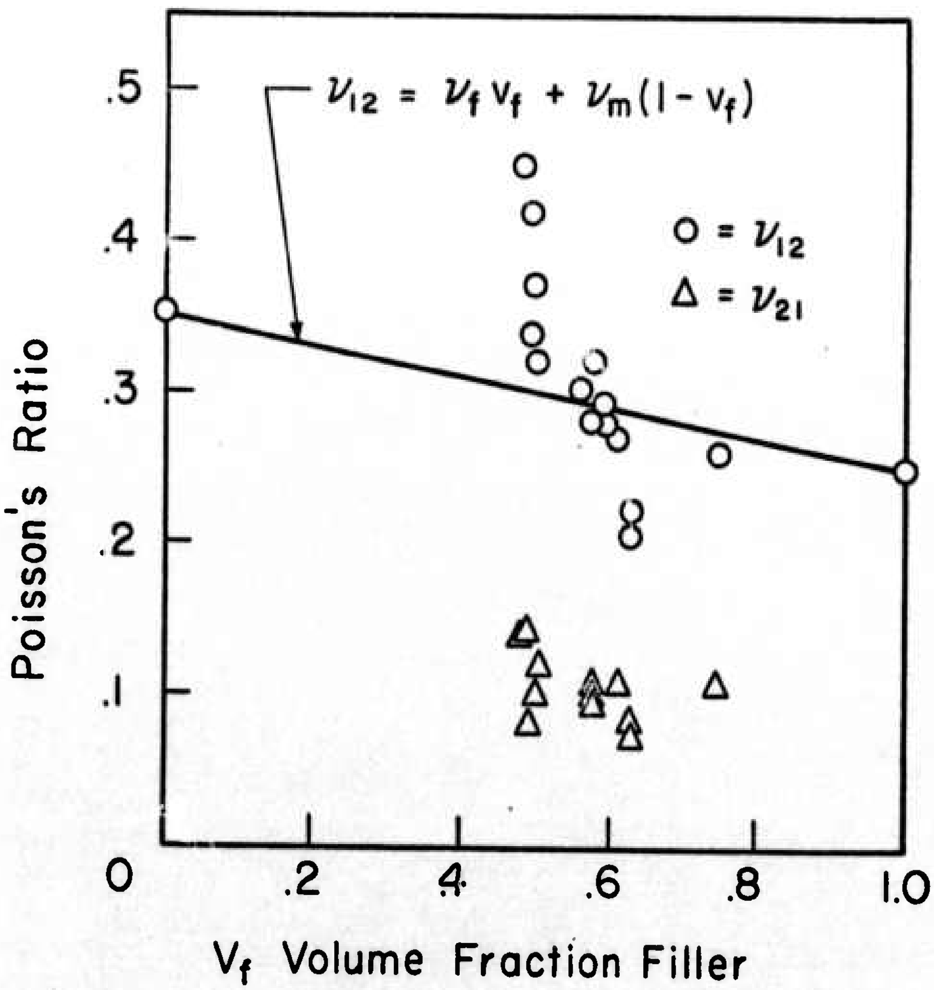

Fig. 9. Poisson's Ratio vs v_f

APPENDIX - EXPERIMENTAL DATA

TABLE A1 - LONGITUDINAL TENSILE DATA

V_f(%)	X (ksi)	E_{11}(Msi)	ε_{11}^{ult}(%)
0	12 *		
30	75.2	-	-
	70.7	-	-
33	75.25	-	-
	79.8	-	-
33.5	80.7	-	-
	85.6	-	-
	94.6	4.3	2.2
	87.1	5.8	1.5
	85.8	4.8	1.8
39	90.53	5.11	1.8
	95.1	5.0	1.9
	87.9	6.2	1.4
	89.2	4.6	1.9
	93.9	4.9	1.9
	95.6	5.3	1.8
	106.2	-	-
41	106.55	-	-
	106.9	-	-
41.5	106.6	-	-
42	102.2	-	-
	94.2	-	-
	96.8	-	-
	96.2	4.6	2.1
42.5	96.1	4.7	1.76
	91.5	4.7	1.9
	95.3	4.9	1.9
	87.3	5.4	1.6
	105.0	4.9	2.2
	93.9	4.7	2.0
	103.2	4.3	2.4
	98.1	-	-

V_f(%)	X (ksi)	E_{11}(Msi)	ε_{11}^{ult}(%)
	107.8	4.7	2.3
	107.9	4.5	2.5
	110.2	5.3	2.1
	111.1	4.6	2.4
43.5	109.7	4.9	2.3
	112.8	5.2	2.2
	105.3	5.1	2.1
	116.0	4.9	2.4
	106.4	-	-
	129.2	5.6	2.3
	122.4	5.8	2.1
	131.6	6.1	2.2
	127.3	5.5	2.3
50.5	133.3	5.42	2.25
	141.0	5.42	2.25
	134.6	6.1	2.2
	134.4	5.6	2.4
	146.1	6.6	2.2
	144.6	-	-
	129.6	-	-
52	133.1	-	-
	130.9	-	-
	127.3	-	-
	118.4	5.8	2.0
	125.9	6.6	1.9
53	124.3	5.85	2.1
	129.0	5.6	2.3
	117.6	5.5	2.1
	129.2	5.5	2.3
	125.8	6.1	2.1
56	145 *	6.0	2.2
57	127.2	-	-

