CHAPTER 33

MECHANICAL PROPERTIES OF RUBBER

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INTRODUCTION

Rubber is a unique material that is both elastic and viscous. Rubber parts can therefore function as shock and vibration isolators and/or as dampers. Although the term *rubber* is used rather loosely, it usually refers to the compounded and vulcanized material. In the raw state it is referred to as an *elastomer*. Vulcanization forms chemical bonds between adjacent elastomer chains and subsequently imparts dimensional stability, strength, and resilience. An unvulcanized rubber lacks structural integrity and will "flow" over a period of time.

Rubber has a low modulus of elasticity and is capable of sustaining a deformation of as much as 1000 percent. After such deformation, it quickly and forcibly retracts to its original dimensions. It is resilient and yet exhibits internal damping. Rubber can be processed into a variety of shapes and can be adhered to metal inserts or mounting plates. It can be compounded to have widely varying properties. The load-deflection curve can be altered by changing its shape. Rubber will not corrode and normally requires no lubrication.

This chapter provides a summary of rubber compounding and describes the static and dynamic properties of rubber which are of importance in shock and vibration isolation applications. It also discusses how these properties are influenced by environmental conditions.

RUBBER COMPOUNDING

Typical rubber compound formulations consist of 10 or more ingredients that are added to improve physical properties, affect vulcanization, prevent long-term deterioration, and improve processability. These ingredients are given in amounts based on a total of 100 parts of the rubber (parts per hundred of rubber).

ELASTOMERS

Both natural and synthetic elastomers are available for compounding into rubber products. The American Society for Testing and Materials (ASTM) designation and composition of some common elastomers are shown in Table 33.1. Some elastomers such as natural rubber, Neoprene, and butyl rubber have high regularity in their

TABLE 33.1   Designation and Composition of Common Elastomers

ASTM designation	Common name	Chemical composition
NR	Natural rubber	*cis*-Polyisoprene
IR	Synthetic rubber	*cis*-Polyisoprene
BR	Butadiene rubber	*cis*-Polybutadiene
SBR	SBR	Poly (butadiene-styrene)
IIR	Butyl rubber	Poly (isobutylene-isoprene)
CIIR	Chlorobutyl rubber	Chlorinated poly (isobutylene-isoprene)
BIIR	Bromobutyl rubber	Brominated poly (isobutylene-isoprene)
EPM	EP rubber	Poly (ethylene-propylene)
EPDM	EPDM rubber	Poly (ethylene-propylene-diene)
CSM	Hypalon	Chloro-sulfonyl-polyethylene
CR	Neoprene	Poly chloroprene
NBR	Nitrile rubber	Poly (butadiene-acrylonitrile)
HNBR	Hydrogenated nitrile rubber	Hydrogenated poly (butadiene-acrylonitrile)
ACM	Polyacrylate	Poly ethylacrylate
ANM	Polyacrylate	Poly (ethylacrylate-acrylonitrile)
T	Polysulfide	Polysulfides
FKM	Fluoroelastomer	Poly fluoro compounds
FVMQ	Fluorosilicone	Fluoro-vinyl polysiloxane
MQ	Silicone rubber	Poly (dimethylsiloxane)
VMQ	Silicone rubber	Poly (methylphenyl-siloxane)
PMQ	Silicone rubber	Poly (oxydimethyl silylene)
PVMQ	Silicone rubber	Poly (polyoxymethylphenyl-silylene)
AU	Urethane	Polyester urethane
EU	Urethane	Polyether urethane
GPO	Polyether	Poly (propylene oxide-allyl glycidyl ether)
CO	Epichlorohydrin homopolymer	Polyepichlorohydrin
ECO	Epichlorohydrin copolymer	Poly (epichlorohydrin-ethylene oxide)

backbone structure. They will align and crystallize when a strain is applied, with resulting high tensile properties. Other elastomers do not strain-crystallize and require the addition of reinforcing fillers to obtain adequate tensile strength.[1]

