

# Time, Temperature, and Strain Effects on Viscoelastic Poisson's Ratio of Epoxy Resins

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**Poisson's ratio of polymeric materials, although generally assumed as a constant, is known to display a viscoelastic dependence on time, temperature, and strain. This article investigates the phenomenology of this dependence on two crosslinked epoxy systems with different glass transition temperatures. Poisson's ratio measurements are performed by contact extensometers simultaneously measuring the axial and transverse deformations under two different tensile testing conditions: (i) constant deformation rate, in which the effects of strain, strain rate, and temperature are highlighted; (ii) stress relaxation (or constant deformation), where the dependence of Poisson's ratio on time is studied at various strain levels. The viscoelastic Poisson's ratio increases as strain, temperature, and time increases, with trends markedly depending on the materials glass transition. POLYM. ENG. SCI., 48:1434-1441, 2008. © 2008 Society of Plastics Engineers**

## INTRODUCTION

In a deformed solid, Poisson's ratio is defined as the negative ratio between the lateral deformation and the axial imposed deformation. It is defined for infinitesimal extensions, and for an ideal elastic solid it is generally considered as a material constant. On the other hand, even at low strain levels, the mechanical behavior of viscoelastic materials, such as polymers and polymer matrix composites, is markedly influenced by time and temperature, and also by strain when deformation occurs in the nonlinear viscoelastic region. This dependence is generally

described, within the framework of linear or nonlinear viscoelastic theories, by material functions with an explicit dependence on time, temperature, and strain. While this dependence is generally accepted and supported by experimental evidence for materials properties, such as moduli, relaxation functions, compliances, and creep functions [1], Poisson's ratio of viscoelastic materials is still often considered as a constant, although the knowledge of its variability could be of general interest in the fields of design, engineering, and material science [2]. A deeper understanding of the viscoelastic nature of Poisson's ratio can be useful in many practical applications, as for example, when considering the data inputs needed by refined methods of computation that demand increasing degrees of accuracy to describe the material behavior [3], or in typical technological coupling of different structural components, that could be affected by the so-called Poisson's strains, originating from misfits in Poisson's ratios of joined materials [1]. A correct determination of the viscoelastic Poisson's ratio could also help in reducing the number of experimental parameters to fit analytical models [4] and in the application of interconversion of other viscoelastic response functions [3].

Theoretical studies on the viscoelastic behavior of Poisson's ratio highlighted a high degree of complexity in the determination of its time dependence with respect to other material properties [1, 3, 5]. In fact, difficulties of experimental nature have led to scarce literature information on this subject. A review article of Tschoegl et al. [3] gives a critical perspective of the problems involved in the experimental determination of a viscoelastic Poisson's ratio. These can be mainly ascribed to the difficult measurement of small transversal strains by common testing devices and to a non trivial mathematical definition of Poisson's ratio as a viscoelastic function.

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Nevertheless, a marked dependence of the Poisson's ratio on strain, temperature, time, and frequency was experimentally evidenced [6–20]. Investigations were carried out by measuring Poisson's ratio both in a direct way, in which the transverse and axial deformations are concurrently measured, or in an indirect way, where Poisson's ratio is derived from the measurement of two different material's viscoelastic constants. Direct measurement can be performed by employing several methodologies, such as optical methods [3, 7, 14, 15, 17], through strain gages [13, 18] or contact extensometers [10]. This latter experimental set-up is not recommended by Tschoegl et al. [3], due to the direct contact with the specimen, but nonetheless good results were obtained by Arzoumanidis and Liechti by means of a biaxial extensometer [10]. Independently from the methodology employed, all these experiments require a high precision and a simultaneous measurement of the two deformations. From available literature data, Poisson's ratio is generally reported as increasing with time (Lu et al. on poly(methylmethacrylate) (PMMA) [7], Di Landro and Pegoraro on poly(etherimide) (PEI) [15]), with temperature (Tcharkhtchi on epoxy resins [16]) and with strain (Steinberger et al. on polypropylene (PP) [14]; Litt and Torp on polycarbonate (PC) [19]). Moreover, a decreasing trend is described for the complex Poisson's ratio with frequency under dynamic conditions (Kästner and Pohl on PMMA [20]; Caracciolo and Giovagnoni on poly(vinylchloride) (PVC) [13]; Pritz on an acrylic elastomer [12]; Arzoumanidis and Liechti on a neat urethane adhesive (Ashland) [10]).

An investigation of a time dependent Poisson's ratio as a viscoelastic function has been attempted on polymeric materials by means of typical experiments for the determination of the viscoelastic parameters, such as ramp [14, 18], creep [14, 17], and stress relaxation [7] tests. Among these methodologies, Hilton and Yi [21] indicated the so called relaxation Poisson's ratio, i.e. the Poisson's ratio measured under a constant axial deformation, as the only one that can be evaluated as a ratio between the transverse and the axial deformations. Nevertheless, a viscoelastic Poisson's ratio can be also measured in ramp or in creep tests, provided that a correct representation in the Laplace transform plane is considered. Consequently, under the above experimental conditions, Poisson's ratio cannot be simply defined as the negative ratio of transverse and axial strains [21], and this parameter could be more appropriately defined as a lateral contraction ratio [3]. Nonrecognition of these subtle distinctions was indicated as a cause of erroneous or inconsistent literature results [3].

