euro•noise '92

NOISE REDUCTION WITH RUBBER

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1. INTRODUCTION

Passive means of reducing airborne noise may take effect either on its transmission and relection, or on its generation by a source of vibration. The latter method can involve either the isolation of the source of vibration from surrounding structures, or the damping of those structures that, if allowed to resonate, would generate the airborne noise. Rubbery materials can be used to advantage in all the above strategies.

It is the purpose of this paper to review the relationship between the physical properties of the rubber and its performance in these applications.

Experimental results are presented for the dynamic shear modulus (G^*) and loss factor (tanδ) of natural rubber (NR) and epoxidized natural rubber (ENR, formed from NR by chemical modification). The effectiveness of these polymers for the damping of laminated beams is assessed experimentally.

2. APPLICATIONS

2.1 Acoustic Barriers

Sound is transmitted through air as longitudinal waves (ie. successive compressions and dilations) travelling at a speed of about 330ms^{-1}. When incident on a solid barrier, the pressure fluctuations will cause oscillatory motion. The barrier, perhaps serving as a wall, will generate sound on the other side according to the amplitude of these motions [1], while the less the motion the greater the reflection of sound. In the mid-frequency range, the amplitude of the motion is approximately inversely proportional to the mass of the barrier, so that massive barriers perform best. Above and below this frequency range, resonance and wave effects in the barrier can impair the sound insulation. The greater the damping within the beam, the smaller the impairment [2,3]. Polymers could be used to achieve such damping (see section 2.4). A wall consisting of a thick rubber core faced with layers of a much stiffer material has also been advocated as a way of avoiding transmission at high frequency due to coupling of flexural waves and airborne sound [3]. However, dense materials such as masonry are more commonly used as the basic material.

In principle, the sound could be absorbed rather than reflected but an absorbing barrier must be at least half a wavelength thick (wavelength in air = 660mm for 500Hz). Such a thick barrier would generally be impractical, but absorbing coatings are used with benefit to reduce noise within a room.

2.2 Anechoic coatings

In a room with hard walls, reflection can cause sound waves to be confused, and thus perceived as noise which may fade only gradually to inaudibility. Although the most effective way of suppressing reflection is to remove the walls, benefit can be obtained by means of 'sound absorbing' or anechoic coatings.

Reflection increases with the mismatch of acoustic impedances ($Z = \rho c$ where ρ is the density and c the speed of sound in the material in question). Thus if a polymer is to be used as an anechoic coating not only its damping is important, but also the density and elasticity (which together determine c and hence Z).

If sound waves are transmitted through a medium with damping, such as a polymer, the amplitude decays exponentially with distance travelled. For modest values of loss factor ($\tan\delta$), the spatial decay of amplitude is $e^{-\alpha x}$, where $\alpha = \pi\tan(\delta)/\lambda$, λ being the wavelength.

Open cell rubber foams are convenient for absorbing sound waves travelling in air, since both viscous flow of air in the pores and deformation of the rubber contribute to damping.

A wide range of methods, such as a wedge structure (this smearing out the impedance mismatch over an adequate depth) and loading with dense filler and vacuoles can also help to provide the properties necessary for particular applications [4,5].

2.3 Vibration Isolation

The amplitude of vibrations reaching a possible 'sounding board' such as a panel, floor or wall can be reduced by using rubber vibration isolation springs. Such springs must have a sufficiently low dynamic stiffness, so that the force required to deflect them at the amplitude of the vibration is small compared to that required to overcome the inertial resistance to motion of the isolated structure. Damping is useful in reducing peaks in transmission associated with the primary mass-spring resonance or internal resonances of the spring but is undesirable at other frequencies, [6]. This is because for polymers damping implies an increase in dynamic stiffness as the frequency f is increased [7]:

$$\frac{d\ln G'}{d\ln f} = \frac{2}{\pi}\tan\delta \qquad (1)$$

where G' is the storage modulus (equal to $|G^*|\cos\delta$).