Natural rubber is widely used in shock and vibration isolators because of its high resilience (elasticity), high tensile and tear properties, and low cost. Synthetic elastomers have widely varying static and dynamic properties. Compared to natural rubber, some of them have much greater resistance to degradation from heat, oxidation, and hydrocarbon oils. Some, such as butyl rubber, have very low resilience at room temperature and are commonly used in applications requiring high vibration damping. The type of elastomer used depends on the function of the part and the environment in which the part is placed. Some synthetic elastomers can function under conditions that would be extremely hostile to natural rubber. An initial screening of potential elastomers can be made by determining the upper and lower temperature limit of the environment that the part will operate under. The elastomer must be stable at the upper temperature limit and maintain a given hardness at the lower limit. There is a large increase in hardness when approaching the *glass transition temperature*. Below this temperature the elastomer becomes a "glassy" solid that will fracture upon impact.

Further screening can be done by determining the solvents and gases that the part will be in contact with during normal operation and the dynamic and static physical properties necessary for adequate performance.

REINFORCEMENT

Elastomers which do not strain-crystallize need reinforcement to obtain adequate tensile properties. Carbon black is the most widely used material for reinforcement. The mechanism of the reinforcement is believed to be both chemical and physical in nature.[2] Its primary properties are surface area and structure. Smaller particle-size blacks having a higher surface area give a greater reinforcing effect. Increased surface area gives increased tensile, modulus, hardness, abrasion resistance, tear strength, and electrical conductivity and decreased resilience and flex-fatigue life. The same effects are also found with increased levels (parts per hundred rubber) of carbon black, but peak values occur at different levels. Structure refers to the high-temperature fusing together of particles into grape-like aggregates during manufacture. Increased structure will increase modulus, hardness, and electrical conductivity but will have little effect on tensile, abrasion resistance, or tear strength.

ADDITION OF OILS

Oils are used in compounding rubber to maintain a given hardness when increased levels of carbon black or other fillers are added. They also function as processing aids and improve the mixing and flow properties (extrudability, etc.).

ANTI-DEGRADENTS

Light, heat, oxygen, and ozone accelerate the chemical degradation of elastomers. This degradation is in the form of chain scission or chemical cross-linking depending on the elastomer. Oxidation causes a softening effect in NR, IR, and IIR. In most other elastomers the oxygen causes cross-linking and the formation of stiffer com-

pounds. Ozone attack is more severe and leads to surface cracking and eventual product failure. Cracking does not occur unless the rubber is strained. Elastomers containing unsaturation in the backbone structure are most vulnerable. Anti-degradents are added to improve long-term stability and function by different chemical mechanisms. Amines, phenols, and thioesters are the most common types of antioxidants, while amines and carbamates are typical anti-ozonants. Paraffin waxes which bloom to the surface of the rubber and form protective layers are also used as anti-ozonants.

VULCANIZING AGENTS

Vulcanization is the process by which the elastomer molecules become chemically cross-linked to form three-dimensional structures having dimensional stability. The effect of vulcanization on compound properties is shown in Fig. 33.1. Sulfur, perox-ides, resins, and metal oxides are typically used as vulcanizing agents. The use of sul-fur alone leads to a slow reaction, so accelerators are added to increase the cure rate. They affect the rate of vulcanization, cross-link structure, and final properties.[3]
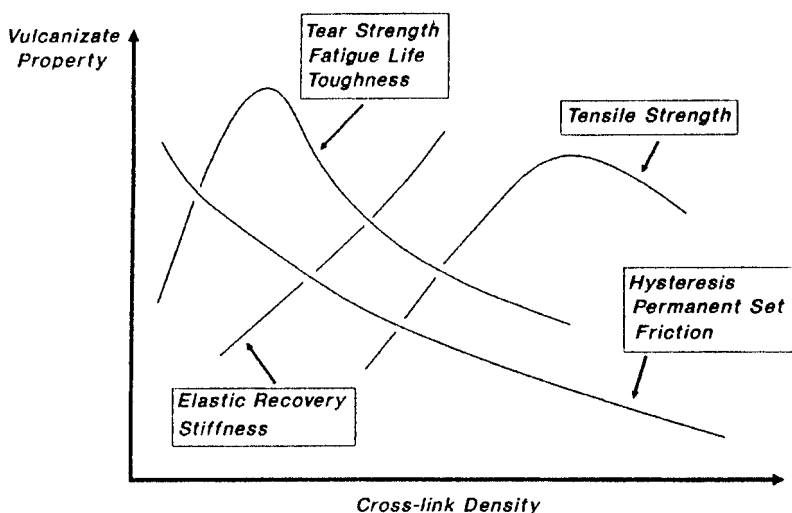

