Strain Rate and Temperature Effects on Tensile Properties and Their Representation in Deformation Modeling of Vinyl Ester Polymer

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This paper discusses the effects of strain rate and temperature on tensile properties and stress-strain behavior of vinyl ester polymer. Tensile strength and modulus were found to increase linearly with the log of strain rate, and decrease linearly with increasing temperature. Ramberg-Osgood and Menges models were used and extended to describe the strain rate and temperature dependency of the stress-strain behavior. The extended Menges model provided better representation of the observed behavior compared to the Ramberg-Osgood model for a wide range of temperatures and strain rates. Mechanical properties obtained from flexure tests are also presented and compared to tensile data.

INTRODUCTION

Thermosetting polymers are used in a wide variety of applications. Vinyl ester (VE) resins as thermoset polymers with low molecular

weight and high cross-link density are becoming increasingly important in new industrial applications. They possess the good characteristics of epoxy, such as excellent chemical resistance and tensile strength, and of unsaturated polyester, such as low viscosity and fast curing.

With the growing use of polymers in various fields, understanding their mechanical behavior is crucial to their effective application. In engineering design and analysis of polymers for structural applications, experimental data and characterization by mechanical tests, such as simple tension tests, are needed to describe their constitutive material behavior. Since polymers are sensitive to loading rate and temperature variations, such behavior and characterization should ideally incorporate strain rate and temperature effects.

For many metallic materials, a plot of true stress vs. plastic strain in log-log coordinates results in a straight line. To avoid necking influence, only data between the yield strength and ultimate tensile strength portions of the stress-strain curve are used to generate the line, represented by the following equation:

$$\sigma = K(\varepsilon_p)^n \tag{1}$$

where K is the strength coefficient (stress intercept at $\varepsilon_p = 1$) and n is the strain hardening exponent (slope of the line). The total true strain is then given by:

$$\varepsilon = \varepsilon_e + \varepsilon_p = \frac{\sigma}{E} + \left(\frac{\sigma}{K}\right)^{\frac{1}{n}} \tag{2}$$

This type of true stress-strain relationship is referred to as Ramberg-Osgood relationship. In this equation n gives a measure of the material's work-hardening behavior [1].

Similar to the Ramberg-Osgood relationship, Adams and Crane [2] employed the following equation as a convenient representation for many epoxies used in composites:

$$\sigma = \frac{E\varepsilon}{[1 + (E\varepsilon/\sigma_0)^n]^{1/n}} \tag{3}$$

Here σ_0 is the asymptotic value of the stress and n is a curvature parameter. The stress-strain response of an epoxy at high temperatures and both dry and moisture-saturated environment based on this model was shown to fit well with the experimental data [3].

The stress-strain profiles can also be regarded as branches of parabola. The analytical equation in Cartesian coordinates is given by

$$y = a_1 x - a_2 x^2 \tag{4}$$

This relationship signifies a non-linear relationship between stress and strain which can be described by

$$\sigma = E\varepsilon - D\varepsilon^2 = \varepsilon(E - D\varepsilon) \tag{5}$$

Since tests are carried out at constant strain rates ($\dot{\varepsilon}$), for small deformations, Eq. 5 can be written as

$$\sigma = E\dot{\varepsilon}t - D\dot{\varepsilon}^2t^2 \tag{6}$$

where the factor E corresponds to a strain rate dependent modulus of elasticity and D represents a measure of non-linearity of the material behavior (a damping effect) [4].

Schmachtenberg and Menges [5] showed that the stress-strain behavior of amorphous thermoplastics can be approximated by the following equation, similar to Eq. 5:

$$\sigma = E_0\varepsilon(1 - D_1\varepsilon) \tag{7}$$

where coefficients E_0 (original modulus) and D_1 (damping coefficient) are functions of strain rate. This function gave good representation of experimental results on PS, PVC, and PC resins for strain up to 4% at temperatures below T_g. For semi-crystalline materials which were tested in the temperature range between T_g and melting temperature, there are more bends in the stress-strain curves. The following description function was proposed for stress-strain behavior at temperatures above T_g [5]:

$$\sigma = \frac{E_0\varepsilon}{1 + D_2\varepsilon} \tag{8}$$

For applications where temperature and strain rate may be constant, a simple analytical representation of a polymer is needed. The following relationship is a combination of Eqs. 7 and 8, which is a universal description function developed for stress-strain behavior [5]:

$$\sigma = E_0\varepsilon\left(\frac{1 - D_1\varepsilon}{1 + D_2\varepsilon}\right) \tag{9}$$

where D_1 and D_2 are functions of strain rate and temperature.

