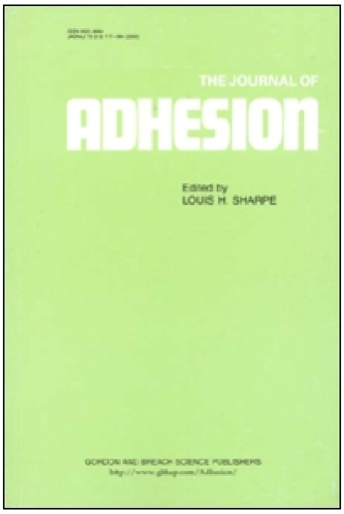

The Journal of Adhesion

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

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C. L. Rao[a][b]; J. J. Connor[a]
[a] Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA [b] Department of Applied Mechanics, Indian Institute of Technology, Madras, India

To cite this Article Rao, C. L. and Connor, J. J.(1993) 'Mechanical Behavior of Butyl Adhesives', The Journal of Adhesion, 43: 3, 179 — 197
To link to this Article: DOI: 10.1080/00218469308026598
URL: http://dx.doi.org/10.1080/00218469308026598

J. Adhesion, 1993, Vol. 43, pp. 179–197
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Printed in the United States of America

Mechanical Behavior of Butyl Adhesives

C. L. RAO* and J. J. CONNOR

Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

(Received February 1, 1992; in final form July 23, 1993)

Butyl adhesives are widely used to bond elastomeric membranes. The results of uniaxial tension tests and simple shear tests conducted on bulk samples of butyl adhesives are presented in this paper. Butyl adhesives were found to have a rate-sensitive mechanical response with very low tensile and shear strengths. The stress-strain curves of the adhesive are characterized by an initial elastic response followed by a region of large plastic flow. A three-element viscoelastic model was used to model the stress-strain behavior of the adhesive. The model effectively combines a viscous dashpot and a network spring to capture the plastic flow in the material after the initial yield. The parameters of the model are calibrated to simulate a wide range of mechanical response of the adhesive.

KEY WORDS butyl adhesives; uniaxial tension tests; lap shear test; stress-strain curves; viscoelastic models; failure strength; mechanical properties.

INTRODUCTION

Butyl and other types of rubber-based adhesives are used mainly to join rubbers or rubber-like materials such as elastomers. These adhesives are currently being used to bond Ethylene Propylene Diene Terpolymer (commonly called EPDM) membranes in the tyre and roofing industries.[1] Adhesively bonded lap joints between elastomeric membranes are known to be very weak at their joints. These joints fail predominantly either at the adhesive-substrate interface (in shear)[2] or by the rupture of the adhesive layer itself (in peel).[3]

Butyl rubbers are relatively long-chain molecules (containing approximately 47,000 to 60,000 polymer units) with very few double bonds or reactive sites, rendering them stable and inert to the effects of weathering, age and heat. These rubbers are often halogenated by substitution of hydrogen atoms, so as to enhance the reactivity of their double bonds as well as to provide additional sites for cross linking. The strength of a halogenated butyl rubber is normally increased by adding curative agents such as zinc oxide[4] to the main polymer. A typical butyl adhesive formulation contains a mixture of: (i) a halogenated butyl rubber, (ii) a pre-crosslinked butyl rubber and (iii) a tri-block copolymer. The copolymer is added to improve

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*Corresponding author. Present address: Department of Applied Mechanics, Indian Institute of Technology, Madras-600036, India.

the cure time of the adhesive, while the low-molecular-weight, high-softening-point aliphatic resin is blended with the main polymer in order to improve the tack (which is a qualitative measure of initial hardening of the adhesive), heat strength and surface polarity of the adhesive formulation.[5] The exact composition of various additives is adjusted to ensure a good ultimate bond strength with the substrates (to which it adheres) as well as to maintain sufficient resistance to creep and cold flow in the wet state. Typically, butyl adhesives have a glass transition temperature of $-20°C$.[6]

Characterization of the mechanical properties of an adhesive in simple states of deformation (such as uniaxial tension and simple shear) is essential for an effective use of the material in any mechanical system. Mechanical properties of adhesives are generally obtained by conducting tests on bulk samples of adhesives.[7-11] Most of these tests have been conducted on epoxy adhesives and the test results were generally found to be sensitive to application parameters such as the curing history as well as the geometry of test samples. The test conditions affect solvent migration and other micro-mechanical processes, which in turn are responsible for the creation of voids and inhomogeneities within the adhesive test samples. These inhomogeneities are postulated to be responsible for a wide scatter in the mechanical properties of epoxy adhesives reported in the literature. Mechanical properties of elastometric adhesives such as butyl adhesives, which are expected to have lower strengths and higher elongations, are not reported in the literature.

The objective of the present work is to characterize the uniaxial tension and simple shear response of butyl adhesives and to compare their mechanical properties with epoxy-based adhesives. Further, the observed mechanical behavior is explained with the help of a physical model. The model is then used to study the sensitivity of the mechanical response to various test parameters.

Two adhesive formulations that are commonly used to join Ethylene Propylene Diene Terpolymer (EPDM) substrates in the roofing industry were selected for the present study. Uniaxial tension tests were conducted at different cross-head displacement rates to evaluate the rate sensitivity of the material. Shear tests were conducted on one of the adhesive formulations for two different thicknesses of the adhesive sample. A three-element viscoelastic model, commonly used to simulate the response of glassy polymers, has been used to simulate test results. The variation in test results, to application parameters such as adhesive thickness and age, are explained using the proposed model. Finally, the behavior of the adhesive is compared with the known behavior of epoxy adhesives and differences between the two types of structural adhesives are noted.

EXPERIMENTAL

Uniaxial Tension Tests on Butyl Adhesives

Butyl adhesives are stored as viscous fluids in sealed containers. The adhesives harden into a rubbery solid on exposure to the atmosphere. Preparation of tensile test specimens from these fluids requires casting of the adhesive into a mould followed by curing. The specimen moulds were prepared using a procedure developed at the National Institute of Standards Technology for preparing test specimens of butyl adhesives.[12]

Specimen Preparation

Moulds were fabricated by nailing square polyurethane sheets onto wooden boards and by gluing thin aluminium strips all around the periphery of the polyurethane sheet. A schematic cross-section of the mould is shown in Figure 1. The adhesive material was stirred well and poured onto the polyurethane sheet. It was then spread over the plane area using a flat metal spatula, level with the thickness of the aluminium strips. The excess adhesive material was sheared off the top of the mould by passing a knife edge all along the length of the aluminium strips. The mould was placed in a vacuum chamber for three hours to facilitate the escape of air bubbles from the adhesive. It was then exposed to atmospheric conditions for seven days to allow sufficient time for solvents to escape and for the adhesive to cure. Narrow test specimens of 150 mm × 12.5 mm were cut from the dried adhesive using a knife edge.