FIGURE 33.1   Vulcanizate properties as a function of the extent of vulcanization. (*Eirich and Coran.*[3])

MIXING

Adequate mixing is necessary to obtain a compound that processes properly, cures sufficiently, and has the necessary physical properties for end use.[4] The Banbury internal mixer is commonly used to mix the compound ingredients. It contains two spiral-shaped rotors that operate in a completely enclosed chamber. A two-step pro-cedure is generally used to ensure that premature vulcanization does not occur.

Most of the ingredients are mixed at about 120°C in the first step. The vulcanizing agents are added at a lower temperature in the second step.

MOLDING

Compression, transfer, and injection-molding techniques are used to shape the final product. Once in the mold, the rubber compound is vulcanized at temperatures ranging from 100 to 200°C. The cure time and the temperature are determined beforehand with a curemeter, such as the oscillating disk rheometer.[5] After removal from the mold, the rubber product is sometimes postcured in an autoclave. The postcuring gives improved compression-set properties.

STATIC PHYSICAL PROPERTIES

Rubber has properties that are drastically different from other engineering materials. Consequently, it has physical testing procedures that are unique.[6] Rubber has both elastic and viscous properties. Which of these properties predominates frequently depends on the testing conditions. A summary of the characteristic properties of different elastomers is shown in Table 33.2.

HARDNESS

Hardness is defined as the resistance to indentation. The *durometer* is an instrument that measures the penetration of a stress-loaded metal sphere into the rubber. Hardness measurements in rubber are expressed in Shore A or Shore D units according to ASTM test procedures.[7] Because of the viscoelastic nature of rubber, a durometer reading reaches a maximum value as soon as the metal sphere reaches maximum penetration into the specimen and then decreases the next 5 to 15 sec. Hand-held spring-loaded durometers are commonly used but are very subject to operator error. Bench-top dead-weight-loaded instruments reduce the error to a minimum.[8]

STRESS-STRAIN

Rubber is essentially an incompressible substance that deflects by changing shape rather than changing volume. It has a Poisson's ratio of approximately 0.5. At very low strains, the ratio of the resulting stress to the applied strain is a constant (Young's modulus). This value is the same whether the strain is applied in tension or compression. Hooke's law is therefore valid within this proportionality limit. However, as the strain increases, this linearity ceases, and Hooke's law is no longer applicable. Also the compression and tension stresses are then different. This is evident in load-deflection curves run on identical samples in compression, shear, torsion, tension, and buckling, as shown in Fig. 32.2. Rubber isolators and dampers are typically designed to utilize a combination of these loadings. However, shear loading is most preferred since it provides an almost linear spring constant up to strains of about 200 percent. This linearity is constant with frequency for both small and large dynamic shear strains. The compression loading exhibits a nonlinear hardening at strains over 30 percent and is used where motion limiting is required. However, it is not recom-