2.4 Damping of Panels

Structure-borne vibrations are converted to airborne noise when they excite vibration of a surface, such as a ceiling or a metal panel [1].

Damping can be used to reduce both the transmission of vibrational waves through the structure and the amplitude of the 'sounding board' vibration. A very effective way of using viscoelastic materials to this end is as constrained or integral damping layers. Essentially, if the modulus of the viscoelastic layer is low it will be deformed largely in shear (Figure 1). The shear strain γ decays along the beam (x-direction) according to:

$$\gamma \propto e^{-gx} \tag{2}$$

where the "shear parameter" g is given by:

$$g^2 = \frac{G_2'}{H_2}\left(\frac{1}{E_1H_1} + \frac{1}{E_3H_3}\right) \tag{3}$$

Assuming that the damping of materials 1 and 3 is negligible compared to that of material 2, the maximum loss factor of the composite beam corresponds to storage of the maximum fraction of strain energy in layer 2. If the thickness of layer 2 is very small, the shear in it decays over a short distance, due to extension and compression of layers 1 and 3 under the shear tractions. If the thickness of layer 2 is large, the shear strain in it is small. According to Ungar [8], in between these extreme cases the fraction of strain energy stored in the rubber reaches a maximum (and so the loss factor of the composite beam also reaches a maximum) at a value of g given by:

$$g^2_{opt} = \frac{4\pi^2}{\sqrt{(1+Y)(1+\tan^2\delta)}\,\lambda^2} \tag{4}$$

where λ is the flexural wavelength, $\tan\delta$ is the loss factor of material 2 and Y is given by:

$$\frac{1}{Y} = \frac{E_1H_1^{\,3} + E_3H_3^{\,3}}{12(H_2+(H_1+H_3)/2)^2}\left(\frac{1}{E_1H_1} + \frac{1}{E_3H_3}\right) \tag{5}$$

Substituting (3) and (5) into (4) leads to a quadratic equation for the thickness H_2 at optimum damping:

$$H_{2opt} = \frac{a^2b(H_1+H_3) \pm a\sqrt{b(H_1+H_3)^2 + 4(1-a^2b)}}{2(1-a^2b)} \tag{6}$$

where a and b are given by:

$$a = \sqrt{1+\tan^2\delta}\,\frac{\lambda^2 G_2'^2}{4\pi^2}\left(\frac{1}{E_1H_1} + \frac{1}{E_3H_3}\right)$$

$$b = \frac{12}{E_1H_1^3+E_3H_3^3}\left(\frac{1}{E_1H_1} + \frac{1}{E_3H_3}\right)^{-1}$$

For typical values of the elastic and geometric constants, equation 7 reduces to:

$$H_{2,opt} \simeq 0.5a\sqrt{b(H_1+H_3)^2 + 4} \qquad (6a)$$

The expression due to Ungar [8] for the loss factor of the beam is:

$$\eta = \frac{YX\tan\delta}{1 + (2+Y)X + (1+Y)(1+\tan^2\delta)X^2} \qquad (7)$$

where $X = \lambda^2 g^2/4\pi^2$

3. DYNAMIC PROPERTIES

3.1 Experimental

As explained above, the dynamic properties of a rubber play a key role in determining its effectiveness in the control of vibration. The purpose of this section is to report the dynamic properties of NR and ENR. The latter is available in two levels of epoxidation, 25% and 50%, which possess increased damping compared to NR. Vulcanizates of ENR-25 and ENR-50 were prepared according to the formulations given in Table 1 and bonded to aluminium alloy endpieces using the Chemlok 205/220 system to form double shear testpieces. A similar testpiece was also prepared from liquid ENR-50 by painting on a solution of the rubber in toluene; once the toluene had evaporated the alloy endpieces could be stuck together, exploiting the adhesive properties of the LENR-50. Dynamic shear tests were carried out on a Schenck VHF7 servohydraulic machine. It subjected each testpiece to a sinusoidal displacement over a range of frequencies (0.5-200Hz) at each of several temperatures in the range -15 → +49°C; the force and displacement signals were analysed with a Solartron 1250 Frequency Response Analyser. By definition:

for a shear strain $\gamma = \gamma_o e^{i\omega t}$
the shear force is $\sigma = \gamma_o G^* e^{i\omega t}$ (7)
where $G^* = |G^*|(\cos\delta + i\sin\delta)$