The determination of Poisson's ratio as a viscoelastic function of time is still considered a difficult task. On the other hand, phenomenological studies of how deformation parameters affect Poisson's ratio usually convey satisfactory descriptions of its time, temperature, and strain dependences. Therefore, the aim of this work is to further investigate the viscoelastic features of Poisson's ratio by

direct measurements on two differently crosslinked epoxy resins, focusing on the effects of the deformation conditions and of the material structure.

## EXPERIMENTAL

### Materials

The investigated materials were two commercial bicomponent epoxy systems, supplied by Elantas Camattini S.p.A. (Collecchio, Parma, Italy). They both consisted of a DGEBA based low-molecular-weight epoxy resin, EC 57 (172–182 g/equiv), stoichiometrically mixed with two different hardeners: (i) a polyamide-amine curing agent, K63 (derived from the partial reaction of tetraethylenepentamine with fatty acids; 88–91 g/equiv); (ii) an amine curing agent, K21 (pentaethylenehexamine; 45 g/equiv).

The resin and the hardener were mixed for 5 min by means of a mechanical stirrer and the resulting compound was subsequently subjected to three degassing treatments under vacuum within 15 min after mixing in order to reduce the presence of air bubbles in the crosslinked resins. Dumb-bell specimens (ISO 527 type 1A) were realized by casting the degassed resins in the cavities of a silicon mold. A curing treatment was carried out for the first 24 h at room temperature and then in an oven at 60°C for 15 h. EC57+K21 resin was subjected to a further treatment at 100°C for 3 h in order to complete the crosslinking reactions. Specimens were then slowly cooled to room temperature in the oven in order to minimize residual stresses.

### Methods

An electromechanical testing machine (Instron, model 4502) was employed to perform tensile tests under displacement control. The longitudinal and transverse deformations of the dumb-bell specimens were simultaneously measured during the test by means of both longitudinal (Instron, model 2640) and transversal (Instron, model 2620) extensometers, clipped on the specimens (see Fig. 1). All the tests were performed in a thermostatic chamber (Instron, model 3199), permitting a temperature control within  $\pm 1^\circ\text{C}$ .

The longitudinal deformation,  $\varepsilon_{\text{AX}}$ , was evaluated as:

$$\varepsilon_{\text{AX}} = \frac{\Delta L_{\text{AX}}}{L_{\text{AX},0}} \quad (1)$$

where  $\Delta L_{\text{AX}}$  represents the displacement registered by the axial extensometer and  $L_{\text{AX},0}$  the initial longitudinal gauge length. The transversal deformation,  $\varepsilon_{\text{TRANS}}$ , was evaluated as:

$$\varepsilon_{\text{TRANS}} = \frac{\Delta L_{\text{TRANS}}}{L_{\text{TRANS},0}} \quad (2)$$

where  $\Delta L_{\text{TRANS}}$  represents the displacement measured by the transverse extensometer and  $L_{\text{TRANS},0}$  the initial specimen width.

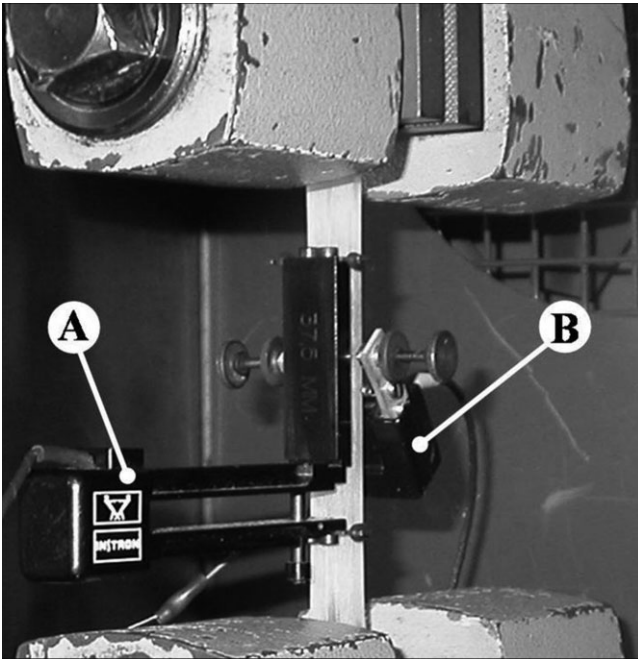


FIG. 1. Experimental set-up for the direct measurement of Poisson's ratio by means of longitudinal (A) and a transversal (B) clip-on extensometers.

The transverse extensometer is a clip-on device, and exerts a certain force on the lateral sides of the specimen, which may lead to a penetration of the extensometer in the specimen. In order to correct the experimental data, this penetration was evaluated as a function of time on an undeformed specimen and then subtracted from the transversal deformation measured on the deformed specimen. The penetration of the transverse extensometer resulted to be of the order of around  $0.5 \mu\text{m}$  in 100 min.

A preliminary characterization of the epoxy resins was performed by dynamical mechanical thermal analysis (DMTA), conducted with a MkII Polymer Laboratories testing machine under bending mode at a frequency of 3 Hz.

Further, the extent of the linear viscoelasticity region was preliminarily studied for both epoxy resins by stress relaxation tests, in order to obtain isochronous stress-strain curves. Tests were performed at room temperature at various strain levels between 0.0025 and 0.0300 and only the axial extensometer was employed.