TABLE 33.2 Relative Properties of Various Elastomers

ASTM designation	NR	BR	SBR	IIR CIIR	EPM EPDM	CSM	CR	NBR	HNBR	ACM ANM	T	FKM	FVMQ	VMQ MQ, PMQ, PVMQ	AU EU	GPO	CO ECO
Durometer range	30–90	40–90	40–80	40–90	40–90	45–100	30–95	40–95	35–95	40–90	40–85	60–90	40–80	30–90	35–100	40–90	40–90
Tensile max, psi	4500	3000	3500	3000	2500	4000	4000	4000	4500	2500	1500	3000	1500	1500	5000	3000	2500
Elongation max., %	650	650	600	850	600	500	600	650	650	450	450	300	400	900	750	600	350
Compression set	A	B	B	B	B-A	C-B	B	B	B-A	B	D	B-A	C-B	B-A	D	B-A	B-A
Creep	A	B	B	B	C-B	C	B	B	B	C	D	B	B	C-A	C-A	B	B
Resilience	High	High	Med.	Low	Med.	Low	High	Med.-Low	Med.	Med.	Low	Low	Low	High-Low	High-Low	High	Med.-Low
Abrasion resistance	A	A	A	C	B	A	A	A	A	C-B	D	B	D	B	A	B	C-B
Tear resistance	A	B	C	B	C	B	B	B	B	D-C	D	B	D	C-B	A	A	C-A
Heat aging at 212°F	C-B	C	B	A	B-A	B-A	B	B	A	A	C-B	A	A	A	B	B-A	B-A
T_g, °C	−73	−102	−62	−73	−65	−17	−43	−26	−32	−24, −54	−59	−23	−69	−127, −86	−23, −34	−67	−25, −46
Weather resistance	D-B	D	D	A	A	A	B	D	A	A	B	A	A	A	A	A	B
Oxidation resistance	B	B	C	A	A	A	A	B	A	A	B	A	A	A	B	B	B
Ozone resistance	NR-C	NR	NR	A	A	A	A	C	A	B	A	A	A	A	A	A	A
Solvent resistance																	
Water	A	A	B-A	A	A	B	B	B-A	A	D	B	A	A	A	C-B	C-B	B
Ketones	B	B	B	A	B-A	B	C	D	D	D	A	NR	D	B-C	D	C-D	C-D
Chlorohydrocarbons	NR	NR	NR	NR	NR	D	D	C	C	B	C-A	A	B-A	NR	C-B	A-D	A-B
Kerosene	NR	NR	NR	NR	NR	B	B	A	A	A	A	A	A	D-C	B	A-C	A
Benzol	NR	NR	NR	NR	NR	C-D	C-D	B	B	C-B	C-B	A	B-A	NR	C-B	NR	B-A
Alcohols	B-A	B	B	B-A	B-A	A	A	C-B	C-B	D	B	C-A	C-B	C-B	B	C	A
Water glycol	B-A	B-A	B	B-A	A	B	B	B	A	C-B	A	A	A	A	C-B	B	C
Lubricating oils	NR	NR	NR	NR	NR	A-B	B-C	A	A	A	A	A	B-C	A-B	D	A

A = excellent, B = good, C = fair, D = use with caution, NR = not recommended

SOURCE: *Seals Eastern, Inc.*

mended where energy storage is required. Tension-loading stores energy more efficiently than either compression-loading or shear-loading but is not recommended because of the resulting stress loads on the rubber-to-metal bond, which may cause premature failure. Buckled-loading is a combination of tension- and compression-loading and derives some of the benefits of both.

FIGURE 33.2 Increase in torsional modulus of elasticity of various elastomers as a function of temperature. (*After Gehman.*[16])

The stress-strain properties of rubber compounds are usually measured under tension as per ASTM procedures.[9] Either molded rings or die-cut "dumbbell"-shaped specimens are used in testing. Stress measurements are made at a specified percentage of elongation and reported as *modulus* values. For example, 300 percent modulus is defined as the stress per unit cross-sectional area (in psi or MPa units) at an elongation of 300 percent. Also measured are the stress at failure (tensile) and maximum percentage elongation. These are the most frequently reported physical properties of rubber compounds.