Recently, Richeton et al. [6] carried out uniaxial compression tests on three commercial amorphous polymers (PC, PMMA, and PAI) under a wide range of temperatures and strain rates. They showed that both temperature and strain rate greatly influence the mechanical response of these three polymers. They also modeled the experimental

data for the compressive yield stress according to a model based on strain rate/temperature superposition principle

$$\sigma_y = \sigma_i(0) - mT + \frac{2kT}{V} \sinh^{-1}\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0 \exp\left(-\frac{\Delta H_\beta}{kT}\right)}\right)^{1/n} \qquad (10)$$

where $\sigma_i(0)$ is the athermal internal yield stress, m is a material parameter, T is the absolute temperature, k is the Boltzmann constant, V is the activation volume, $\dot{\varepsilon}_0$ is a constant pre-exponential strain rate, and ΔH_β is the activation energy. This model for the description of the yield stress was found to be capable of depicting the experimental results for a wide range of temperatures and strain rates. The model was also extended through the glass transition temperature.

In this study, tensile deformation behavior of vinyl ester polymer for a wide range of strain rates and temperatures was investigated. Relatively simple models were developed for describing the strain rate and temperature dependency of the stress-strain behavior. In this article, first the experimental program and results are presented. This is followed by development of Ramberg-Osgood and Menges models by incorporation of both strain rate and temperature effects. The models are then applied and compared to the experimental results obtained in this study. Results from flexural tests and moisture absorption tests are also presented and discussed.

EXPERIMENTAL

Materials

The resin used in this study was Hetron® 942/35 with molecular weight of 628 g/mol supplied by Ashland Chemical Company which is a vinyl ester material diluted with approximately 35 wt% styrene. By dilution with styrene, the material used for making test specimens had a formulation of 55 wt% vinyl ester and 45 wt% styrene with a measured density of 1.04 g/cm³. This formulation is common in industrial application of this material. The following additives were added based on the total weight of the vinyl ester-styrene material: 0.02 wt% N-Dimethylaniline (promoter), 0.2 wt% Cobalt Naphthoate (promoter), and 1.25 wt% Methyl Ethyl Ketone Peroxide (initiator), All supplied by Ashland Chemical Company.

Specimen and Test Equipment

Mechanical test samples were cut out by milling from the vinyl ester plaques. Note that the specimen thickness was the same as the
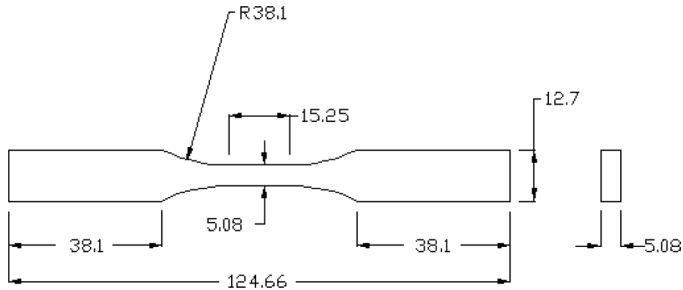
FIGURE 1 Specimen configuration for tensile tests (dimensions are in mm).

thickness of the plaques, therefore milling was only used to cut out the specimen shape, but not change the thickness. Tensile test samples were machined and finished to desired specifications based on ASTM Standard D 638–89 [7]. Specimen configuration used for tensile tests is shown in Figure 1. A closed-loop servo-hydraulic axial load frame in conjunction with a digital servo-controller was used to conduct the tests. The hydraulic gripping system was of the wedge action type suitable for flat specimens. Repeatability of the grips ensured the alignment of the test specimen in the direction of strain without any bending.

Total strain was measured for all tests using an extensometer rated as ASTM class B2. The extensometer had a gage length of 12.7 mm and was capable of measuring strains up to 15%. In order to protect the specimen's surface from the knife edges of the extensometer, three layers of tape were used to cushion the attachment.

Tensile tests were conducted based on ASTM Standard D 638–89 [7] at different temperatures, humidity, and strain rates. Tensile tests at cold temperatures ($-35°C$ and $-10°C$), room temperature (RT) ($23°C$), and high temperatures (50, 75, and $100°C$) lower than the T_g of about $127°C$ for vinyl ester polymer were performed inside an environmental chamber. Temperatures were controlled using a precision thermocouple attached to the center of the specimens. In order to minimize temperature effects upon extensometer and load cell calibrations, fluctuations were maintained within $\pm 2°C$. Addition of extension rods to the load train allowed for the positioning of the grips inside the environmental chamber and protection of the load cell from temperature changes. For lowering the temperatures below room temperature, liquid nitrogen was used.

Tests were conducted at low (0.0001/s) to high (1/s) strain rates. For the experiments performed at high strain rates of 0.1/s and 1/s, the extensometer could not be used and the test was conducted in displacement control. The strain was related to displacement by the

relationship between strain and displacement ($\varepsilon \cong 2\delta$) from other tests performed at lower strain rates.

