Low modulus-high damping rubber for vibration control devices - development and outlook

M.Minowa*


1. INTRODUCTION

High-damping polymer viscoelastic materials have in recent years been widely used for the aseismic protection of buildings and control of vibration in precision machinery. Apart from high damping performance, viscoelastic polymers of this kind must have the elastic modulus, strength, durability and other properties suitably adjusted at the materials level if the protective device is to exhibit the intended vibration control performance. In particular, reduction in the elasticity of the material enables the period of the vibration control device to be lengthened and allows application to lightweight structures. Another crucial requirement is that the properties of the materials should be stable in the range of temperatures they are exposed to in the service environment. As will be seen from Figure 1, however, a trade-off relation exists between the properties required. In practice, therefore, a judicious balance in performance must be struck to match the application.

One technique of raising the damping performance of polymer viscoelastic materials is to utilise the glass transition region of the polymer (Figure 2 [1]). This is effective in imparting very high damping performance (loss tangent, loss modulus) to the materials but has the

*M.Minowa: Graduated from Chemistry Department, Faculty of Sciences, Rikkyo University in 1993, joining Showa Electric Wire & Cable the same year. Specialises in rubber and plastics formulation design; Secretary, Vibration Control Research Association.

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Figure 1 Relation between properties sought from polymer viscoelastic materials

Figure 2 Storage modulus and loss factor as functions of temperature
drawback of greatly restricting the service environment, since the transition region generally occupies a narrow temperature range over which there is a large change in elastic modulus. TPE vibration control materials [2] and organic hybrid vibration control materials [3, 4] have therefore recently been investigated in an attempt to widen the temperature range of the transition region and increase the working temperature range.

Another embodiment of high-damping polymer viscoelastic materials is found in the high-damping rubbers used in aseismic applications. The polymer is here used in the rubber-like region and vibration damping is imparted by incorporating a filler such as carbon black. Although peak damping performance is inferior to that of transition type materials, the use of rubber materials has the merit that properties stable over a wide temperature range are easily obtained. There follows a detailed account of low modulus high-damping rubber materials utilising the rubber-like region, including their dynamic viscoelasticity, the temperature, frequency and strain dependence of damping performance and elastic modulus in test pieces, the ultimate performance exhibited in model rubber laminate bearings, and evaluation of perpendicular loading performance.

2. BASIC PROPERTIES OF LOW MODULUS HIGH-DAMPING RUBBER

Table 1 shows the recipe and basic properties of two low modulus high-damping rubber formulations (HDR). HDR2 is a novel material [6] designed for lower modulus of elasticity and higher damping, based on the previously described HDR1 [5]. Both formulations use isoprene rubber as the base polymer and impart damping performance by addition of carbon black and other fillers.

<table>
<thead>
<tr>
<th>Table 1. Recipes and basic properties</th>
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<tbody>
<tr>
<td><strong>Formula w%</strong></td>
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<tr>
<td>isoprene rubber</td>
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<tr>
<td>carbon black</td>
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<tr>
<td>process oil</td>
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<tr>
<td>other fillers</td>
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<tr>
<td>crosslinking agent</td>
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<tr>
<td>accelerator</td>
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<tr>
<td><strong>Basic properties</strong></td>
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<tr>
<td>hardness</td>
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<tr>
<td>100% tensile stress, MPa</td>
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<tr>
<td>tensile strength, MPa</td>
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<td>elongation, %</td>
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Figure 3 shows the dynamic viscoelasticity of HDR1 and a high damping polynorbornene rubber (NOR) utilising the glass transition region. NOR has a glass transition region in the range -10°C to 60°C and compared with HDR1 at 10°C it exhibits a very high peak in tanδ. At the same time, however, both the storage modulus (E′)
and loss modulus (E") change by a factor of about 100. In contrast, HDR1 exhibits a rubber-like flat response in the observation temperature range; consequently no peak appears in tanδ and both E' and E" take almost constant values. Moreover, the value of E" is higher than in NOR above 20°C, showing that energy absorption is stable over a wide temperature range.

2.2 Evaluation of basic properties and their temperature dependence with test pieces

Since high-damping rubbers utilising the rubber-like region combine damping properties with rubber-like elasticity, vibration control devices are commonly designed on the premise of use at relatively large strain (around 100%). The properties of the materials can in this case be conveniently evaluated by dynamic shear vibration testing with a test piece of the kind shown in Figure 4, for example. Figure 5 shows a model of the hysteresis loop in the load-displacement characteristic obtained by vibration testing. As characteristic values respectively expressing elastic modulus and damping performance, the equivalent shear modulus (G_{eq}) and equivalent damping constant (H_{eq}) may be obtained from the model using the following relationships:

\[ G_{eq} = \frac{K_{eq} \cdot \tau_{R}}{A} \]  

\[ H_{eq} = \frac{1}{4\pi} \frac{\Delta W}{W} \]  

where: K_{eq} - equivalent stiffness; \( \tau_{R} \) - shear thickness; A - area in shear; \( \Delta W \) - energy absorbed; W - elastic strain energy.