The stiffness (spring rate) is the ratio of stress to strain expressed in newtons per millimeter. It is dependent not only on the rubber's modulus but also on the shape of the specimen or part being tested. Since rubber is incompressible, compression in one direction results in extension in the other two directions, the effect of which is a bulging of the free sides. The *shape factor* is calculated by dividing one loaded area by the total free area.
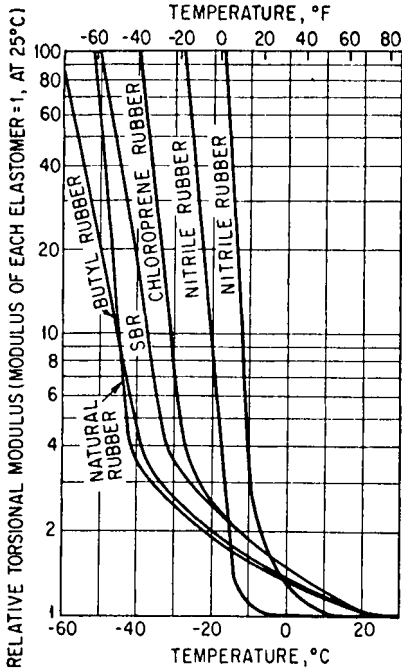
TEAR

Vibration isolators and dampers that are subjected to cyclical loads frequently fail due to a fracturing of the rubber component. A fracture may initiate in an area where stress concentration is at a maximum. After initiation, the fracture increases in size and progresses into a tearing action. Tear properties are therefore important in some applications. Tensile tests are run on dumbbell-shaped samples containing no flaws. The stress is therefore evenly distributed across the sample. Tear-testing procedures concentrate the stress in one area, either through sample design or by cutting a nick in the sample.[10] Samples are die cut (die A, B, or C) from tensile testing sheets. The peak force and sample thickness are recorded. Tear values are reported in units of pounds per inch or kilonewtons per meter. Tear and tensile testing provide the same rank ordering of different types of rubbers.

COMPRESSION SET AND CREEP

Dimensional stability is necessary for vibration isolators and dampers that function under applied loads, i.e., the static deflection of an isolator should not increase with time. Such an increase is a result of creep and compression set. *Compression set* is the change in dimension with an applied strain; *creep* is the change in dimension with an applied force. Compression set and excessive creep will induce a large change in stiffness and dynamic properties over a period of time. Compression set is determined by compressing a specimen (of specified size) to a preset deflection and exposing it to an elevated temperature.[11] After exposure the specimen is allowed to recover for one-half hour and the thickness is measured. Percent compression set is the decrease in thickness divided by the original deflection and multiplied by 100. Typical rubber compounds used for vibration isolation have compression set values of from 10 to 50 percent. The exposure time is usually 22 or 70 hours at a temperature relevant to the intended use of the isolator or damper. Creep is determined by placing a specimen in a compression device, applying a compressive force, and exposing it to an elevated temperature.[12] Percent creep is the decrease in thickness divided by the original thickness and multiplied by 100.

ADHESION

Adequate rubber-to-metal adhesion is imperative in the fabrication of most vibration isolators and dampers. Adhesive is first applied to the metal; then the rubber is bonded to the metal during vulcanization. Various adhesives are available for all types of elastomers. In testing for adhesion, a strip of rubber is adhered to the face of a piece of adhesive-coated metal.[13] After vulcanization (and possible aging), the rubber is pulled from the metal at an angle of 45° or 90°, and the adhesion strength is measured. The mode of failure is also recorded.

Another ASTM method[14] is used to determine the rubber-to-metal adhesion when the rubber is bonded after vulcanization, i.e., for *postvulcanization bonding*. In this procedure a vulcanized rubber disk is coated on both sides with an adhesive and assembled between two parallel metal plates. Then the assembly is heated under compression for a specified period of time. The metal plates are then pulled apart until rupture failure.