Some tests were also performed on water-soaked specimens at RT. Based on ASTM Standard D 570–95 [8], these specimens were dried inside an oven at 50°C for 24 hours, cooled in desiccator for a few minutes, and then immersed in distilled water for one day, one week, and one month.

Flexural tests were also conducted in three-point bending, from which flexural modulus and flexural strength were obtained. The specimens used for three-point bending flexural tests were based on ASTM Standard D 790–86 [9] with a length of 101.6 mm, a width of 12.7 mm, and a thickness of 4.76 mm. The distance of the sample span between supports was about 16 times greater than the sample thickness (e.g. 76.2 mm). For these tests, the load was applied to the specimen at the specified crosshead rate of 2 mm/min. All flexure tests were conducted at room temperature and humidity.

Strain Rate, Temperature, and Moisture Effects

The average mechanical properties obtained from tensile tests are shown in Table 1. To evaluate the tensile test result repeatability, at least two tests were conducted at each strain rate and temperature. The properties determined from monotonic tensile tests are modulus of elasticity (E) or secant modulus defined at 1% strain, yield strength (S_y) measured at 0.2% strain offset, ultimate tensile strength (S_u) at the peak stress, percent elongation, strength coefficient (K), and strain hardening exponent (n). These properties are obtained from stress-strain curves shown in Figure 2.

Tensile strength and modulus are strain rate and temperature dependent. In order to find the relationship between mechanical properties with strain rate and temperature, the average tensile properties (average of the data from the duplicate test specimens broken inside the gage section) shown in Table 1 were used. Mechanical properties (E, S_y, and S_u) were found to have linear relationships with temperature and logarithmic strain rate, as shown in Figures 3 and 4. Microsoft Excel was used to calculate the best fit line by using least squares method. The following equations represent the best fits for these properties:

$$E = 0.17 \log(\dot{\varepsilon}) - 0.013\,T + 4.13 \quad (R^2 = 0.953) \tag{11}$$

$$S_y = 2.59 \log(\dot{\varepsilon}) - 0.343\,T + 77.2 \quad (R^2 = 0.957) \tag{12}$$

TABLE 1 Tensile Properties Obtained by Averaging Data from Duplicate Tests at Each Temperature and Strain Rate for Vinyl Ester Specimens

Strain rate (1/s)	T (°C)	S_u (MPa)	S_y (MPa)	E (GPa)	Elongation (%)	K (MPa)	n	D_1 (GPa)	D_2 (MPa)
0.0001	−35	120.0	80.0	4.08	4.12	345.7	0.221	4.45	36825
0.0001	−10	101.3	70.0	3.57	3.82	345.6	0.244	3.86	31159
0.0001	23	84.0	58.2	3.36	11.5	172.8	0.167	3.72	41698
0.0001	50	66.8	49.3	2.65	9.69	123.7	0.135	3.08	35742
0.0001	100	30.2	26.4	2.09	29.0	51.4	0.108	2.50	52366
0.001	−35	114.3	84.2	4.23	3.50	405.1	0.241	4.56	35820
0.001	−10	107.8	72.4	3.58	3.95	304.7	0.201	3.99	31476
0.001	23	93.0	63.4	3.37	7.71	185.5	0.158	3.80	38777
0.001	50	76.9	54.7	3.10	10.1	154.7	0.155	3.52	40221
0.001	75	59.2	43.9	2.71	13.4	110.2	0.134	3.13	41315
0.001	100	39.9	32.5	2.32	17.8	77.7	0.135	2.70	44935
0.01	−35	76.7	80.0	4.29	1.98	516.4	0.278	4.55	31822
0.01	−10	113.7	75.3	3.73	4.47	389.9	0.240	4.06	30366
0.01	23	82.6	66.1	3.23	3.16	262.7	0.210	3.48	26680
0.01	50	81.5	62.2	3.02	5.56	153.4	0.133	3.51	36604
0.01	100	48.5	40.8	2.58	12.5	98.8	0.137	2.95	41240
0.1	23	102.2	63.5	3.70	3.94	432.9	0.303	3.93	34679
1	23	101.6	62.9	3.78	3.77	479.3	0.310	4.00	33137
1	50	99.2	63.4	3.58	4.03	339.8	0.256	3.86	33881
1	100	68.9	43.3	2.97	4.84	239.0	0.258	3.25	36323

$$S_u = 5.62 \log(\dot{\varepsilon}) - 0.486\,T + 113 \quad (R^2 = 0.785) \tag{13}$$

where $\dot{\varepsilon}$ is the strain rate in (1/s) and T is temperature in (°C).