Test Results and Discussion

Uniaxial tension tests were conducted on test specimens with a gauge length of 50 mm as recommended by the Standard Test Methods for Tension Properties of Thin Plastic Sheeting (ASTM D882-88). The tests were conducted at room temperature on adhesives supplied by two different manufacturers (designated as A and B) at three different displacement rates of 5 mm/min, 50 mm/min and 500 mm/min. Adhesive A was an aged sample that was more than one year old, while adhesive B was manufactured only two months prior to sample preparation. The wet state thickness of the adhesive samples was 1 mm. Five samples were tested at each

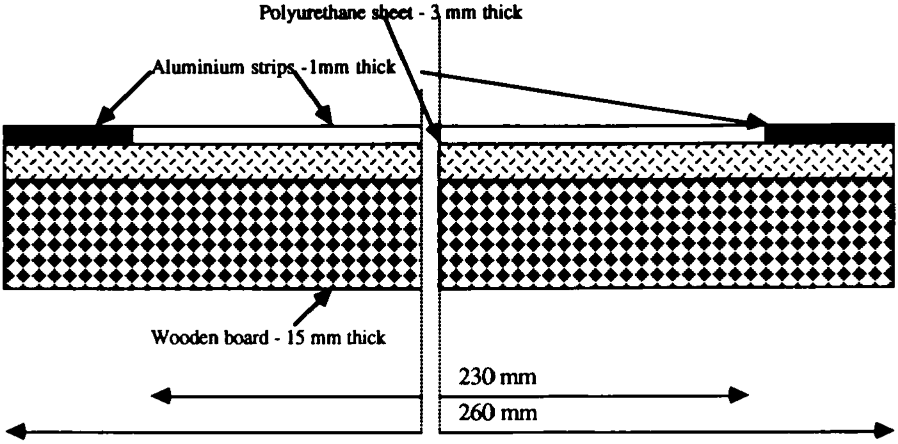

FIGURE 1 Schematic diagram of specimen moulds used to prepare bulk adhesive samples for testing in uniaxial tension.

displacement rate. The test specimens of adhesive A had an average dry state thickness of 0.41 mm with a standard deviation of 0.064 mm. This shows that adhesive A experienced a volume shrinkage of 59% from its wet state. Adhesive B, which contained more solvents in its wet state, experienced a shrinkage of 77% from its wet state. This volume shrinkage for adhesive B correlates with the solids contents of 29% reported by Martin *et al.*[6] for the butyl adhesives which they tested. The specimens were loaded at room temperature using a universal testing machine and the load displacement curves were used to obtain the nominal stress-nominal strain curves in tension for each test specimen.

The curves in Figures 2a, b and c show the stress-strain response for adhesive A at each of the specified displacement rates. Figures 3 a, b and c show the stress-strain curves in uniaxial tension for adhesive B. Figure 4 shows an average stress-strain plot in uniaxial tension for adhesive A and Figure 5 shows a similar plot for adhesive B. The mean value of maximum strength was 577.78 kPa (standard deviation = 12.65 kPa) for adhesive A and 1063.172 kPa (standard deviation = 88.9 kPa) for adhesive B. The average failure strength of the two adhesives at various displacement rates are listed in Table I. It may be observed that the stress-strain response as well as the failure strength of both the adhesive materials were rate sensitive. Adhesive A exhibits an increased ductility with an increase in displacement rate, reaches its ultimate strength fairly early in its load history, and shows strain softening effects after the initial yield. Adhesive B, on the other hand, shows considerable strain-hardening effects after the initial yield while maintaining the strain rate sensitivity of the peak strength. The ultimate strength of the material is reached gradually and there is very little post-peak softening in adhesive B.

Thick Adherend Lap Shear Tests on Butyl Adhesive

Bulk shear properties of any adhesive can be obtained either by a torsion-ring shear test or by a thick-adherend lap shear test. The torsion shear test has the capability of applying pure shear stresses on the adhesive through the application of a torque.[7] In a lap shear test, shear stresses are induced on the adhesive due to load eccentricities in the adjoining adherends. The adherends are normally made thick and rigid in comparison with the adhesive, so as to minimize the bending stresses that may be generated in the test setup. The test setup of a thick adherend lap shear test is shown in Figure 6.

The nature of shear stresses induced in the mid-plane of the adhesive layer in a lap shear test is a function of the geometry of the joint as well as the relative stiffness between the adherend and the adhesive.[20] Analysis of stress distributions in a lap joint indicate that the singular shear stresses induced at the lap ends due to the axial straining of the adherend are negligible if the adherend is very rigid compared with the adhesive. The current test setup consisting of aluminium adherends with butyl adhesive satisfies this requirement. The shear stresses induced in the mid-plane by such a test are the average shear stresses induced due to a uniform translation of the adherend.

In spite of the fairly uniform induced stresses on an adhesive test sample in a thick adherend lap shear test, considerable variations are observed in the load/displacement curves measured from such tests. The effective moduli, as interpreted