#### Poisson's Ratio Evaluation

The viscoelastic features of Poisson's ratio were evaluated under two different testing conditions: (i) constant deformation rate tests (CDR), and (ii) constant deformation tests (REL), as schematically depicted in Fig. 2.

In constant deformation rate tests, a lateral contraction ratio was evaluated as:

$$\text{lateral contraction ratio} = -\frac{(\varepsilon_{\text{TRANS}} - \varepsilon_{\text{TRANS},0})}{\varepsilon_{\text{AX}} - \varepsilon_{\text{AX},0}} \quad (3)$$

where  $\varepsilon_{\text{TRANS}}$  is the transverse deformation corresponding to an axial deformation  $\varepsilon_{\text{AX}}$ , whereas  $\varepsilon_{\text{TRANS},0}$  is the transverse deformation related to an arbitrary axial deformation  $\varepsilon_{\text{AX},0} = 0.0005$ . According to the indications of Tschoegl et al. [3] and Hilton and Yi [21], the term lateral contraction ratio was preferred to that of Poisson's ratio for the data collected under these testing conditions. The effect of strain rate and temperature was evaluated by testing the specimens at various strain rates (between  $8.3 \times 10^{-5} \text{ s}^{-1}$  and  $5.8 \times 10^{-4} \text{ s}^{-1}$ , at room temperature) and temperatures (between 10 and  $65^\circ\text{C}$ , at a strain rate of  $1.3 \times 10^{-4} \text{ s}^{-1}$ ). No higher temperatures were investigated due to the limitation imposed by the operating temperature range of the transverse extensometer.

A second type of test was performed by applying a constant axial deformation and measuring the time evolution of the specimen width. This testing condition is generally referred as stress relaxation, and thus the label REL was used to indicate this type of test. A time dependent viscoelastic Poisson's ratio was evaluated as

$$\nu(t) = -\frac{\varepsilon_{\text{TRANS}}(t)}{\varepsilon_{\text{AX}}} \quad (4)$$

where  $\varepsilon_{\text{TRANS}}(t)$  is the time dependent transverse deformation measured under a constant longitudinal deformation  $\varepsilon_{\text{AX}}$ . It is important to remark that, since the axial deformation is constant, Eq. 4 represents a true viscoelastic time dependent Poisson's ratio [3, 21].

Various axial deformations were reached ( $\varepsilon_{\text{AX}} = 0.0050, 0.0075, 0.0100, 0.0125, 0.0150$ ) in a constant loading time of 30 s. Thus, in accordance to the indication of Moore and Turner [22], the data acquired within the first 300 s (corresponding to 10 times the loading time) were neglected in order to avoid loading history effects.

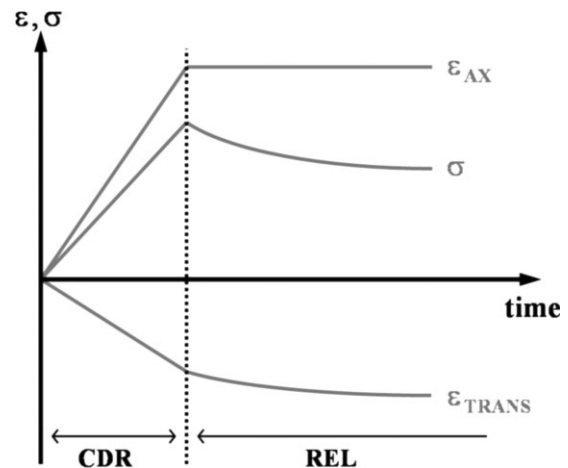


FIG. 2. Schematic representation of input ( $\varepsilon_{\text{AX}}$ ) and output ( $\sigma, \varepsilon_{\text{TRANS}}$ ) data under constant deformation rate (CDR) and constant deformation (REL) tests.

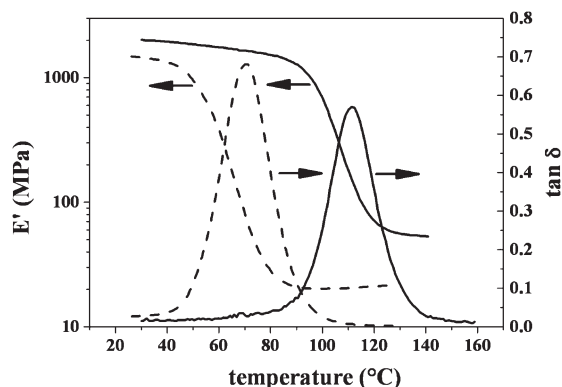


FIG. 3. Storage modulus ( $E'$ ) and loss tangent ( $\tan \delta$ ) for LTG (dashed line), and HTG (solid line) resins.

The experimental errors in the measurement of the Poisson's ratio depend on accuracy and precision of the two extensometers and on the method adopted for the Poisson's ratio evaluation. In our experience, this experimental set-up never led to errors greater than  $\pm 3\%$  on the measured values.