* Data from Ref. [3]

Underlined value corresponds to average

TABLE A1 - Continued

V_f(%)	X(ksi)	E_{11}(Msi)	ε_{11}^{ult}(%)
	149.3	7.3	2.1
	147.6	7.2	2.0
	143.8	6.6	2.2
60.5	143.1	7.18	2.0
	145.2	7.1	2.1
	140.9	7.7	1.8
	131.8	7.2	1.8
61	129.5	-	-
64.5	135.6	-	-
65.5	140.6	-	-
66	127.9	-	-
	123.3	7.2	1.7
	165.5	7.4	2.2
	171.7	6.6	2.6
	-	6.8	-
69	159.5	7.1	2.2
	167.3	7.2	2.3
	169.6	7.5	2.3
	153.2	6.7	2.3
	183.0	7.8	2.4
	183.2	6.9	2.6
70	169.2	7.1	2.38
	177.6	7.4	2.4
	172.8	6.7	2.6
	157.1	6.7	2.3
	157.6	7.6	2.1

Underlined value corresponds to average

TABLE A2 - LONGITUDINAL COMPRESSIVE DATA

V_f(%)	X'(ksi)	V_f(%)	X'(ksi)
28.5	74.9		95.9
32	76.3		97.1
	81.5	42	84.1
	80.5		84.8
	70.6		86.4
	75.0		89.3
	84.2	42.5	94.7
33	77.1	44	92.6
	82.0	50	86.7
	76.2	53	92.7
	75.5		97.6
	73.7		98.2
	72.3	55	98.2
33.5	82.1		98.8
40.5	90.6		110.2
	85.8		101.2
	91.7	57	100.3
	94.8		103.9
	98.4'		86.0
	84.3		84.3
	88.7		84.5
	89.6		84.9
42	89.0		96.4
	92.5		102.3
	81.1		84.1
	83.2	67	92.1
	81.1		86.9
	87.6		83.5
	90.7		83.1
	88.6		105.3
	89.7		102.3
	88.9		100.2
	92.3		100.2

TABLE A3 - TRANSVERSE TENSILE DATA

V_f(%)	Y(ksi)	E_{22}(Msi)	ϵ_{22}(%)
	5.4	-	-
33	5.4	-	-
	6.9	1.0	.71
	5.9	1.1	.55
	6.6	-	-
39	6.56	1.05	.65
	6.5	1.0	.66
	6.9	1.1	.69
	7.2	-	.73
	6.8	-	.67
	6.1	-	.60
42.5	6.68	-	.654
	7.3		.67
	6.0		.60
	5.5	1.3	.64
43.5	7.04	1.28	.69
	8.9	1.3	.68
	6.0	1.3	-
	7.9	1.3	.73
	7.9	1.2	.70
47.5 **	6.5	-	-
	6.2	-	.4
49 **	7.2		
	8.2	-	-
49.5	6.4	-	-
50 **	9.1		
	6.2	-	.41
	6.8	1.5	.48
50.5	6.55	1.46	.458
	5.8	1.2	.44
	6.8	1.4	.51

V_f(%)	Y(ksi)	E_{22}(Msi)	ϵ_{22}(%)
50.5	6.9	1.6	.45
	6.8	1.6	.46
51	6.1		
52.5	5.5		
56 *	8.0	1.6	.45
	6.8	1.8	.38
	6.9	1.9	.37
60.5	6.7	2.0	.35
	6.4	2.3	.30
61.5 **	7.3	-	.30
63	9.3	-	-
64.5	6.7	-	-
	6.6	-	-
66	7.0	-	-
	7.4	-	-
67	8.5	-	-
	8.7	2.8	.34
	9.4	3.1	.32
	8.9	3.6	.27
	8.0	2.9	.28
70	9.03	2.95	.331
	9.3	2.5	.38
	9.9	2.8	.40
73 **	6.6	-	.36
75 **	7.7	-	.33

** Data from tubular sample

* Data reported in Ref. [3]

DATA A4 - TRANSVERSE COMPRESSIVE DATA

V_f(%)	Y'(ksi)
	19.7
	19.7
	19.6
	18.3
33	19.4
	19.5
	19.6
	21.3
	19.9
	20.4
	20.7
48	20.4
	19.8
	19.8
	20.7
	20.5
	21.3
49	20.8
	20.3
	22.1
	22.6
	24.0
	24.1
53	22.0
	21.0
	20.3
	20.9
	21.1

V_f(%)	Y'(ksi)	$-\varepsilon_{22}^{ult}$(%)
57.5	24.7	3.14
58.5 **	24.1	3.20
60 **	26.1	3.12
61.5 **	26.9	2.74
65 **	23.3	1.41
	20.8	
	20.0	
67	24.4	-
	26.6	
	24.9	
68.5 **	25.9	2.6
71.5 **	24.2	-
	27.3	1.37
74.5 **	25.9	
	24.5	1.22

** Data from tubular sample

TABLE A5 - POISSON'S RATIO

V_f (%)	ν_{21}
48	.133
49	.148
	.081
50	.120
	.103
58	.112
	.098
59	.106
	.109
61	.112
63	.077
	.068
75	.117