The dynamic properties of the NR vulcanizate (formulation is given in Table 1) were determined by a wave propagation technique for frequencies in the range 300-2000Hz and temperatures in the range -50°C to 35°C. The details of the technique have been reported elsewhere [9].

3.2 Results and Discussion

Mastercurves are given in Figure 2. These were generated by horizontal shifts of the $|G^*|$ data sets for individual temperatures along the log (f) axis. The same shifts were then applied to the tanδ data. In all cases the shift factors obeyed the WLF transform [10], and experimental values for T_s are given in Table 1.

The segments of mastercurves given in Figure 2 for vulcanizates of NR, ENR-25 and ENR-50 are similar in shape, although superposing them by shifts along the frequency axis suggests that as the level of epoxidation is increased the mastercurve broadens slightly. The magnitudes of these horizontal shifts are in good agreement with the differences in the empirical values of T_s given in Table 1 and the WLF transform [10]. The values of T_s for NR, ENR-25 and ENR-50 are approximately 50°C above their Tg values as expected [10].

In general there is no reason to expect polymers to have the same shape for their mastercurve. An example of a different shape of mastercurve is provided by LENR-50. The lack of crosslinks and a molecular weight only of the order of that required for physical entanglements results in the complete absence of a plateau region for the modulus as the frequency is reduced [11]. Consequently the loss factor remains high. Over the range of experimental conditions tanδ was found to be constant and in consequence $\log|G^*|$ would be expected (from equation 1) to increase linearly with log (f) as is seen to be the case in the Figure. However, the gradient $d\ln|G^*|/d\ln(f)$ is 0.51 instead of the value of 0.6 predicted from equation 1 with tanδ ≈ 0.95. It is intriguing that T_s was found to be only 8.5°C, ie. 16°C below that of ENR-50 while the Tg of the LENR-50 is 5°C above that of ENR-50.

4. DAMPING OF BEAMS

4.1 Experimental

The free decay of beams consisting of a polymer layer sandwiched between steel and aluminium layers was assessed in a manner similar to that of BS AU125 (1966), Appendix A. The polymeric materials used were as given in Table 1.

Tests were carried out using a steel bar 300x40x5mm suspended on cotton 67mm from each end, corresponding to the nodal positions. The configuration corresponded to "b" of [12]. The out-of-plane fundamental resonance of each bar is ~290Hz, the in-plane resonance being around 2180Hz. Polymeric damping layers (2mm thick) were stuck to the steel bars using double sided tape, and an aluminium plate 300x40x2mm was likewise stuck to the other side of the polymer layer. The damping characteristics were first assessed by striking the steel bar and comparing the time that the characteristic ringing tone was audible.

Subsequently, samples of ENR-50 cores of a wider range of thickness were prepared (using LENR-50, in a layer about 10μm thick, as the adhesive) and damping was measured using a microphone and a Solarton 1201FFT analyser to capture the data. It was found necessary to use a Butterworth fifth order filter to attenuate signals from higher modes. The damping was assessed from the logarithmic decrement of the fundamental mode (~290Hz). Further measurements were made of the decay of the in-plane mode (~2180Hz) using a miniature accelerometer mounted on the edge of the steel plate as a pick-up. For some samples the damping in this mode was so low that the logarithmic decrement method proved inaccurate, and damping was calculated instead from the half-power bandwidth.

4.2 Results and Discussion

The ringing tone was sometimes audible for several seconds, but by ear it proved possible only to rank the different samples. Rankings for temperatures of -15, 0, 23 and 50°C are given in Table 2, where rank 1 is taken as the material giving the shortest time of ringing.