## RESULTS

### Materials Characterization

The DMTA thermograms of the two different epoxy systems are reported in Fig. 3. The two resins show different glass transition temperatures, evaluated in correspondence of the  $\tan \delta$  peak: the epoxy system EC57 + K21 displays a  $T_g$  close to  $110^\circ\text{C}$ , while the system EC57 + K63 has a lower  $T_g$  close to  $70^\circ\text{C}$ . Consequently, the two resins will be labeled as HTG (high  $T_g$ ) and LTG (low  $T_g$ ), respectively. As expected, the HTG resin displays a higher storage modulus in the rubbery plateau, due to its higher crosslinking degree. A lower difference is found for the storage modulus in the glassy plateau, with higher values for the HTG resin. The LTG resin presents a lower glass transition temperature and, at each temperature, lower  $E'$  values with respect to the HTG resin. These differences can be ascribed to a larger molecular mobility for the LTG resin, as induced by the presence of longer hydrocarbon segments in the polyamide-amine hardener and by its lower crosslinks density.

In order to collect information on the extent of the linear viscoelastic region, isochronous stress-strain curves have been obtained from stress relaxation tests performed at room temperature at various axial deformation levels. The isochronous stress-strain curves reported in Fig. 4 reveal that the HTG resin displays a linear viscoelastic behavior up to a deformation level of about 0.0075, deviating toward a nonlinear viscoelastic behavior at higher strains. The time dependence becomes significant only for strains within the nonlinear viscoelasticity region. For the LTG epoxy resin, it is more difficult to determine the

extent of the linear viscoelasticity field, since a region of clear linearity cannot be easily assessed. Anyway, an evident departure from a linear trend takes place at deformation values higher than 0.0050. Therefore, this could be assumed as a limiting value for the linear viscoelastic behavior of LTG resin.

### Constant Deformation Rate Tests

In constant deformation rate tests (CDR) the specimen lateral contraction was measured while a linear axial deformation ramp was applied at various temperatures and strain rates. Figure 5 reports the time evolution of transverse strain,  $\varepsilon_{\text{TRANS}}$ , and axial stress,  $\sigma$ , within CDR tests performed on both resins at a fixed strain rate ( $1.3 \times 10^{-4} \text{ s}^{-1}$ ) and at three temperatures ( $25^\circ\text{C}$ ,  $45^\circ\text{C}$ ,  $65^\circ\text{C}$ ). As expected, for both resins, the application of an axial elongation induces a lateral contraction that becomes more pronounced as the axial deformation increases. Further, in the case of the LTG resin a marked effect of temperature is observed, and the contraction is enhanced as the temperature increases. On the other hand, for the HTG resin only a slight decrease of the transverse deformation with temperature is displayed. Consistently with the temperature effect on  $\varepsilon_{\text{TRANS}}$ , it is noteworthy to remark that the deformation temperature has a larger effect on axial stress in the case of the LTG resin rather than for HTG resin.

The lateral contraction ratio is evaluated at various temperatures in correspondence of a strain value  $\varepsilon_{\text{AX}} = 0.0025$ , i.e. at small strains, and the effect of temperature is reported in Fig. 6a for both resins. Within the investigated temperature range, the lateral contraction ratio of LTG resin shows a pronounced temperature dependence that follows a sigmoidal increasing trend. It is interesting to observe that the lateral contraction ratio of the LTG resin exhibits a rather steep transition for temperatures close to  $45^\circ\text{C}$ , i.e. a temperature  $25^\circ\text{C}$  lower than the  $T_g$  evaluated by DMTA as  $\tan \delta$  peak temperature. This

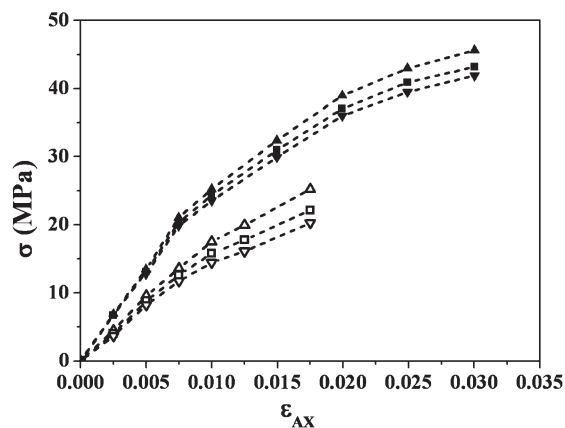


FIG. 4. Isochronous stress-strain curves at various instants: 1000 s ( $\triangle$ ;  $\blacktriangle$ ); 3000 s ( $\square$ ;  $\blacksquare$ ); 6000 s ( $\nabla$ ;  $\blacktriangledown$ ) evaluated at  $25^\circ\text{C}$ . Open symbols refer to LTG resin while full symbols refer to HTG resin.