The shape of the stress-strain curves of vinyl ester illustrates the very strong rate dependent nature of this polymer. In Figure 3, it can be seen that at a constant temperature the tensile strength and modulus of elasticity increase with increasing strain rate, while elongation (ductility) of the material decreases by increasing the strain rate. At lower strain rates, there is sufficient time to plastically flow or relax the induced stress. The material thus appears as a ductile polymer. At higher rates, the material cannot plastically respond rapidly enough and so it appears as a brittle polymer. K and n values also increase by increasing the strain rate at a constant temperature. From Figure 3 it can also be seen that for a given temperature Eqs. 10 to 12 correlate well with the experimental data at different strain rates. The best correlations were obtained for modulus of elasticity and yield strength.
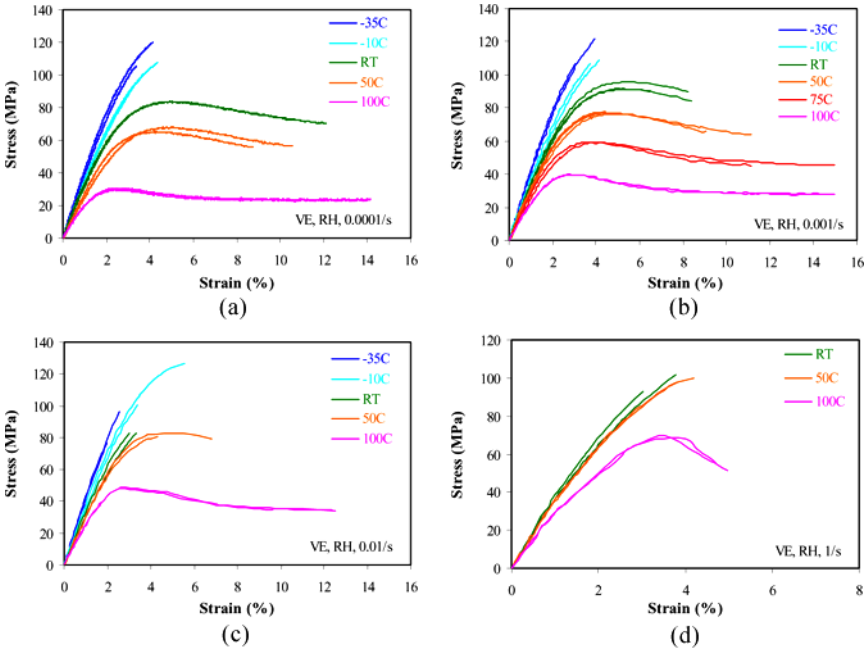
FIGURE 2 Stress-strain behavior of vinyl ester polymer at room humidity and temperatures from −35 to 100°C, and at strain rate of (a) 0.0001/s, (b) 0.001/s, (c) 0.01/s, and (d) 1/s.

The effect of temperature on stress-strain behavior of vinyl ester polymer at several constant strain rates and temperatures ranging between −35° and 100°C is shown in Figure 2. The effect of temperature on mechanical properties is shown in Figure 4. In these figures, it can be seen that the modulus and strength of this material decrease with increasing temperature because of thermal softening, while ductility increases with increasing temperature. K and n values also increase by decreasing the temperature at a constant strain rate.

Increasing the temperature of the polymer increases its molecular mobility and reduces the van der Waals forces that hold the molecules together. This increase in intermolecular mobility results in greater polymer ductility and reduced ultimate stress. As testing temperature approaches T_g (about 127°C), vinyl ester exhibits increasing rubber-like characteristics. This polymer becomes very brittle below room temperature, because the free volume between the molecules in this polymer is reduced by restricting or slowing down their movement.
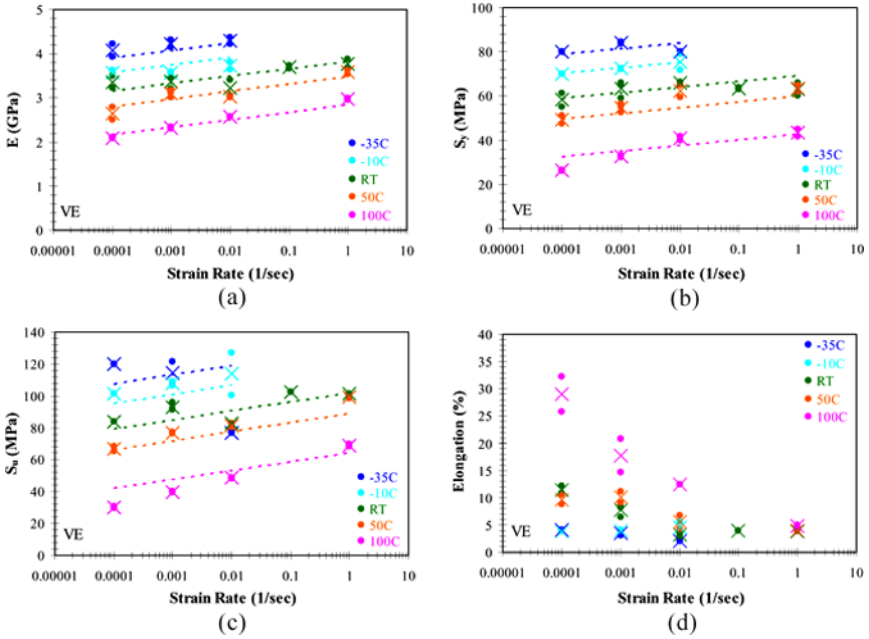
FIGURE 3 Relationship between logarithmic strain rate and (a) modulus of elasticity, (b) yield strength, (c) ultimate tensile strength, and (d) elongation, and comparison between experimental results and fits shown with dotted lines based on (a) Eq. 11, (b) Eq. 12, and (c) Eq. 13 for vinyl ester polymer (× indicates the average data shown in Table 1).