Using the FFT analyser, the loss factors associated with the 290Hz (out-of-plane) and 2180Hz (in-plane) of these testpieces at room temperature are given in Table 3. Values of loss factor calculated from the dynamic properties of the polymers using equation 7 are included in the Table for comparison. It is apparent that the loss factors at 290Hz bear little relationship to the ranking given in Table 2. However, the measurements of loss factor of the 2180Hz mode suggest that the ranking by ear may reflect an admixture of (at least) these two modes.

It is thought that the effectiveness of the polymers to damp the in-plane vibrations is related to their influence on the coupling between the aluminium and steel beams. A high degree of coupling would be associated with a thin or high-modulus polymer layer; the strain energy in the polymer and hence the composite loss factor would then be low.

The predictions of equation (7) are not in good agreement with the measurements, even though the technique gives a loss factor for the steel bar alone in fair agreement with the literature value [12,13]. It was thought that the extra damping apparent in the measurements may relate to the use of double-sided tape on each side of the rubber - unlike the 'bonded' boundary conditions assumed by the theory. For this reason subsequent tests were performed using LENR-50 as an adhesive to replace the double-sided tape. In the case of LENR-50 alone, equation 7 does seem to provide a fair prediction (Table 3), but when used as an adhesive for vulcanized sheets of ENR-50 of various thicknesses the predicted and measured loss factors are still not in good agreement (Figure 3). However, the general trend and magnitudes of measured loss factors resemble the predictions, although displaced to thicker layers. The suggestion of an increase in loss factor at high rubber thickness is not predicted by the Ungar theory [8] which is not applicable for rubber layers thick enough to modify the shape of flexure.

In the case of LENR-50 alone, the optimum thickness and beam loss factor predicted from equations 6 and 7 are 7.3μm and 0.1 respectively. It is apparently nearly as effective as using a thicker (optimum) layer of vulcanized ENR-50, and rather easier to construct. However, because of the absence of crosslinking in the LENR-50 it is subject to viscous flow.

5. CONCLUSIONS

An important application of rubbers in controlling noise is in the damping of panels and beams. Such damping may help reduce transmission of airborne noise across a panel acting as a barrier. It may also help to reduce structure borne vibrations and their conversion into airborne noise.

In general not only the loss factor of a 'damping material' is important in determining its effectiveness but also its dynamic shear modulus. Precisely how one chooses the optimum properties depends on the application and geometrical details.

The effect of epoxidation of natural rubber is to increase the Tg while not greatly altering the shapes of the mastercurves of dynamic properties versus frequency. Thus the dynamic properties af ENR at a temperature significantly above its Tg are similar to those of NR at a lower temperature, so that the loss factor, dynamic modulus and frequency sensitivity are all increased.

An investigation of damping of composite beams by means of a constrained rubbery layer has demonstrated that the ear may be misled by ringing from in-plane modes, while the measured loss factors are strongly influenced by the details of how the rubbery layer is stuck to the metal layers. Nevertheless, the experimental results confirm the prediction of Ungar's theory that the rubber thickness for optimum damping is very small, of the order of that of a layer of adhesive. This suggests it could be more convenient to use a liquid rubber rather than a sheet of pre-vulcanized material. The dynamic properties of liquid ENR-50 have been measured. The lack of crosslinks is beneficial in that the loss factor is constant over a broad frequency range, but stability of the composite structure is impaired by viscous flow.