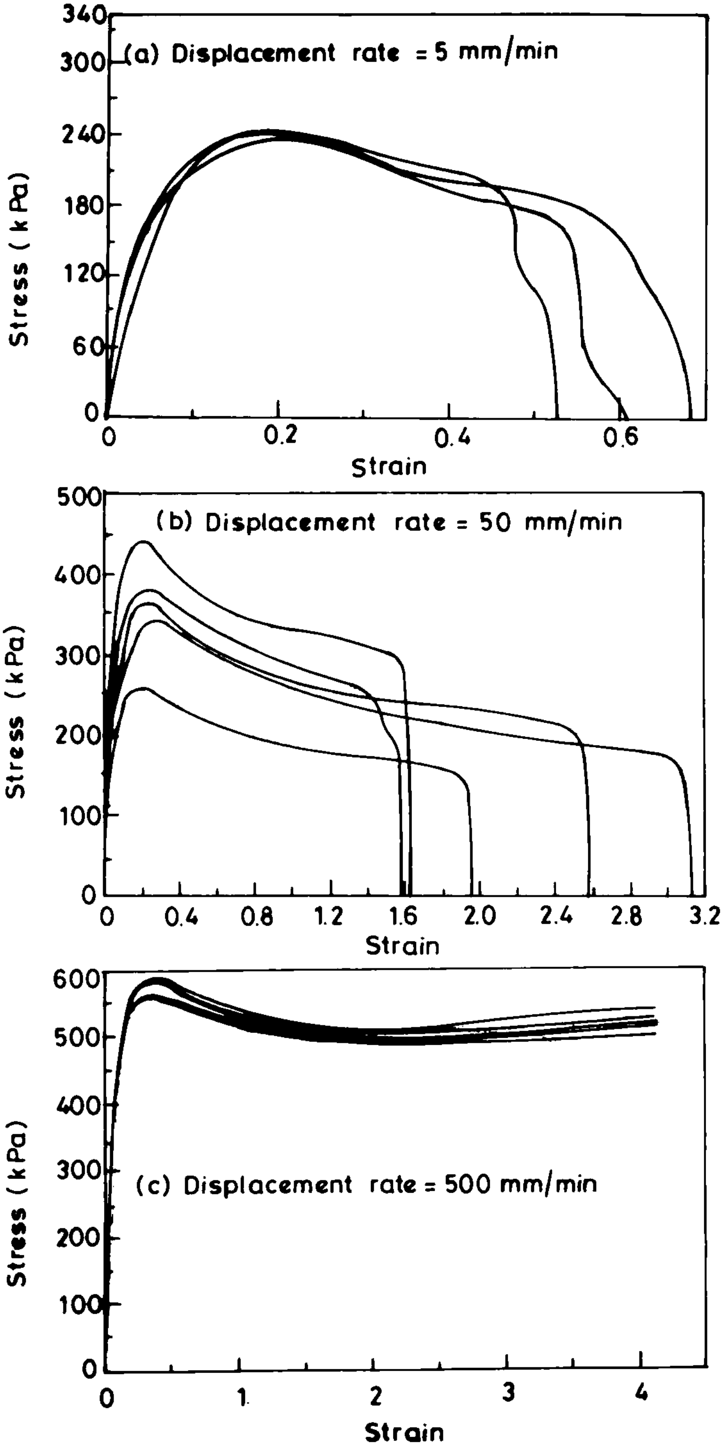

FIGURE 2 Stress-strain curves in uniaxial tension for adhesive A.

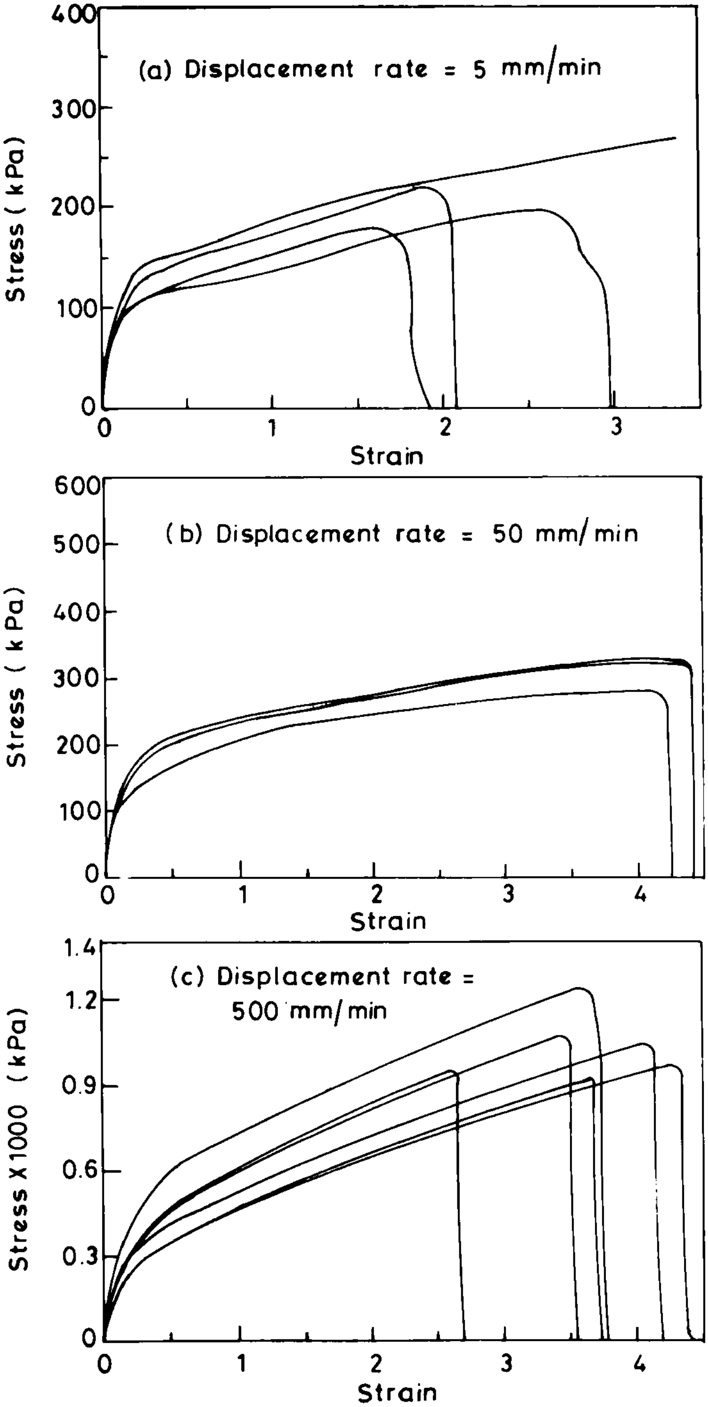

FIGURE 3 Stress-strain curves in uniaxial tension for adhesive B.

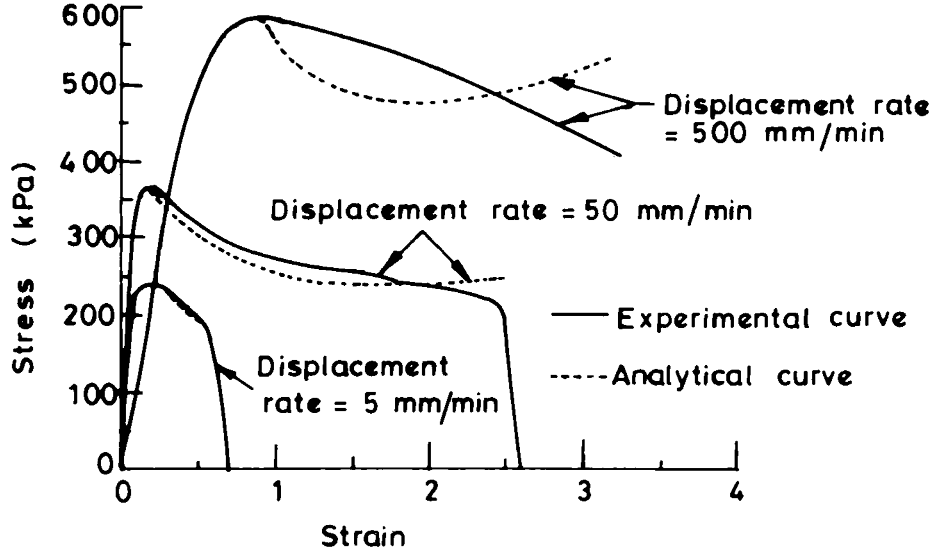

FIGURE 4 Stress-strain curves in uniaxial tension for adhesive A at different cross-head displacement rates: Comparison of experiments with analytical simulation.