The increase in weight of vinyl ester specimens was 0.02 g or 0.27% after one day and one week exposure and 0.06 g or 0.8% after one month exposure to distilled water. The effect of humidity on mechanical properties of vinyl ester polymer is shown in Table 2. This Table shows that humidity absorption decreases the mechanical properties, especially the strength of vinyl ester polymer.

Flexural properties of this material are shown in Table 3. According to ASTM Standard D 790–86 [9] for flexural properties, σ is calculated from the elastic bending equation $\sigma = 3PL/2bd^2$ and ε from $\varepsilon = 6Dd/L^2$, where P is load at a given point, D is deflection, L is the span, d is specimen thickness, and b is specimen width. Young's modulus was taken as secant modulus at 1% strain based on the ASTM standard. Flexural strength was obtained from the maximum stress in flexural stress-strain curve.

The average flexural strength, flexural secant modulus at 1% strain, and maximum strain at break are shown in Table 3. Using
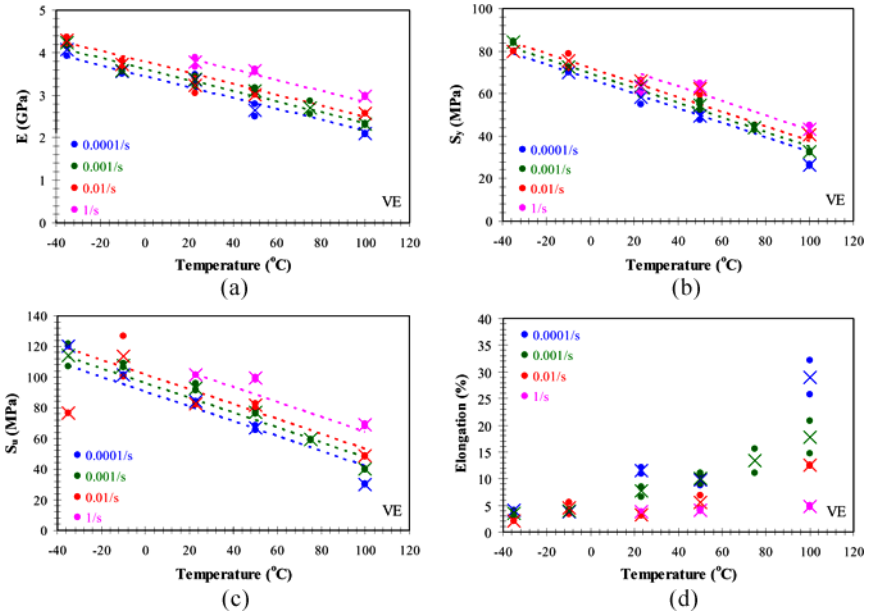
FIGURE 4 Relationship between temperature and (a) modulus of elasticity, (b) yield strength, (c) ultimate tensile strength, and (d) elongation, and comparison between experimental results and fits shown with dotted lines based on (a) Eq. 11, (b) Eq. 12, and (c) Eq. 13 for vinyl ester polymer ($\times$ indicates the average data shown in Table 1).

$\dot{\varepsilon} = 6\dot{D}d/L^2$ and displacement rate of $\dot{D} = 2\,\text{mm/min}$, the corresponding strain rate of about 0.0001/s was obtained. At this strain rate, the average tensile strength, tensile modulus of elasticity at 1% strain, and tensile elongation are calculated as 84 MPa, 3.36 GPa, and 11.5%, respectively. For flexure tests the corresponding values are 150.1 MPa, 3.54 GPa, and 6.60%, as shown in Table 3. Therefore,

TABLE 2 Effect of Humidity on Tensile Properties Obtained at Strain Rate of 0.001/s and Room Temparature for Vinyl Ester Specimens

Soak time (hrs)	S_u (MPa)	S_y (MPa)	E (at 1% ε) (GPa)	Elongation (%)	K (MPa)	n
24	90.1	63.3	3.08	5.22	173.2	0.145
168	86.9	59.3	3.25	6.87	170.9	0.153
720	81.2	56.2	2.93	6.84	161.2	0.156