TABLE 1: Formulation of the Elastomers used

ENR-50	100	-	-	-
ENR-25	-	100	-	-
NR (SMR L)	-	-	100	-
Liquid ENR-50	-	-	-	100
Calcium Stearate	5	5	5	-
Zn Oxide	5	5	5	-
Stearic Acid	2	2	2	-
Anti-oxidant	1	1	1	-
Sulphur	1.5	1.5	1.5	-
TBBS	1.5	1.5	1.5	-
Cure temperature (°C)	130	130	130	-
Cure time (min)	34	30	47	-
Tg (DSC from -100°C @ 20°C/min)	-23.8	-41.5	-68.1	-18.5
T_s (WLF time-temp superposition)	24.5	2.5	-19.5	+8.5
Mn (by GPC)	-	-	-	12 400

TABLE 2: Ranking of Damping Treatments by Ear
(rank 1 = greatest damping; all polymer layers 2mm thick)

	Test Temperature (°C)			
Damping Material	-15	0	23	50
None	4	4	4	4
NR	1	2	2	3
ENR-25	2	1	1	1
ENR-50	3	3	3	1

TABLE 3: Measured loss factors for the testpieces of Table 2 (at 23°C) and some LENR-50 testpieces

Damping Material	Out-of-plane (~290Hz) Theory*	Experiment A	Experiment B	In-plane (~2180Hz) Experiment A	Experiment B
None	-	-	0.5×10^{-4}	-	1.3×10^{-4}
NR	0.0007	0.003	-	0.022	0.016
ENR-25	0.004	0.020	-	0.010	0.006
ENR-50	0.030	0.080	-	0.006	0.002
LENR-50 (125μ)	0.021	0.034	-	-	2.0×10^{-4}
LENR-50 (25μ)	0.070	0.092	-	-	1.8×10^{-4}

* - Equation (7); A - calculated from logarithmic decrement; B - calculated from half band width.

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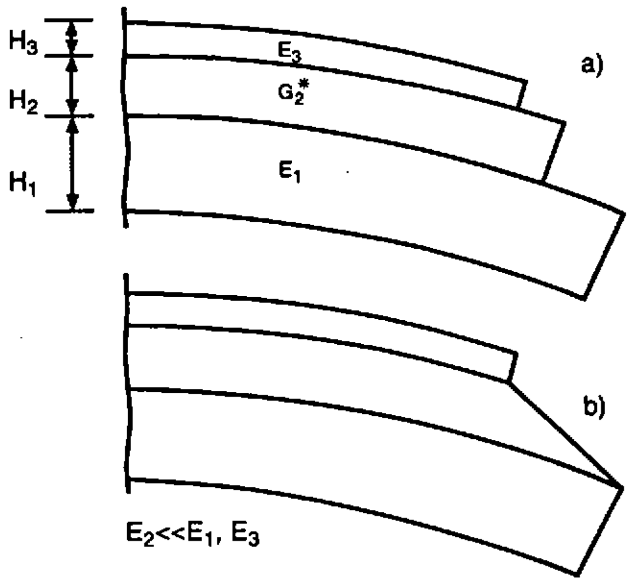

Figure 1 Deformation of a composite beam consisting of a soft viscoelastic material (complex shear modulus G_2^*) sandwiched between stiff materials of Youngs' moduli E_1 and E_3. Boundary conditions are:

(a) zero shear traction at the interfaces between materials,
(b) zero slip at the interfaces, resulting in shear of the visco-elastic layer.