Figure 6 shows the hysteresis loops of HDR1 and HDR2 at a temperature of 20°C, frequency of 0.1 Hz, and shear strain of 100%. The values of G_{eq} calculated from the third cycle hysteresis loop are 0.29 MPa for HDR1 and 0.18 MPa for HDR2, while the respective values of H_{eq} are 20.4% for HDR1 and 29.1% for HDR2. As high-damping rubber materials utilising the rubber-like flat response, the formulations thus support both a low elastic modulus and high damping.

Figures 7 to 9 show the variation in G_{eq} and H_{eq} with respect to temperature, frequency and shear strain. In the temperature range 10°C-40°C, the changes in G_{eq} and H_{eq} in HDR1 referred to 20°C are respectively ±15% and ±5%, respectively. Although the changes at the high temperature end of the range are somewhat greater in HDR2 than HDR1, the trends are essentially the same. The frequency-dependence over the range up to 5 Hz referred to a base frequency of 0.1 Hz indicates a tendency for G_{eq} to increase and H_{eq} to diminish slightly. G_{eq} referred to 100% shear strain increases in the range of low shear strain below 50%, but the change in G_{eq} as the shear
strain increases from 100% to 150% is small and there is no evidence of hardening (the phenomenon whereby the slope of the stress-strain curve increases as the strain increases). \( H_{eq} \), referred to 100% shear strain is essentially independent of strain in HRD1, but in HRD2 the same measure tends to decrease slightly at low strain. The results from measurement of dynamic viscoelastic behaviour would thus suggest that dependence on temperature, frequency and strain is very small compared with high-damping materials utilising the glass transition region. Nevertheless, in designing actual vibration control devices, it is important to allow for changes in these properties with method of use and environment.

3. EVALUATION WITH MODEL RUBBER LAMINATE BEARING

One example of the application of low elastic modulus high-damping rubber to vibration control devices is the rubber laminate bearing. The bearing is formed by stacking together sheets of pliable rubber material and hard steel; the laminate is therefore flexible to horizontal deformation but rigid in the perpendicular direction and thus has the great advantage of combining vibration control and isolation with load support performance.

Figure 11 shows the hysteresis loop in shear vibration tests with a rubber laminate model (Figure 10, rubber thickness 1.5 mm per layer x 15 layers) together with the results obtained from test pieces under the same conditions. The hysteresis loops are in close agreement, showing that the same performance as in test pieces is obtained despite conversion to laminate bearing geometry.

Rubber laminate bearings are normally used under compressive load but if the superstructure has a high centre of gravity, the input of horizontal vibration generates a tilting moment with the result that the laminate may experience tensile force. Figure 12 shows the stress-strain characteristic up to failure in constant rate tensile break tests on the HDR1 laminate bearing \( (N = 3) \). All three specimens have a yield point where the tensile strain exceeds 20% and tensile stress exceeds 2 MPa. Thereafter, repeated fine fluctuations in stress occur until tensile stress
earthquake, use below the initial yield stress would be essential to assure the safety of the superstructure or installation.

Finally, Figure 14 presents the results of compressive creep tests carried out as part of an evaluation of the perpendicular loading performance of rubber laminate bearings. The data in Figure 14 show the fractional creep strain (amount of creep/total thickness of the laminate) up to around 10,000 hours, after temperature correction. The creep strain after 10,000 hours was approximately 0.2%. It may hence be inferred that, in the range of perpendicular load examined (0.26 MPa per unit area of nominal contact), perpendicular creep is unlikely to cause practical difficulties.

4. CONCLUDING REMARKS

Low modulus-high damping rubbers utilising the rubber-like region have been reviewed with reference primarily to the results from evaluation of mechanical properties with test pieces and model rubber laminate bearings. As noted at the outset, it is important that, in addition to

Figure 11 Comparison of hysteresis loops of test piece and model rubber laminate bearing

Figure 12 Results of constant strain rate tensile break tests (HDR1)

Figure 13 Photograph of specimens under constant strain rate tensile testing (HDR1)

Figure 14 Results of compressive creep tests (HDR1)
damping performance, the elastic modulus, strength and endurance are suitably adjusted at the materials level when high-damping polymer viscoelastic materials are to be applied to vibration control devices. Viewed in this context, the materials reviewed can be seen as high-damping rubbers with well balanced properties.

Reduction in the elastic modulus of high-damping rubbers makes it possible to improve the performance of vibration control devices and extend the scope of application. In the present case the material should be suited to vibration control devices for lightweight structures in indoor applications, though from the device perspective, there is always room for improvement to the materials. There will doubtless continue to be a need for materials in which the properties inclusive of damping performance are balanced to a higher level.

REFERENCES
6. M. Minowa: unpublished data

(No date given)