TABLE 3 Mechanical Properties Obtained from Flexural Tests for Vinyl Ester Polymer at Room Temperature and Humidity and at Crosshead Displacement Rate of 2 mm/min

Flex. strength (MPa)	Flex. modulus (at 1% ε) (GPa)	Max. strain at break (%)
147.4	3.42	6.95
150.4	3.55	7.17
152.5	3.65	5.69
150.1 (average)	3.54 (average)	6.60 (average)

even though the flexural and tensile modulus values are similar, flexural and tensile strength as well as ductility values are quite different. A study of tensile and flexural behaviors conducted by Xu et al. [10] on thermoset epoxy at room temperature found a similar difference between tensile strength measures as 62 MPa and flexure strength calculated as 109 MPa.

In flexural tests there are stress and strain gradients as opposed to tensile tests where the stresses and strains are uniform. Flexural strengths tend to be greater than tensile strengths. This is largely a result of the nonlinearity of the stress-strain curve after yielding, resulting in nonlinear variation of the stress across the specimen cross section. Flexural strengths are generally somewhat in error because the commonly used flexure bending equations used to calculate them assume linear elastic behavior.

REPRESENTATION OF STRESS-STRAIN BEHAVIOR

There are several models to describe the mechanical behavior of vinyl ester polymer up to the maximum tensile strength of the material. In this study, mathematical representations of the observed behavior for vinyl ester thermoset polymer were developed based on Ramberg-Osgood (see Eq. 2) and Menges (see Eq. 7) models. These models have mostly been used for thermoplastic polymers, are relatively simple, and were found to better represent vinyl ester deformation behavior, as compared to other models (see Eq. 3, 8, and 9). Note that the stress-strain functions presented in Eq. 8 and 9 are applicable to material's behavior at temperatures higher than T_g, and therefore were not used in this work. Also, the strain rate/temperature superposition model represented by Eq. 10 was not applied to the vinyl ester data in this work because of the lack of information necessary for application to this material.

Ramberg-Osgood Model

The Ramberg-Osgood (R-O) model given by Eq. 2 was used to represent the stress-strain behavior of vinyl ester up to ultimate tensile strength. In Eq. 2, constants K and n were obtained from Eq. 1 using experimental data from each stress-strain curve for a given strain rate.

From Figure 5 it is observed that there are good correlations between K and S_y and between n and E by fitting exponential curves to the data. These correlations were obtained without considering the data at the highest strain rates of 0.1/s and 1/s. Since an extensometer could not be used at those high rates for measuring strain rates, it could cause error in calculation of K and n for these highest strain rate tests.
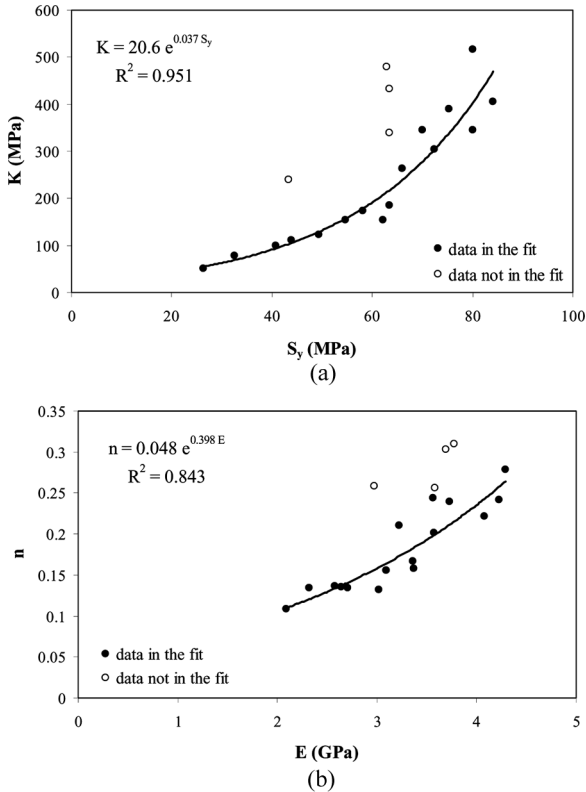
FIGURE 5 Correlation between (a) K and S_y and (b) n and E for vinyl ester polymer (• relates to the data at strain rates ≤ 0.01/s used in the fit and ○ relates to the data at strain rates ≥ 0.1/s not used in the fit).

The following equations were obtained from Figure 5 based on the Ramberg-Osgood model:

$$K = 20.6 \, e^{(0.037 S_y)} \qquad (R^2 = 0.951) \tag{14}$$

$$n = 0.048 \, e^{(0.398 E)} \quad (R^2 = 0.843) \tag{15}$$

In these equations, E and S_y could be substituted by Eqs. 11 and 12, respectively. Therefore, K and n could be related to the strain rate and temperature of testing.