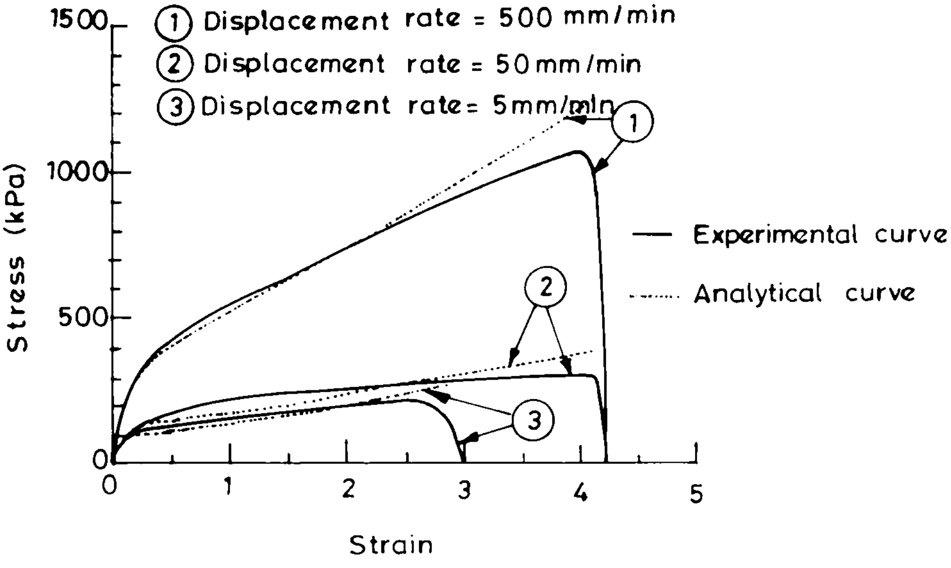

FIGURE 5 Stress-strain curves in uniaxial tension for adhesive B at different cross-head displacement rates: Comparison of experiments with analytical simulation.

TABLE I
Parameters used in the physical model

Adhesive type	Eyring values	Displacement rates											
		5 mm/min				50 mm/min				500 mm/min			
		k_H (kPa)	G (kPa)	G_2	σ_f (kPa)	k_H (kPa)	G (kPa)	G_2	σ_f (kPa)	k_H (kPa)	G (kPa)	G_2	σ_f (kPa)
A	$\dot{\gamma}_o = 8.955 \times 10^{-5}$/sec $V = 2.192 \times 10^{-22}$ m^3 $G_1 = 75.586$ kPa	1200	40	19	170	1825	50	186	220	773.33	120	1865	—
B	$\dot{\gamma}_o = 8.16 \times 10^{-4}$/sec $V = 2.585 \times 10^{-22}$ m^3 $G_1 = 64.103$ kPa	950	75	2	203	1100	75	20	298	1133.33	250	200	1030

σ_f = failure stress of the adhesive.

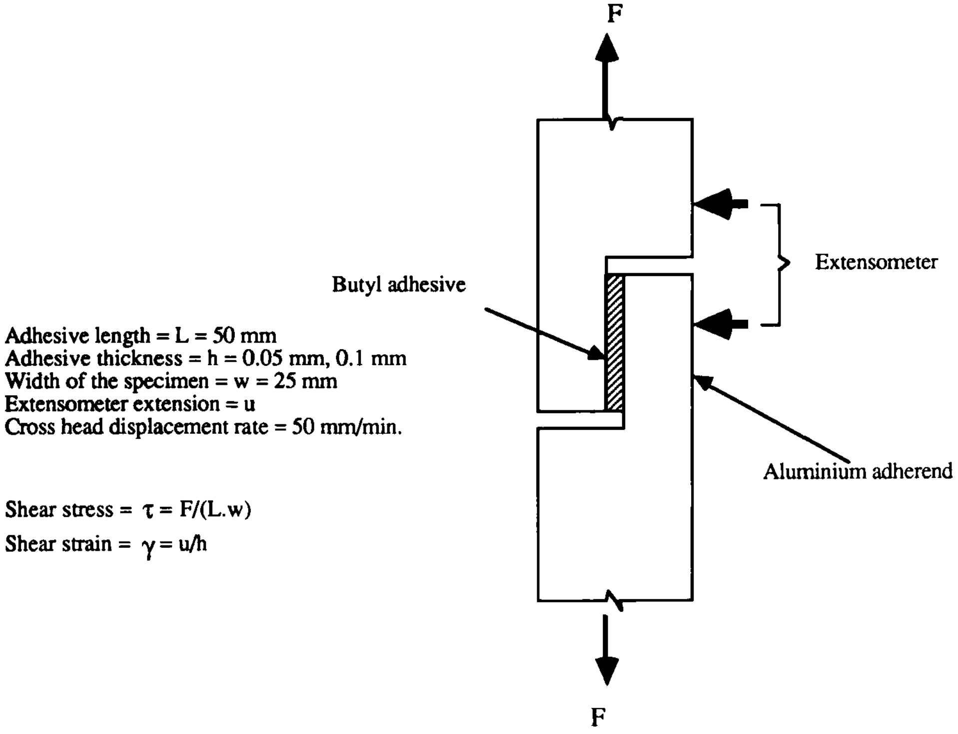

FIGURE 6 Schematic representation of thick-adherend lap shear test setup for butyl adhesive.

from these curves, were found to be a function of lap length and adhesive thickness.[8] This dependence suggests the influence of material inhomogeneities in the interpreted properties, indicating that it is very difficult to isolate a plane of homogeneous shear deformation in very thin samples. Hence, the effective properties, as interpreted from the load-displacement curves in these tests, must be judged to be indicative of the true properties. Such properties are useful to compare with properties derived from similar tests conducted on other adhesives.

The shear tests were conducted on adhesive A at a displacement rate of 50 mm/min, which corresponds to the rate at which lap shear tests are conducted on EPDM joints with butyl adhesives.[2] The predictions from the viscoelastic model developed in the earlier section are compared with the experimental results and some observations are made regarding the mechanics of shear deformations in the adhesive.

Specimen Preparation

Aluminium bars with cross-sectional dimensions of 25 mm × 25 mm were cut across their cross-section so as to make a half-lap geometry as shown in Figure 6. The adhering surfaces of the half-lap specimens were roughened by sand blasting to ensure good bonding of the adhesive with the substrate. Two thin aluminium strips of the desired adhesive thicknesses of 0.5 mm and 1 mm were glued on one of the substrates at a distance of 50 mm from each other so as to serve as a guide to maintain the geometry of adhesive when applied to the substrate. Adhesive A was applied on each substrate with the help of a rectangular metal strip and the adhesive was allowed to dry for 15 minutes so that it was not tacky to the touch. The two adherends were then joined to form a lap. The excess adhesive was scraped off the sides of the joint. A nominal deadweight of 20 kgf was placed on the joint to facilitate the formation of a good bond between the two laps. The joint was allowed to cure in this state for seven days under ambient atmospheric conditions before testing it in shear. The aluminium strips were removed after curing the test specimens.

Test Results and Discussion

Lap shear tests were conducted at a displacement rate of 50 mm/min at room temperature on adhesive A. The tests were conducted on this adhesive at two different values of adhesive thickness.