LOW-TEMPERATURE PROPERTIES

Rubber becomes harder, stiffer, and less resilient with decreasing temperature. These changes are brought about by a reduction in the "free volume" between neighboring molecules and a subsequent reduction in the mobility of the elastomer molecules. When approaching the glass transition temperature (T_g), its rubber-like characteristic is lost and the rubber becomes leathery. Finally it changes to a hard, brittle glass. The glass transition temperature is a second-order transition as opposed to crystallization, which is a first-order transition. A first-order transition is accompanied by a abrupt change in a physical property, while a second-order transition is accompanied by a change in the rate of change. The glass transition temperature can be detected by differential scanning calorimetry or changes in static or dynamic mechanical properties. This is described in the section on dynamic properties of rubber.

The effect of temperature on stiffness is measured using a Gehman apparatus.[15] It provides torque to a strip of rubber by a torsion wire. The measurement is first made at 23°C and then at reduced temperatures. The *relative modulus* at any temperature is the ratio of the modulus at that temperature to the modulus at 23°C. The results are expressed as the temperatures at which the relative moduli are 2, 5, 50, and 100. Figure 33.2 shows the effect of temperature on the relative torsional modulus of various elastomers.[16] Young's modulus can also be measured at low temperature using a flexural procedure.[17]

HIGH-TEMPERATURE PROPERTIES

Some vibration isolators and dampers function in high-temperature environments. The rubber compounds used in these applications must have resistance to high-temperature degradation. The stability at high temperatures is related to the chemical structure of the elastomer and the chemical cross-linking bonds formed during vulcanization. Elastomers containing no unsaturation (chemical double-bonds) in the backbone have better high-temperature properties. Rubber compounds containing EPDM, for example, have better high-temperature resistance than ones containing natural rubber or SBR. In a sulfur cure, mono or disulfide cross-linking bonds have better high-temperature stability than polysulfide bonds. Cure system modifications are therefore used to improve high-temperature stability.

The high-temperature resistance of rubber compounds is determined by measuring the percentage of change in tensile strength, tensile stress at a given elongation, and ultimate elongation after aging in a high-temperature oven as per ASTM procedure.[18]

OIL AND SOLVENT RESISTANCE

Some vibration isolators and dampers, particularly those used in automotive products, have contact with oils or solvents. The effect of a liquid on a particular rubber depends on the solubility parameters of the two materials. The more the similarity, the larger the effect. A liquid may cause the rubber to swell, it may extract chemicals from it, or it may chemically react with it. Any of these can lead to a deterioration of the physical properties of rubber. The effect of liquids on rubber is determined by measuring changes in volume or mass, tensile strength, elongation, and hardness after immersion in oils, fuels, service fluids, or water.[19]

EXPOSURE TO OZONE AND OXYGEN

Ozone is a constituent of smog; in some areas, ozone may occur in concentrations that are deleterious to rubber. Vibration isolators and dampers also may be exposed to ozone generated by the corona discharge of electrical equipment. Elastomers containing unsaturation in their backbone structure are especially prone to ozone cracking, since ozone attacks the elastomer at the double bonds. Elastomers such as NR, SBR, BR, and NBR have poor resistance, while EPDM and GPO have excellent resistance to ozone cracking. Ozone cracking will not occur if the rubber is unstrained. There is a critical elongation at which the cracking is most severe. These strains are 7 to 9 percent for NR, SBR, and NBR, 18 percent for CR, and 26 percent for IIR.[20] Both static[21] and

dynamic[22] testing procedures are used. In the static test the sample is given a specified strain. Results are expressed as cracking severity using arbitrary scales or as time until first cracks appear. In Method A, the dynamic procedure tests strips of rubber in tension at 0.5 Hz. Method B adheres the test strips to a rubber belt that is rotated around two pulleys at 0.67 Hz. The number of cycles to initial cracking is reported.

DYNAMIC PROPERTIES

VISCOELASTICITY

Rubber has elastic properties similar to those of a metallic spring and has energy-absorbing properties like those of a viscous liquid.[23] These viscoelastic properties allow rubber to maintain a constant shape after deformation, while simultaneously absorbing mechanical energy. The viscosity (which varies with different elastomers) increases with reduced temperature. The elasticity follows Hooke's law and increases with increased strain, while the viscosity follows Newton's law and increases with increased strain rate. Therefore, when applying a strain, the resultant stress will increase with increasing strain rate.