Using Eqs. 2, 11, 12, 14, and 15, the stress-strain behavior of vinyl ester polymer at different temperatures and strain rates was modeled. Experimental stress-strain curves using K and n values measured from experimental fits listed in Table 1 are compared with the curves based on K calculated from Eq. 14 and n calculated from Eq. 15 in Figure 6. From this figure it can be observed that at lower temperatures the stress-strain behavior of the material is well represented by the model, while there is more difference between experimental curve
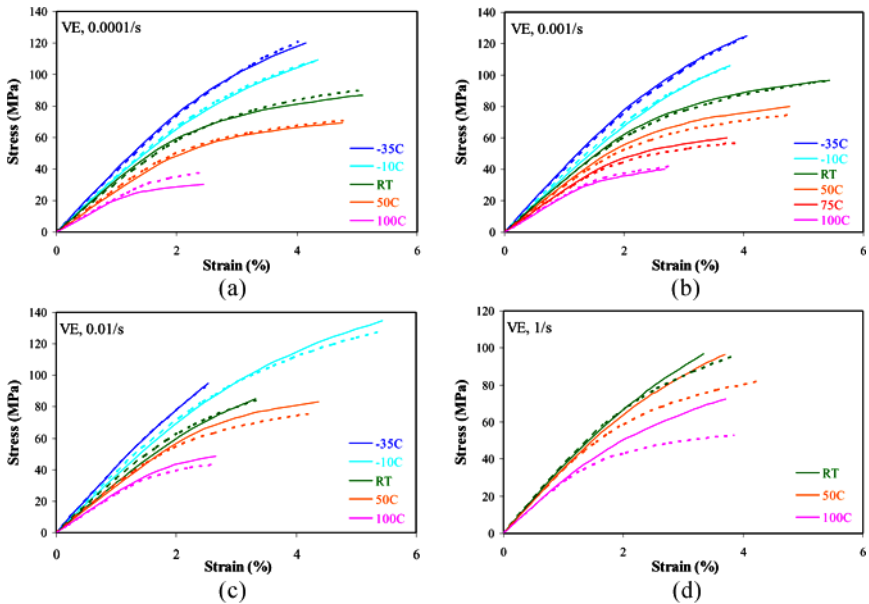

FIGURE 6 Comparison between stress-strain curves obtained using experimental K and n, shown as solid curves, and stress-strain curves obtained using calculated K and n, shown as dotted curves, for vinyl ester polymer at different temperatures and constant strain rate of (a) 0.0001/s, (b) 0.001/s, (c) 0.01/s, and (d) 1/s.

and the model at higher temperatures, as the temperature gets closer to the T_g for vinyl ester.

Menges Model

The Menges model is another simple model used to describe the deformation behavior of vinyl ester polymer up to its tensile strength. For this material a parabolic function similar to the one proposed by Schmachtenberg and Menges [5] was used to describe its stress-strain behavior:

$$\sigma = D_1\varepsilon - D_2\varepsilon^2 \tag{16}$$

This parabolic function was fitted to the experimental data to obtain constants D_1 and D_2. The curves based on D_1 and D_2 obtained from
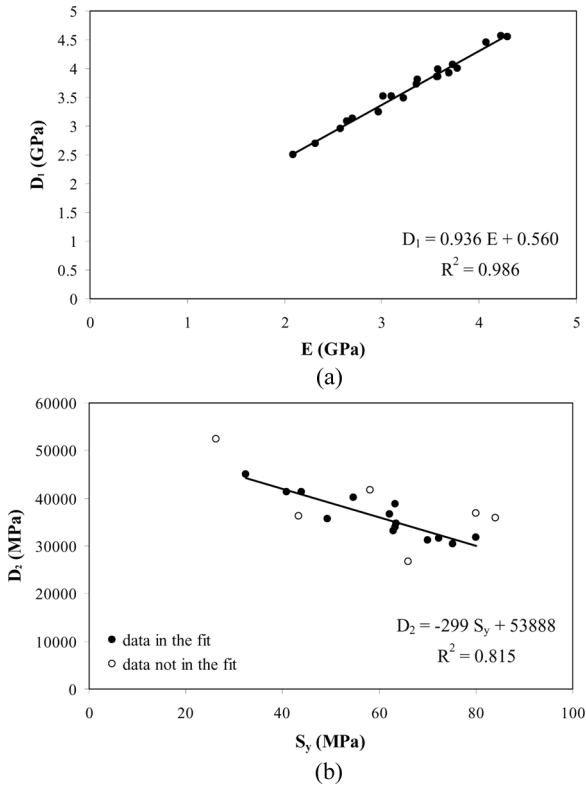

FIGURE 7 Correlation between (a) D_1 and E and (b) D_2 and S_y for vinyl ester polymer.

experimental data and listed in Table 1 provide good representations of the experimental curves obtained at different temperatures and strain rates.