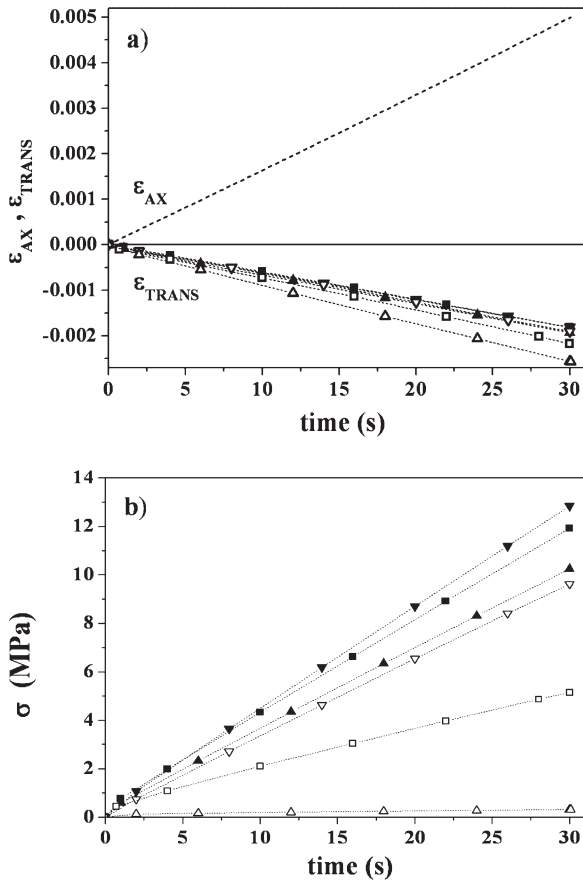


FIG. 5. Strains (a) and stress (b) time evolution in CDR experiments performed on LTG (open symbols) and HTG (full symbols) resins at a loading rate of  $1.3 \times 10^{-4} \text{ s}^{-1}$  and at various temperatures [25°C ( $\nabla$ ;  $\blacktriangledown$ ); 45°C ( $\square$ ;  $\blacksquare$ ); 65°C ( $\triangle$ ;  $\blacktriangle$ )].

observation is consistent with the transition range reported by Tcharkhtchi et al. [16] for the Poisson's ratio of a similar epoxy resin. The steeper increase takes place at temperatures close to the early decreasing stage of  $E'$ , and it is believed that such transition is related to the glass transition phenomenon, either evaluating  $T_g$  as  $\tan \delta$  peak ( $T_g = 70^\circ\text{C}$ ) or as the first decreasing stages for the storage modulus  $E'$  ( $T_g = 50^\circ\text{C}$ ).

The lateral contraction ratio of LTG resin exhibits a lower plateau close to 0.420 below  $35^\circ\text{C}$  and reaches an upper plateau at a value of 0.5, typical of an incompressible material in the rubbery state, for temperatures higher than  $55^\circ\text{C}$ , i.e. approaching its  $T_g$ .

As expected, in the same temperature range the HTG resin displays a less pronounced variation of the lateral contraction ratio that increases from 0.370 to 0.410. The lateral contraction ratio measured at a temperature of  $70^\circ\text{C}$  (i.e.,  $40^\circ\text{C}$  lower than the material's  $T_g$ ) is similar to those displayed by the LTG resin at  $10\text{--}20^\circ\text{C}$ , i.e. at temperatures that are at a similar distance from the corresponding material's  $T_g$ . The absence of a sigmoidal trend for the HTG resin is justified by the fact that the highest investigated temperature is still too far from the  $T_g$  of this

material. The simultaneous measurement of axial stress allows us to evaluate the Young's modulus,  $E$ , for both resins, and the results are represented in Fig. 6b as a function of temperature. It can be seen that for the LTG resin the temperature window permits to analyze part of the glass transition region. Interestingly enough, there are indications that when the temperature corresponding to the inflection point of the lateral contraction ratio is reached, the Young's modulus has just started its decreasing trend. This indicates that the Poisson's ratio transition takes place at temperatures slightly lower than those at which a transition for the elastic modulus is observed. On the other hand, consistently with the lateral contraction ratio results, no great changes in the Young's modulus are detected for the HTG resin within the range of investigated temperatures.

The strain rate dependence of the lateral contraction ratio at room temperature is reported in Fig. 7, as evaluated at the same given deformation ( $\epsilon_{\text{AX}} = 0.0025$ ). The overall trend is not clear even if a tendency to decrease can be noticed.

An evaluation of how lateral contraction ratio changes with the strain level has been also attempted by applying

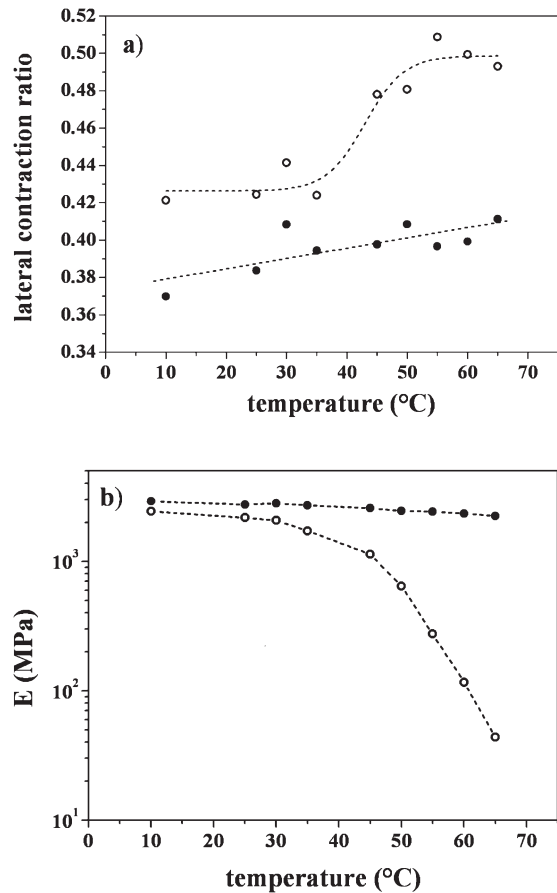


FIG. 6. Effect of temperature on the lateral contraction ratio (a) and on Young's modulus (b) at a strain of 0.0025 in CDR experiments performed on LTG ( $\circ$ ) and HTG ( $\bullet$ ) resins at a loading rate of  $1.3 \times 10^{-4} \text{ s}^{-1}$ .