Six bulk shear samples were tested at an adhesive thickness of 0.5 mm and their stress-strain curves in shear are shown in Figure 7 (a). Nine samples were tested at an adhesive thickness of 1 mm and the stress-strain curves in shear for this thickness are shown in Figure 7 (b). Nominal stresses and nominal strains calculated from original undeformed cross-sectional dimensions were used to deduce the stress-strain curves from the load-displacement curves of the test specimens. The curves shown in Figures 7 have been truncated after their peak strength. Test samples with 0.5 mm thick adhesives had an average strength of 102.5 kPa (standard deviation = 28.7 kPa) while the 1 mm thick samples had an average strength of 78.9 kPa (standard deviation = 21.4 kPa). Average shear stress-strain plots for the two adhesive thicknesses giving the details of post-peak characteristics are shown in Figure 8. It may be observed that the adhesive undergoes a rapid stress decay after reaching an initial peak stress. The peak stresses are larger, and the post-peak stress decay is faster, with shear samples with an adhesive thickness of 0.5 mm, as compared with samples with an adhesive thickness of 1 mm.

CONSTITUTIVE MODEL FOR BUTYL ADHESIVE

Viscoelastic Models for Polymers

Any viscoelastic model should have the basic elements that can capture (a) small strain elastic response of the material, (b) yielding and rate sensitivity of the yield stress and (c) post-yield plastic flow in the material. One such model that is widely used to characterize the mechanical response of glassy polymers below their glass transition temperature, has been proposed by Haward and Thackray[13] and is illustrated in Figure 9. The model is similar to the standard linear solid used in the theory of viscoelasticity[14] and consists of (a) a Hookean spring, K_H, which is in series with a parallel combination of (b) a network spring, K_N, and (c) a viscous damper, C_V. The significance of each of these elements is explained below.

The Hookean Spring

The small strain elastic response of the polymer is captured by the Hookean spring, K_H. The resistance offered by the Hookean spring is due primarily to the intermolec-

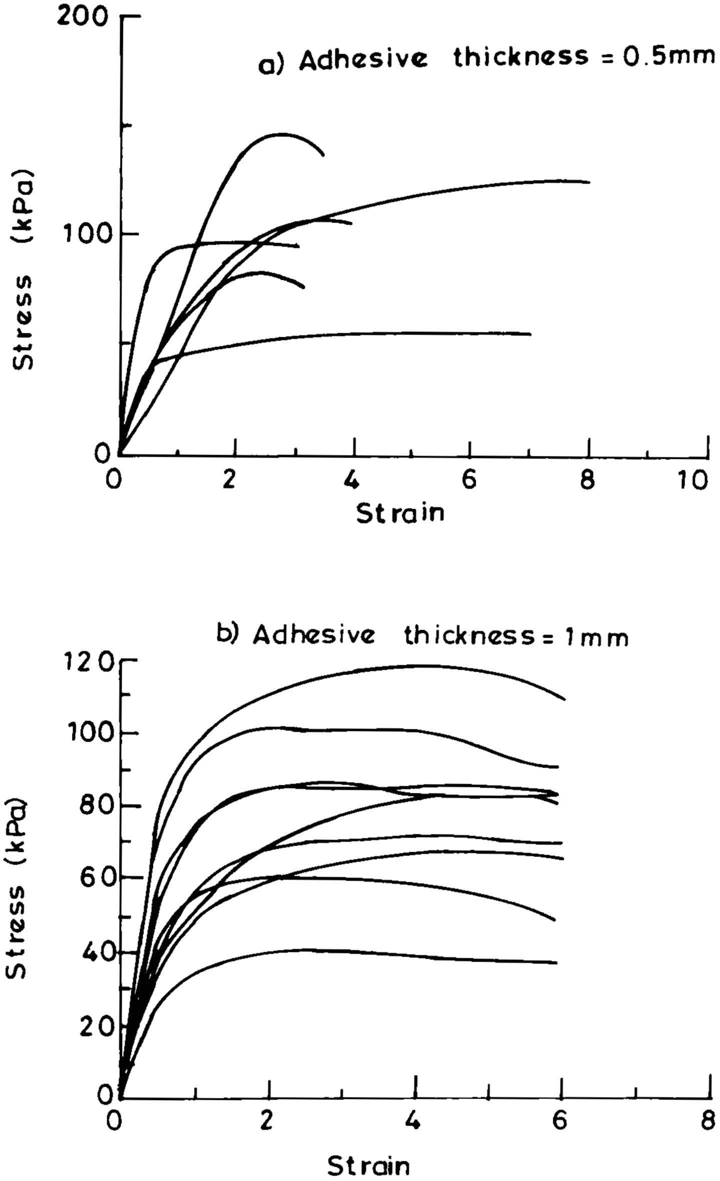

FIGURE 7 Shear stress-strain curves for adhesive A: (a) Adhesive thickness = 0.5 mm. (b) Adhesive thickness = 1 mm.

ular forces that determine polymer elasticity. For rubbery adhesives, the initial response is nonlinear, and is due mainly to network resistance offered by chemical crosslinks to freely-moving molecular chains. This resistance is activated immediately upon loading and dominates the response until the viscous force built up is sufficient to cause plastic flow.

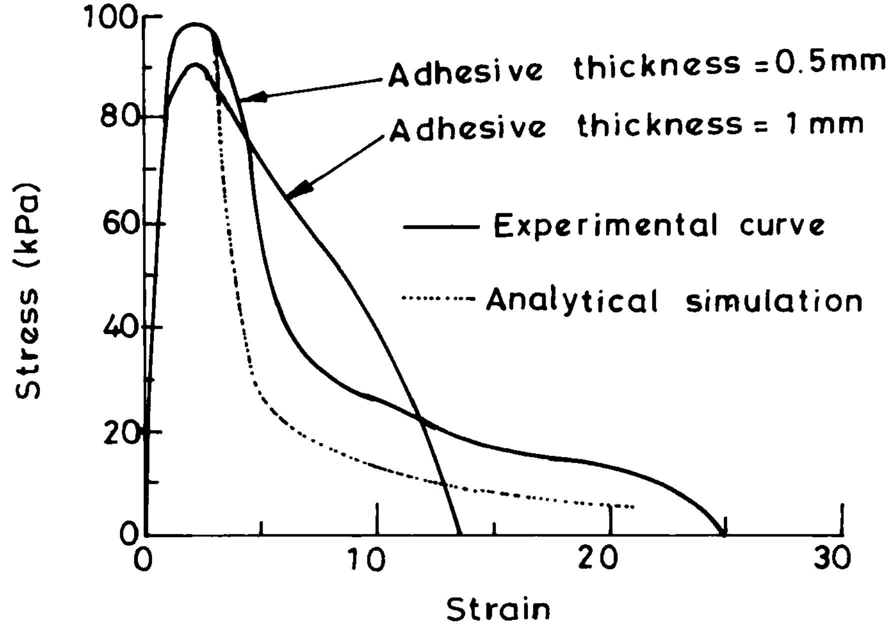

FIGURE 8 Shear stress-strain curves for adhesive A—comparison of experiments with analytical simulation.