It can be observed from Figure 7 that D_1 and D_2 can be correlated with E and S_y, respectively. The following equations were obtained from these fits:

$$D_1 = 0.936E + 0.560 \quad (R^2 = 0.986) \tag{17}$$

$$D_2 = -299S_y + 53888 \quad (R^2 = 0.815) \tag{18}$$

Using Eqs. 11, 12, 16, 17, and 18, the stress-strain behavior of vinyl ester polymer at different temperatures and strain rates was modeled. Stress-strain curves based on Eq. 16 and experimental D_1 and D_2 values listed in Table 1 are compared with the stress-strain curves based on D_1 calculated from Eq. 17 and D_2 calculated from Eq. 18 in Figure 8. From this figure it can be observed that the model can represent the stress-strain behavior of the material well, at all
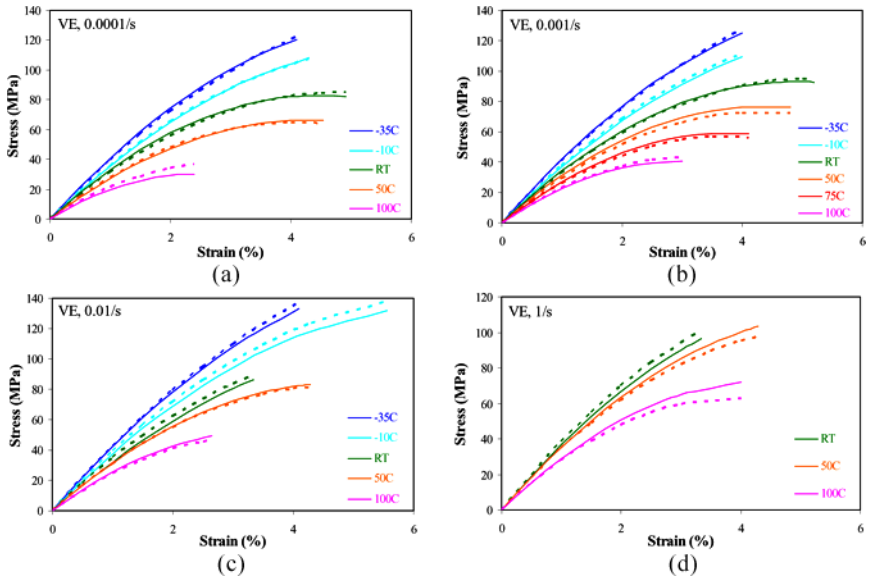

FIGURE 8 Comparison between stress-strain curves obtained using experimental D_1 and D_2, shown as solid curves, and stress-strain curves obtained using calculated D_1 and D_2, shown as dotted curves, for vinyl ester polymer at different temperatures and constant strain rate of (a) 0.0001/s, (b) 0.001/s, (c) 0.01/s, and (d) 1/s.

temperatures. There is only a small difference between the model and experimental results, in most cases.

Comparisons between experimental results with predicted models using Ramberg-Osgood and Menges models for vinyl ester polymer at strain rates of 0.0001/s, 0.001/s, 0.01/s, and 1/s at different temperatures show that at low and room temperatures and for lower strain rates, the predicted results based on the two models are very similar. At higher strain rates (i.e. 0.01/s and 1/s) and higher temperatures, the Menges model could predict the stress-strain behavior of the polymer better than the Ramberg-Osgood model. At high temperature close to T_g for the polymer both models overestimated the stress-strain behavior of the material at strains higher than 1%.

CONCLUSIONS

Based on the analysis and discussion of the experimental data and models presented, the following conclusions can be made:

1. Mechanical properties including modulus of elasticity, tensile strength, yield strength, and ductility of vinyl ester were shown to be strongly strain rate and temperature-dependent. Tensile strength and modulus of elasticity increased by increasing the strain rate at various temperatures, while ductility decreased. Tensile strength and modulus of elasticity decreased by increasing the temperature at various strain rates, while ductility increased.
2. Mechanical properties including modulus of elasticity, tensile strength, and yield strength showed a linear relationship with temperature and log of strain rate. The best linear correlations with temperature and log of strain rate were for the modulus of elasticity and yield strength.
3. Preliminary experimental investigation indicated that moisture absorption decreased the strength of vinyl ester polymer at RT, while there was little or no influence on stiffness, and a slight increase in ductility.
4. At low and room temperatures and for lower strain rates, stress-strain curve representations based on Ramberg-Osgood and Menges models were very similar for the vinyl ester polymer investigated. At higher strain rates (i.e. 0.01/s) and higher temperatures, the Menges model could predict the stress-strain behavior of the polymer better than the Ramberg-Osgood model. At high temperature, close to T_g for the polymer, both models overestimated the stress-strain behavior of the material at strains higher than 1%.

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