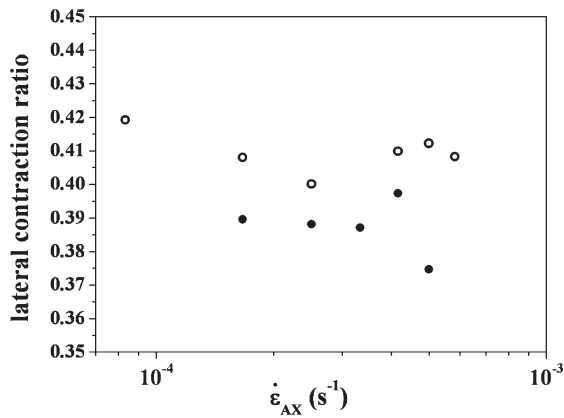


FIG. 7. Effect of strain rate on the lateral contraction ratio at a strain of 0.0025 in CDR experiments performed at 25°C on LTG (○) and HTG (●) resins.

Eq. 3 for strain levels higher than 0.0025 in CDR tests performed at room temperature and at a loading rate of  $4.2 \times 10^{-4} \text{ s}^{-1}$ . The results, displayed in Fig. 8, show that the lateral contraction ratio tends to increase with the axial deformation for both resins. For small axial deformations, the lateral contraction ratio of HTG resin rapidly increases. The rate of this increase reduces for axial deformations higher than 0.0075, corresponding to the beginning of the nonlinear viscoelastic region of this resin. Such strain dependence has not been observed for the LTG resin. This could be due to its lower limit of the linear viscoelastic behavior (evaluated at around 0.0050).

It has to be remarked that this evaluation of the strain dependence of the lateral contraction ratio does not take the possibility of a time effect on the measured values into account. It is therefore advisable to obtain separate information on the time and strain dependences by performing constant deformation experiments at various strain levels.

In all the performed tests, at any given value of temperature, strain rate and strain level, LTG resin always

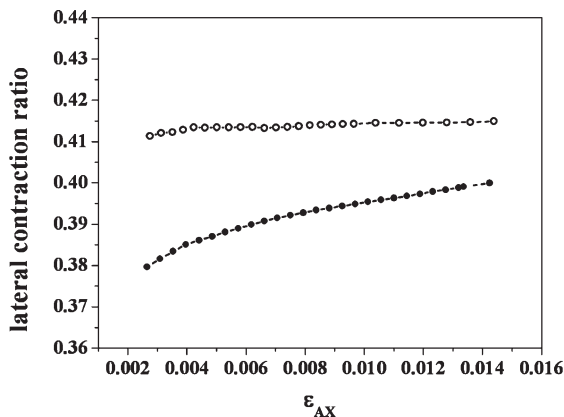


FIG. 8. Lateral contraction ratio as a function of strain in CDR experiments performed on LTG (○) and HTG (●) resins at 25°C and at a loading rate of  $4.2 \times 10^{-4} \text{ s}^{-1}$ .

presents higher lateral contraction values than HTG, consistently with its larger molecular mobility.

### Constant Deformation Tests

In constant deformation experiments, the evolution of the transverse deformation as a function of time is followed during the application of a constant axial deformation. This approach eventually leads to the evaluation of a true viscoelastic Poisson's ratio,  $\nu(t)$ . The time-dependence of the transverse deformation and axial stress are reported in Fig. 9 for the two resins and for three applied strain levels (0.0050, 0.0100, 0.0150). Figure 9a shows that a progressive contraction is measured in all the specimens although the axial deformation is kept constant, thus indicating a certain dependence of Poisson's ratio on time. As expected, the higher the applied axial deformation, the larger the lateral contraction. Time and strain seem to have a larger influence on the LTG resin rather than on the HTG one. The axial stress decreases, as expected in a stress relaxation experiment (Fig. 9b).

The dependence of the viscoelastic Poisson's ratio,  $\nu(t)$ , on time is reported in Fig. 10 for both LTG and

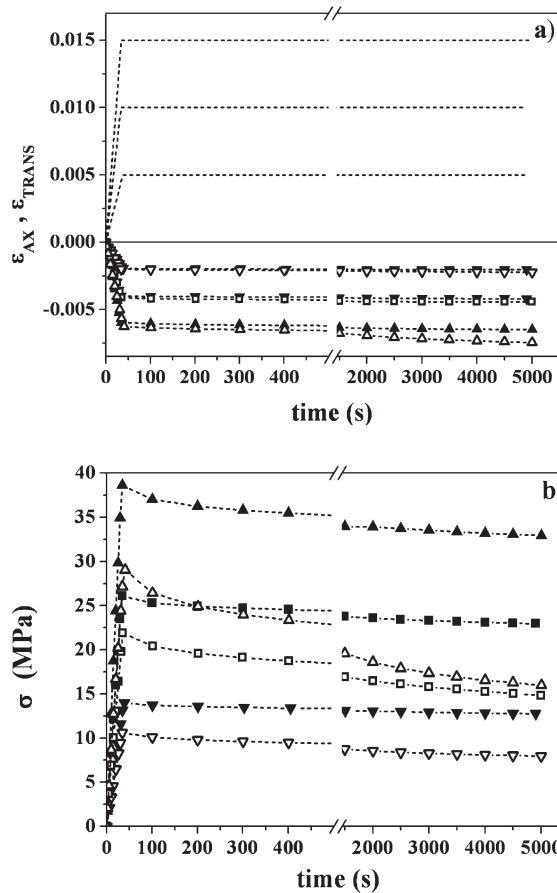


FIG. 9. Strain (a) and stress (b) time evolution in constant deformation (REL) experiments performed on the LTG (open symbols) and HTG (full symbols) resins at 25°C and at various strain levels,  $\epsilon_{AX}$ : 0.0050 (▽; ▼); 0.0100 (□; ■); 0.0150 (△; ▼).