The Damper with Eyring Viscosity

The viscous damper, C_V, captures the rate-sensitivity of yield stress and the post-yield stress decay of the polymer. The plastic flow is induced by the rupture of primary cross-links that are holding the molecular chains in the polymer. A number of molecular mechanisms can be postulated to explain the macroscopically-observed plastic flow in the polymer. For low-temperature deformations of rigid glassy polymers, Argon[15] has proposed a model that visualizes this plastic flow to be the effect of molecular alignments by the production of small molecular kink pairs in the polymer. While the Argon model gives a good explanation for the plastic deformation of polymers below their glass transition temperature, the plastic flow of polymers in their rubbery state is not likely to be governed by such mechanisms. Polymers that deform above their glass transition temperature (such as butyl adhesives) are already in a state of high mobility and are restrained in their motion only by the chemical or physical crosslinks with the neighboring molecules. The shear flow due to such mobile units is better captured by other viscous models. One such viscous model that is adopted for butyl adhesives in the present work is described below.

Based on the rate of mobility of individual molecules past potential energy barriers, Eyring[16] derived an expression for the viscous drag experienced by molecules when they are in a state of motion. Haward and Thackray[13] have used the shear flow model derived from such an assumption to characterize the post-peak

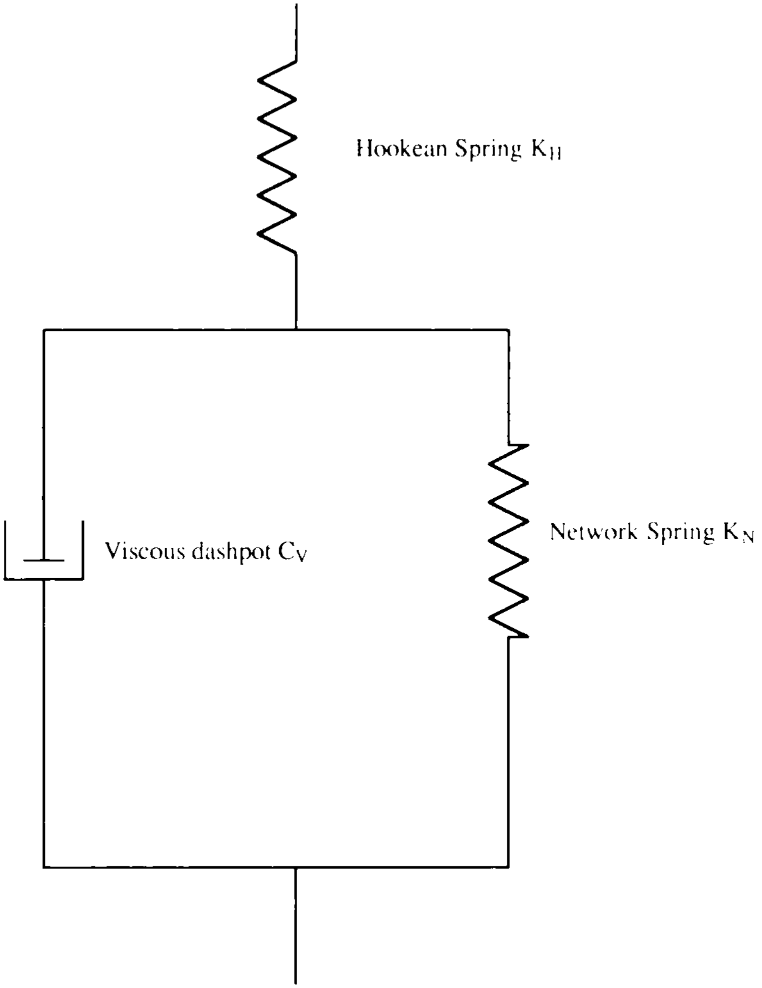

FIGURE 9 Viscoelastic model to characterize the mechanical properties of butyl adhesive.

plastic flow in polymers. Eyring's viscous model is a two-parameter model that relates the rate of shear flow inside the polymer to the applied shear stress and is of the form

$$\dot{\gamma} = \dot{\gamma}_0 \operatorname{Sinh} \frac{V\tau}{2kT} \qquad (1)$$

where k is Boltzmann's constant, T is the absolute temperature and τ is the applied shear stress. The constant $\dot{\gamma}_0$ governs the magnitude of the shear flow rate, while the constant V, also known as the Eyring volume, determines the rate of decay of the plastic flow of the polymer. In an uniaxial tension test, the internal shear stress, τ, is related to the externally-applied nominal tensile stress, σ, through the relation:[13]

$$\tau = \frac{\sigma \cdot \lambda}{2} \tag{2}$$

where λ is the extension ratio of the tensile specimen. Treating $\dot{\gamma}$ as the axial plastic flow strain rate, substituting the expression for shear stress from Equation 2 into Equation 1 and neglecting the negative exponential terms, we get the following stress-strain relations for the post-peak stress decay of the polymer with Eyring dashpot:[13]

$$\sigma_{vis} = \frac{4kT}{V\lambda} \ln\left(\frac{1}{\dot{\gamma}_o}\frac{\dot{\lambda}}{\lambda}\right) \tag{3}$$

where $\dot{\lambda}$ is the applied strain rate on the tensile specimen.

The Network Spring

The network spring captures the recoverable portion of the post-yield response of the polymer. Because of the recoverable nature of deformation, the stress generated by this spring is also called the elastic backstress. The backstresses are generated by the secondary cross-links which are still active in the polymer. The resistance due to this elastic backstress can be modelled by any of the network models of rubber elasticity. In the present study, a Gaussian model of rubber elasticity is used to model the backstress and is given by:[17]

$$\sigma_{bs} = G\left(\lambda - \frac{1}{\lambda^2}\right) \tag{4}$$

where σ_{bs} is the elastic backstress and G is the shear stiffness of the molecular network.

Post-Yield Response of Butyl Adhesive

The post-yield behavior of the stress-strain curve is determined by the slope, s, of the plastic flow, σ_p, which is the sum of the backstress, σ_{bs}, and viscous flow stress, σ_{vis}. Using Equations 3 and 4, we get

$$s = \frac{d\sigma_{p'}}{d\lambda} = \frac{d(\sigma_{vis} + \sigma_{bs})}{d\lambda} = -\frac{G_1}{\lambda^2}\left[\ln\left(\frac{G_2}{\lambda}\right) + 1\right] + G\left(1 + \frac{2}{\lambda^3}\right)$$

$$\text{where } G_1 = \frac{4kT}{V} \text{ and } G_2 = \frac{\dot{\lambda}}{\dot{\gamma}_o} \tag{5}$$

We now examine the nature of s for various values of G_1, G_2 and λ. We observe that

a) If $G_2 \ll \lambda$, $\ln\left(\frac{G_2}{\lambda}\right) + 1 < 0$; and $s > 0$ for all λ

b) If $G_2 > \lambda$, $\ln\left(\frac{G_2}{\lambda}\right) + 1 > 0$; and $s > 0$ if $G\left(1 + \frac{2}{\lambda^3}\right) > \frac{G_1}{\lambda^2}\left(\ln\left(\frac{G_2}{\lambda}\right) + 1\right)$

$$s < 0 \text{ if } G\left(1 + \frac{2}{\lambda^3}\right) < \frac{G_1}{\lambda^2}\left(\ln\left(\frac{G_2}{\lambda}\right) + 1\right) \tag{6}$$