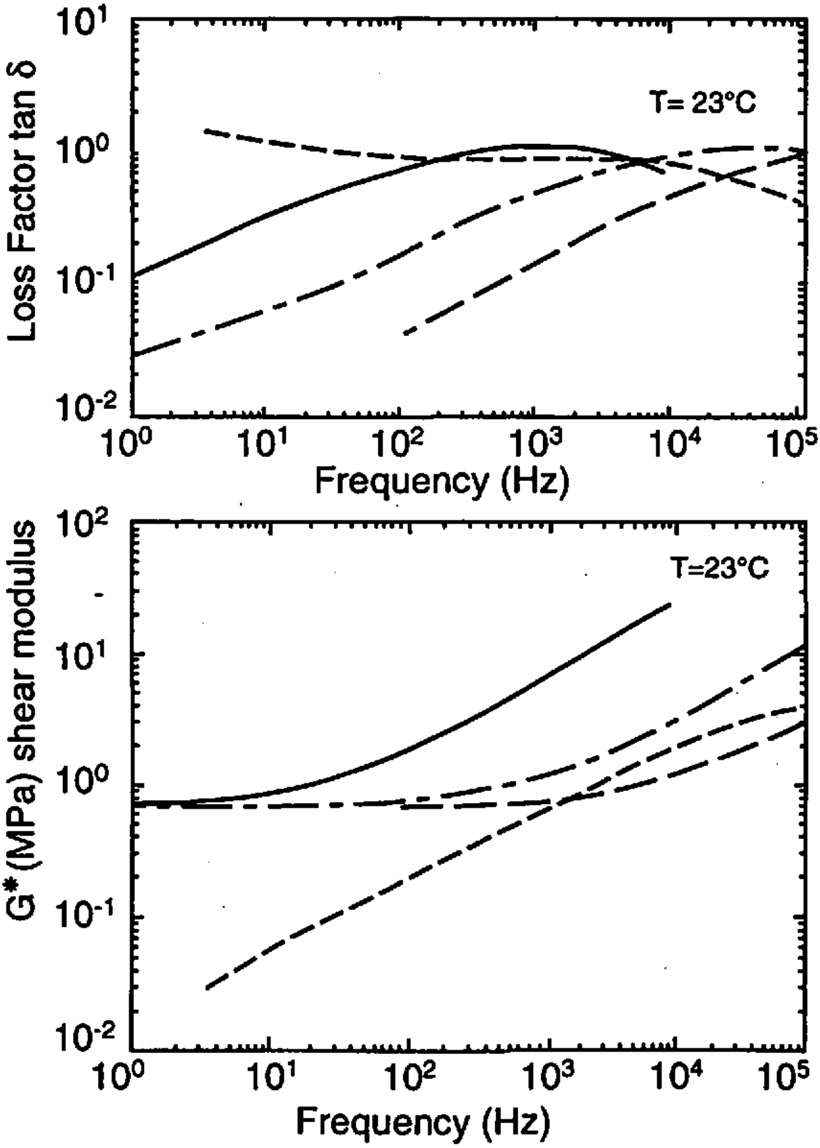

Figure 2 Mastercurves for dynamic properties of ———— ENR-50, – – – – – LENR-50 —·—·— ENR-25 and —— —— —— NR.

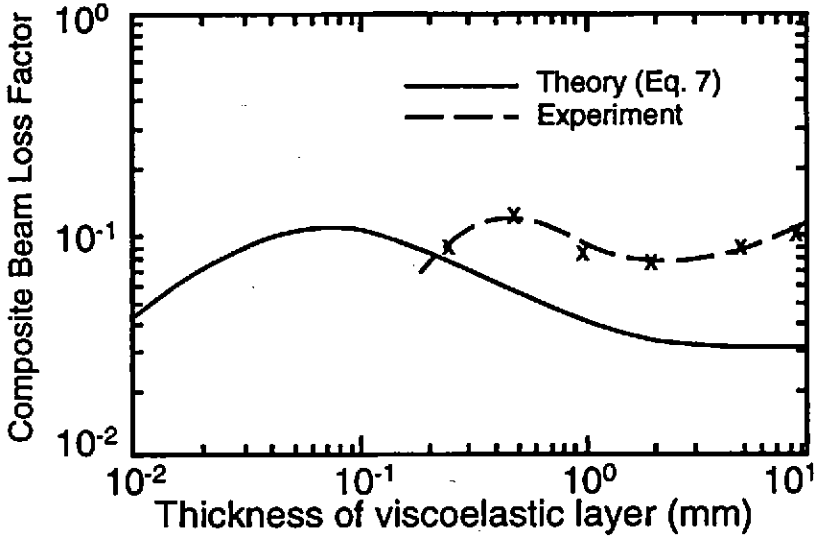

Figure 3 Composite beam loss factor (out-of-plane, first mode) for ENR-50 cores of a range of thicknesses. LENR-50 was used as the adhesive.