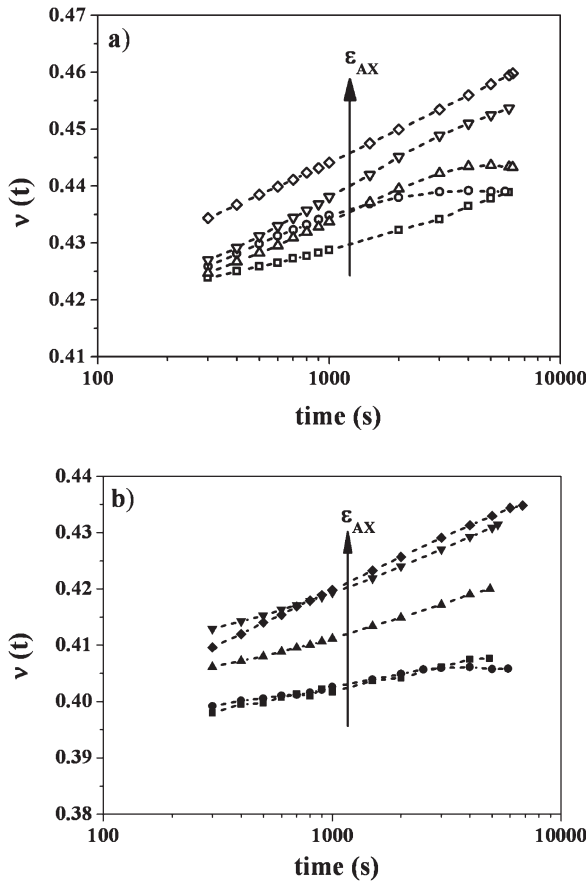


FIG. 10. Viscoelastic Poisson's ratio,  $\nu(t)$ , evaluated in REL tests as a function of time on a) LTG (open symbols), and b) HTG (full symbols) epoxy resins at various longitudinal deformations,  $\epsilon_{AX} = 0.0050$  ( $\square$ ;  $\blacksquare$ );  $0.0075$  ( $\circ$ ;  $\bullet$ );  $0.0100$  ( $\triangle$ ;  $\blacktriangle$ );  $0.0125$  ( $\nabla$ ;  $\blacktriangledown$ );  $0.0150$  ( $\diamond$ ;  $\blacklozenge$ ).

HTG resins. For both resins an increase of the Poisson's ratio with time and with the applied deformation is observed.

Viscoelastic Poisson's ratio of the LTG resin (Fig. 10a) is seen to cover a range of values between 0.425 and 0.440 in 100 min at the lowest axial deformation level ( $\epsilon_{AX} = 0.0050$ ), while at the highest axial strain ( $\epsilon_{AX} = 0.0150$ ) the Poisson's ratio assumes higher values that increase on a larger extent, from 0.435 up to 0.460. At any given deformation, the HTG resin displays lower Poisson's ratio values with respect to the other resin on the whole time window (see Fig. 10b). In 100 min  $\nu(t)$  increases from 0.398 to 0.410 at the lowest deformation level ( $\epsilon_{AX} = 0.0050$ ), and from 0.410 to 0.430, at the highest applied strain ( $\epsilon_{AX} = 0.0150$ ). Further, Poisson's ratio curves of the HTG resin are quite close to each other for deformation levels up to 0.0075, becoming more distant for higher strains and returning again very close for strains above 0.0125.

The strain dependence of the Poisson's ratio is compared for the two resins in Fig. 11 by means of isochronous curves, in which  $\nu(t)$  is represented for a given time as a function of the applied axial deformation. For every

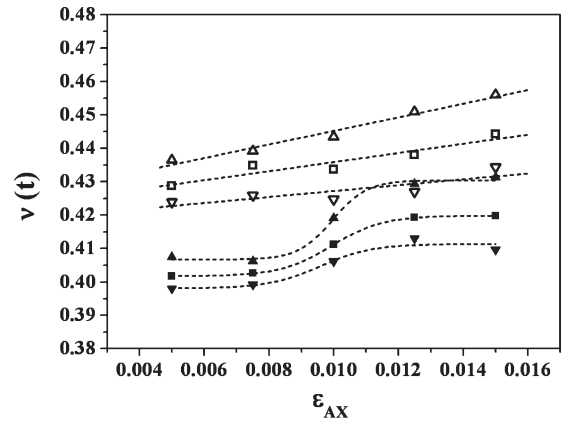


FIG. 11. Isochronous curves for viscoelastic Poisson's ratio,  $\nu(t)$ , evaluated in REL tests on LTG (open symbols), and HTG (full symbols) epoxy resins as a function of the longitudinal deformation,  $\epsilon_{AX}$ , at various instants: 300 s ( $\nabla$ ;  $\blacktriangledown$ ); 1000 s ( $\square$ ;  $\blacksquare$ ); 4000 s ( $\triangle$ ;  $\blacktriangle$ ).

investigated time and deformation level, the Poisson's ratio of the LTG resin is higher than that of the HTG resin. Further, the Poisson's ratio of the LTG resin displays a regular increase with strain that can be fitted with a linear trend with a positive slope. On the other hand, the strain dependence of the Poisson's ratio of the HTG resin clearly follows a sigmoidal trend. This trend could be tentatively ascribed to the entrance in the nonlinear viscoelasticity field for axial deformations higher than 0.0075, at which the curve shows its steepest slope.