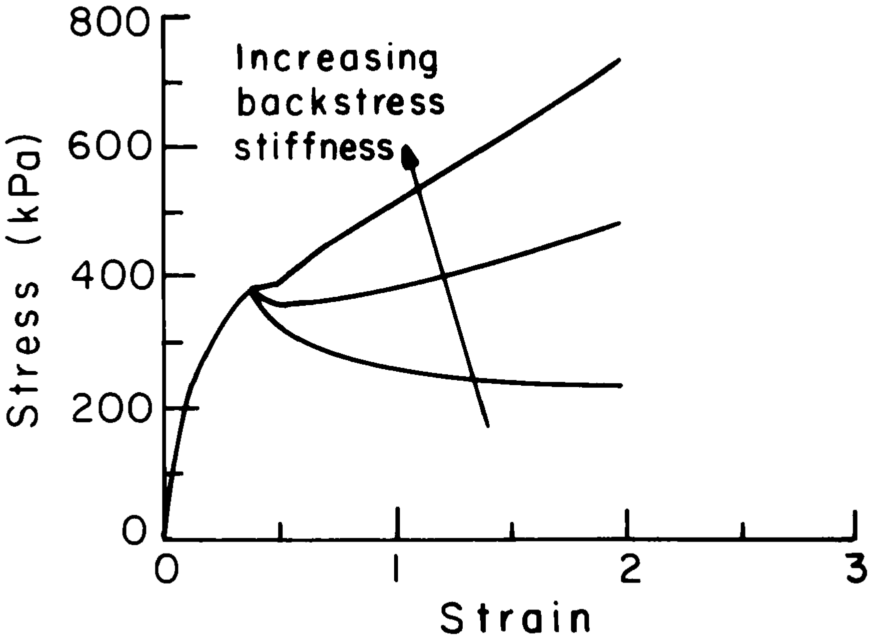

FIGURE 10 Representative stress-strain plots for a polymer, generated from the assumed physical model.

Equations 6 indicate that the parameters of the physical model can be adjusted to simulate a range of post-yield stress-strain characteristics of the polymer. Figure 10 illustrates this point schematically where the model parameters were modified to simulate the strain-softening as well as the strain-hardening response of the polymer. The yield stress itself is normally related to micromolecular processes such as local rupture of primary bonds in the molecule. These mechanisms cannot be captured by phenomenological models that are primarily based on mathematical description of observed macromechanical behavior of the polymer. The yield stresses are estimated experimentally and fitted into the assumed physical model of the polymer.

Model Parameters for Butyl Adhesive

The constitutive model described in the above section has been used to simulate the average uniaxial stress-strain curves shown in Figures 4 and 5. The stiffness of the Hookean spring is taken to be the secant modulus corresponding to the initial rise in the stress-strain curve. The parameters of the Eyring viscosity model, *i.e.*, $\dot{\gamma}_0$ and V, are computed by making a least-squares fit of the Eyring Equation (3) rewritten for incipient plastic flow ($\lambda = 1$) as:

$$\ln \dot{\lambda} = \ln \dot{\gamma}_0 + \frac{V}{4kT}\sigma_y \qquad (7)$$

Equation 7 gives a linear relation between the yield stress and the logarithm of the applied strain rate. For adhesive A, σ_y is defined to be peak stress and for adhesive B it is defined as the stress at which there is a change of slope in the tangent modulus. The stiffness, G, of the network models given by Equation 4 is adjusted so as to obtain a least-squares fit with the post-yield response of the polymer.

Table I shows the model parameters that were obtained for both of the adhesives that were considered for the present study. It may be seen that the stiffness, K_H, for adhesive A decreases at higher displacement rates while the K_H increases with displacement rates for adhesive B. The decrease in stiffness in the aged adhesive is probably due to low mobility in the aged polymer which prevents the molecules from aligning themselves in the most favored configurations that would resist the applied loads. The Eyring values $\dot{\gamma}_o$ and V are reflected in the parameters G_1 and G_2 of the model. While G_1 is approximately the same for both models, G_2 for adhesive A is ten times as high as G_2 for adhesive B. It may be seen that the backstress stiffness, G, used to simulate the response at higher displacement rates is two to three times the values used for lower displacement rates.

A comparative study of both adhesives indicates that the viscous flow of adhesive A, (as reflected in G_2) is high compared with the viscous flow of adhesive B. This correlates with the shrinkage characteristics of the two adhesives that were reported earlier in this paper. The increase in stiffness (of the Hookean spring as well as the backstress spring) with displacement rate in both adhesives is explained by the fact that a greater number of physical entanglements come into play at higher displacement rates and contribute to the resistance of the network, when compared with deformations at lower displacement rates. The failure strengths of adhesive B are generally higher than the failure strengths of adhesive A. The difference in strengths could be due to the difference in the chemical characteristics of the adhesive or due to the deterioration of polymeric networks of adhesive B due to aging.

Tensile Strength of Butyl Adhesives

Failure of a tensile test specimen occurs due to unstable growth of a dominant flaw in the test specimen. Tensile strength is a macroscopic phenomenon which is an aggregate effect of opening up a number of flaws in the specimen. The test results indicate that the failure strength increases with increase in displacement rate in a uniaxial tension test. A fundamental property that is indicative of this macroscopic behavior is the tear energy associated with crack propagation when the crack is subjected to tensile loading. Tear energy is measured as the strain energy released due to crack propagation over a unit distance in the test specimen. Lake and Thomas[18] have measured the tear energy for natural rubbers and have found that the critical tear energy for unstable crack propagation is high for rubbers with large mechanical hysteresis. Similarly, Gent and Schultz[19] have observed that mechanical hysteresis is responsible for the dependence of peel strength of the adhesives on displacement rate. Local hysteresis effects are directly proportional to global displacement rates on any specimen and are responsible for large energy absorption in any test situation.[18] Hence, the rate dependency of the tensile strength observed in butyl adhesives in the present work is consistent with the results reported by the above researchers for rubbers and other adhesives.

Shear Response of Butyl Adhesives

The viscoelastic model for butyl adhesives developed in the earlier section could be used to simulate the post peak response of the adhesive in shear. The response simulated by the model would strictly correspond to the behavior of a bulk sample in shear. However, the model predictions would also be indicative of the response of thin adhesive layers in a lap shear test. The rapid post-peak stress decay in the shear tests indicates the absence of contributions from the elastic backstress (due to K_N) to the overall shear strength of the adhesive. The analytical simulation of the shear response based on such assumptions ($K_N = 0$), as shown in Figure 8, is close to the post-peak characteristics observed in the experiments.