Springs or dashpots are frequently used to make theoretical models which illustrate the interaction of the elastic and viscous components of rubber. The springs and dashpots can be combined in series or in parallel, representing the Maxwell or Voigt elements (see Table 36.2). Rubber actually consists of an infinite number of such models with a wide spectrum of spring constants and viscosities.

MEASUREMENT OF DYNAMIC PROPERTIES

Resilience, measured by several relatively simple tests, is sometimes used for estimating the dynamic properties of a rubber compound. In these test methods a strain is applied to a rubber test sample by a free-falling indentor. *Resilience* is defined as the ratio of the energy of the indentor after impact to its energy before impact (expressed as a percentage). Two widely used methods include the pendulum[24] and the falling weight methods.[25] Although resilience is a crude measurement of the dynamic properties of rubber, it is attractive because of its simplicity and cost.

In *free vibration methods,* the rubber sample is allowed to vibrate at its natural frequency.[26] To change the natural frequency the sample size or added weights must be changed. Since it is a free vibration, the amplitude A decreases with each oscillation. Resilience is defined as A_3/A_2, expressed as a percentage.

In *forced vibration methods,* the dynamic properties (or viscoelasticity) of a rubber compound are determined by measuring its response to a sinusoidally varying strain.[27] In this manner, both the strain and the strain rate vary during a complete cycle. The ratio of the energy dissipated in overcoming internal friction to the energy stored is a function of the viscoelasticity of the rubber. In a simple apparatus for measuring dynamic properties, a sinusoidally varying strain is applied to the sample by means of a motor-driven eccentric. The resultant force is measured at the opposite end of the sample with a dynamometer ring or electronic measuring device. The angular distance between the input strain and the resultant stress is measured by mechanical or electronic methods. A graph of the sinusoidal strain and resultant stress, both plotted as a function of time or angle, is shown in Fig. 33.3. The measured
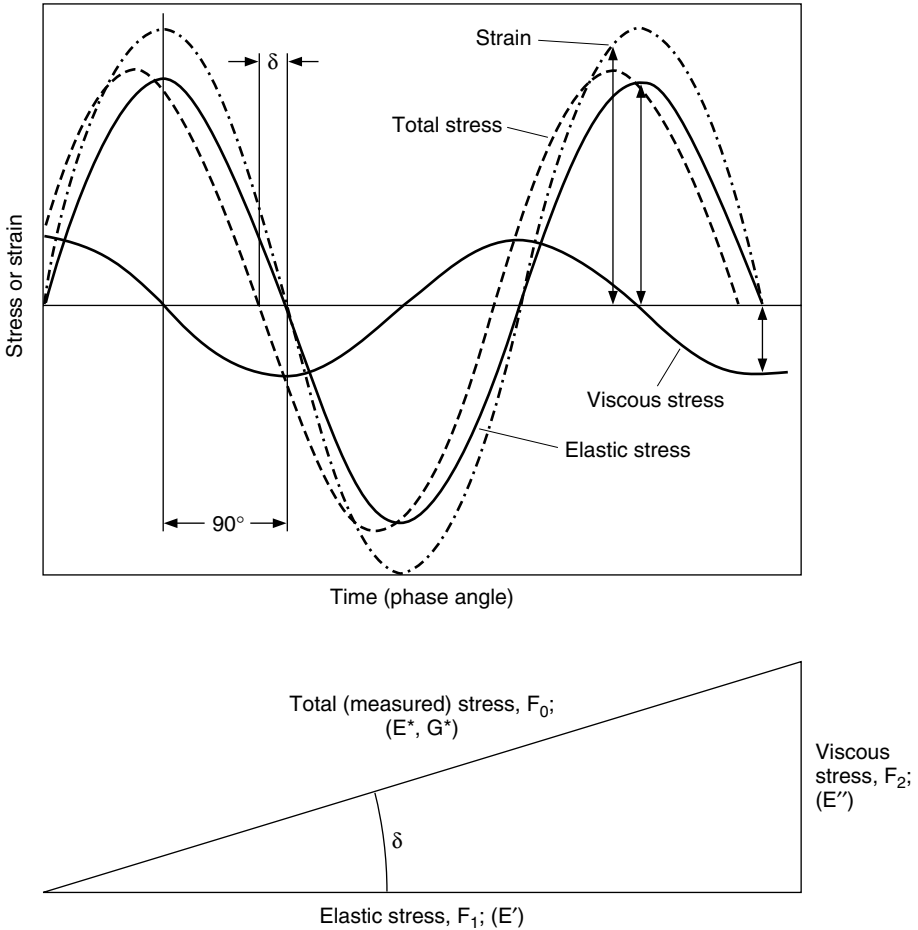
FIGURE 33.3   The applied sinusoidal strain and the resultant stress plotted as a function of time or phase angle. The maximum elastic and viscous stress, and the elastic and viscous modulus values are calculated using simple trigonometry. (*After Schaefer.*[23])