The dependence of the relaxation modulus,  $E_{REL}$ , on time and strain is reported in Figs. 12 and 13, respectively.  $E_{REL}$  decreases as both strain and time increase. Higher values of the relaxation modulus are found for HTG resin at each strain level, and a less marked effect of time and strain is observed with respect to LTG resin. Figure 13 shows that the relaxation modulus of the LTG resin follows a regular decrease at each instant, consistently with the trend displayed by its Poisson's ratio. On the other hand, in the case of the HTG resin,  $E_{REL}$  does

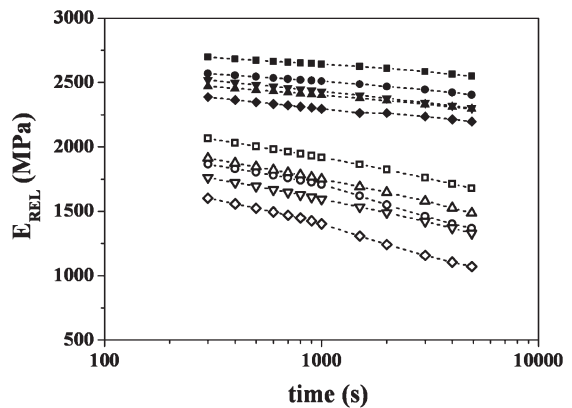


FIG. 12. Relaxation modulus,  $E_{REL}$ , measured in constant deformation tests on LTG (open symbols), and HTG (full symbols) epoxy resins at various longitudinal deformations,  $\epsilon_{AX}$ :  $0.0050$  ( $\square$ ;  $\blacksquare$ );  $0.0075$  ( $\circ$ ;  $\bullet$ );  $0.0100$  ( $\triangle$ ;  $\blacktriangle$ );  $0.0125$  ( $\nabla$ ;  $\blacktriangledown$ );  $0.0150$  ( $\diamond$ ;  $\blacklozenge$ ).

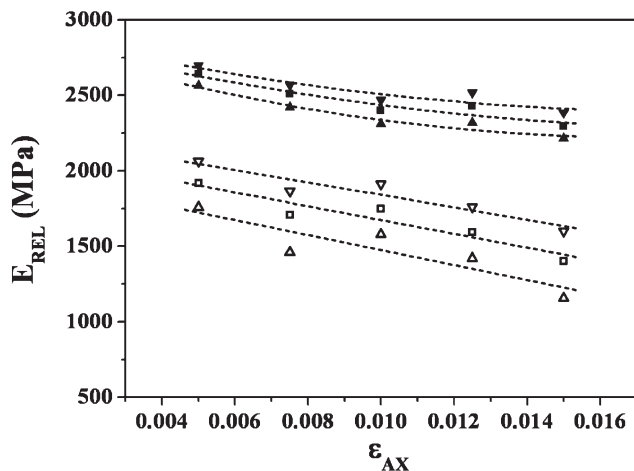


FIG. 13. Isochronous curves for relaxation modulus,  $E_{REL}$ , measured in constant deformation tests on the LTG (open symbols) and HTG resin (full symbols) as a function of the longitudinal deformation level,  $\epsilon_{AX}$ , at various instants: 300 s ( $\nabla$ ;  $\blacktriangledown$ ); 1000 s ( $\square$ ;  $\blacksquare$ ); 4000 s ( $\triangle$ ;  $\blacktriangle$ ).

not show an evident transition from a linear to a nonlinear region, such as that displayed by the Poisson's ratio.

## CONCLUSIONS

Poisson's ratio of two differently crosslinked epoxy resins was measured under different testing conditions, in order to evaluate the phenomenology of its viscoelastic behaviour as a function of the strain, strain rate, and time.

For both resins a marked influence of the deformation parameters on Poisson's ratio can be observed. Consistently with a time-temperature equivalence principle, Poisson's ratio is seen to increase with temperature and time, and an overall decreasing trend is found with the strain rate. The temperature dependence is quite marked when material approaches the glass transition temperature, displaying at  $T_g$  a Poisson's ratio value around 0.5, typical of rubbery materials. Further, for both epoxies, Poisson's ratio increases with the longitudinal deformation.

Poisson's ratio seems to be markedly affected by strain in the vicinity of the threshold of the nonlinear viscoelasticity region, whereas for higher deformation levels a slighter but steady increase is displayed.

The crosslinking degree also plays a relevant role on the Poisson's ratio. In the investigated temperature range, it is found that the resin with lower  $T_g$  displays higher values of Poisson's ratio with respect to the resin having a higher  $T_g$ .

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