The absence of backstress in the shear samples can be attributed to the presence of a large number of air voids that were entrapped within the adhesive cross-sectional area while conducting the experiments. These voids introduce discontinuities in the local stress fields and contribute to the rupture of the secondary cross-links that are responsible for the development of backstresses in the adhesive. The evidence for air voids is obtained by looking at the photographs of a typical fractured shear test sample shown in Figure 11. Since the volume fraction of air voids in extremely thin samples is likely to be very high, we find evidence of faster stress decay (due to lack of backstress) in the 0.5 mm samples as compared with the 1 mm samples. The increase in strength, and decrease in plastic strain to failure, with the reduction of the adhesive thickness has also been observed in shear tests with epoxy adhesives and has been attributed to end effects in the bonded joint.[7]

The thickness of adhesive layers reported for typical EPDM lap joints is about 0.125 mm.[2] The estimation of the true engineering properties of adhesive layers of such small thickness would require us to conduct shear tests with very thin adhesive layers. It is difficult to fabricate thin homogeneous shear test samples of adhesives with low shear strength (such as the butyl adhesives), which also have low viscosity in their wet state. Furthermore, it is difficult to ensure that the failure in the thin samples occurs within the adhesive and not at the adhesive-substrate interface. Thus, the shear properties of the adhesive in its thinner states must be extrapolated from tests on samples that are several orders thicker than the actual thickness of the adhesive in operating conditions.

SUMMARY AND DISCUSSION

Uniaxial tension tests and lap shear tests were conducted on bulk samples of butyl adhesives. A three parameter viscoelastic model consisting of a Hookean spring, an Eyring dashpot and a network spring has been used to model the mechanical response of butyl adhesive. The model effectively captures the initial elastic response and rate sensitive yield as well as post-yield strain hardening/strain softening

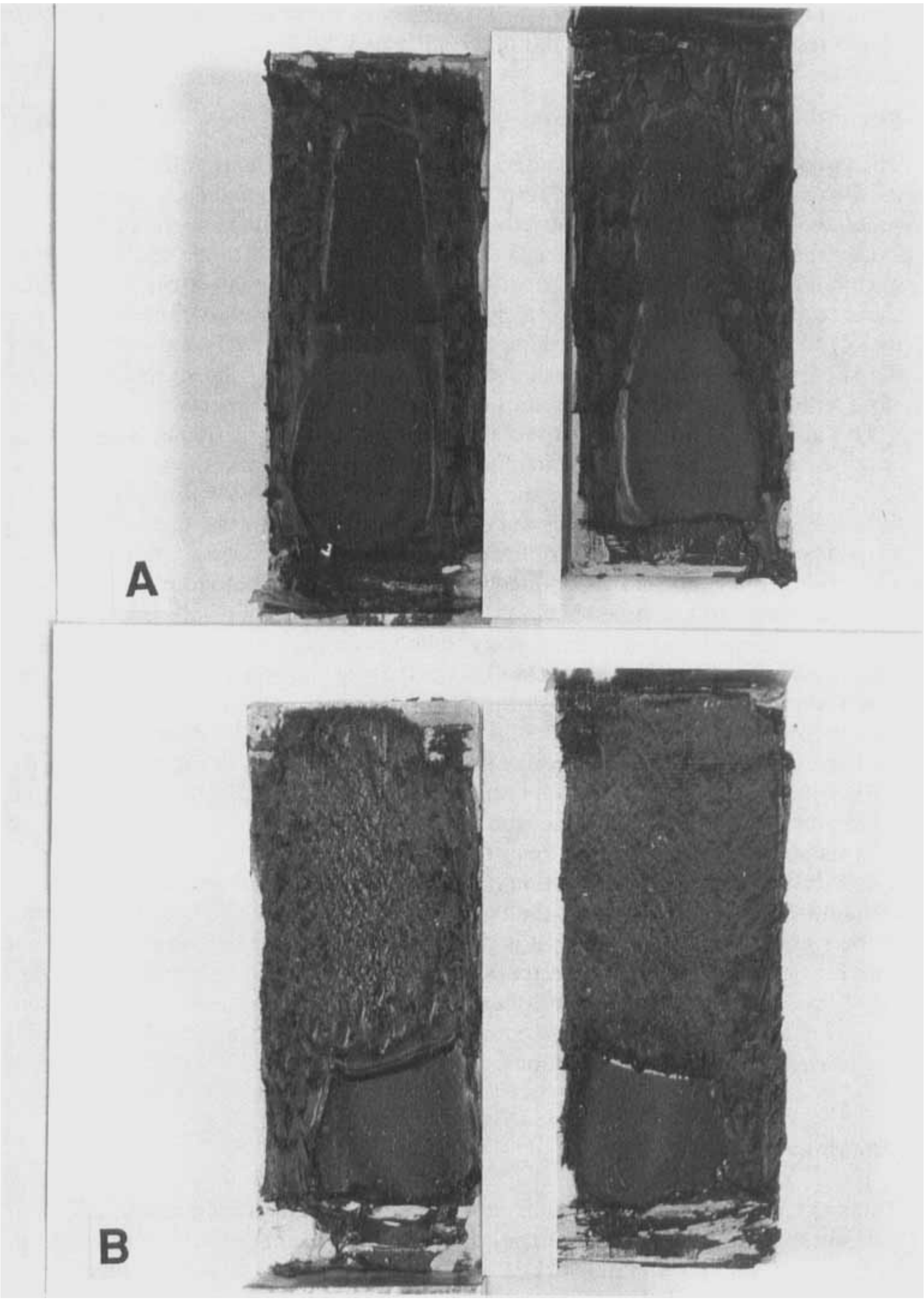

FIGURE 11 Failed surfaces of thick adherend lap shear tests with butyl adhesives, showing the presence of voids. A: Specimen with large void ratio. B: Specimen with small void ratio.

response of the material. The viscoelastic responses of the two adhesives chosen for the study were found to be sensitive to displacement rates applied to the test samples. The observed test results were vastly different for the two adhesives and it is suggested that this difference could be due to difference in (a) age of the samples, (b) inhomogeneities associated with the samples and (c) chemical composition of the two adhesive formulations.

The peak strengths of the butyl adhesives in tension as well as in shear were found to be significantly lower than the strengths that are normally observed in epoxy-based adhesives. Bulk samples of epoxy-based adhesives are reported to have tensile strengths ranging from 10 MPa to 80 MPa and a failure strain ranging from 0.05 to 4.5.[9] The shear strengths of epoxy-based adhesives are reported to range from 20 to 58 MPa with failure strains ranging from 0.4 to 2.8.[7,8,11] The strengths of butyl adhesives are at most one-tenth those reported for epoxies. The observed failure strains are about ten times as large as those observed in most epoxy adhesives. The differences in the properties are mainly attributed to the differences in the nature of the polymeric networks that constitute these adhesives.

Acknowledgements

The authors express their appreciation to Mr. Walter J. Rossiter of the National Institute of Standards Technology for his guidance as well as for allowing the authors to use the facilities of NIST for preparing the bulk samples of butyl adhesives. The work was supported by grants from the Program for Advanced Construction Technology of the Army Research Office at MIT.

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