maximum stress amplitude precedes the maximum strain amplitude by the phase angle δ. The stress amplitude (F_0) is composed of contributions from both the elastic stress (F_1) and the viscous stress (F_2). The amount contributed by each is a function of the phase angle. Following Hooke's Law, the resultant stress due to the elastic portion of the rubber is in phase with, and proportional to, the strain. When the imposed strain reaches a peak value, the resultant elastic stress also reaches a peak value. The resultant stress due to the viscous portion of the rubber is governed by Newton's law and is 90° out of phase with the imposed strain. When the strain is at a maximum value, the strain rate (slope of the strain curve) is zero. Consequently, the resultant viscous stress is zero. At zero strain, the strain rate is at a maximum, and the

resultant viscous stress is at a peak value. The only values measured are the stress amplitude and the phase angle δ. The complex modulus is calculated by dividing the resultant maximum stress amplitude by the maximum imposed strain amplitude. Both the maximum elastic stress amplitude and the maximum viscous stress amplitude are calculated from the measured stress amplitude and the phase angle δ using simple trigonometric functions. Dividing these stress values by the strain gives the elastic modulus (E') and the loss modulus (E''). Tan δ equals E''/E'. The value of tan δ (the ratio of the viscous to the elastic response) is a measurement of damping or hysteresis.

INFLUENCE OF COMPOUNDING INGREDIENTS

ELASTOMERS

The dynamic properties of an elastomer are determined by its glass transition temperature (T_g). Elastomers having the lowest T_g will have the lowest tan δ (or highest resilience). Natural rubber has a fairly low T_g (−60°C) and thus has a low tan δ. Butyl rubber has a low T_g (−60°C), but the transition region extends above ambient temperature. It consequently has a high tan δ and is frequently used in vibration damping applications. The effect of temperature on the dynamic stiffness (dynamic spring rate) and damping of compounds containing different elastomers is shown in Fig. 33.4.

CARBON BLACK

Carbon black has a major influence on the dynamic properties of compounded rubber.[28] It is a source of hysteresis or damping. The amount of damping increases with the surface area of the carbon black and the level used in the compound.

VIBRATION ISOLATION AND DAMPING

Dynamic properties, which are a function of the elastomer and other compounding variables, determine the vibration isolation and damping characteristics of a rubber compound. Springs and dashpots are used to describe how the viscoelastic properties relate to the vibration isolation and damping properties.[29] The quantity tan δ, being the ratio of the viscous to elastic response, can be substituted for $\zeta = c/c_c$ in the equations for transmissibility derived in Chap. 2. Figure 33.5 summarizes the effect of dynamic properties on transmissibility. Transmissibility curves of different compounded elastomers are shown in Fig. 33.6.[30] The NR, EPDM, CR, and SBR rubbers have low T_g's and therefore have low damping properties. As a result they have the highest transmissibility at the resonating frequency and the lowest transmissibility at higher frequencies. The opposite effect is seen with IIR and NBR, which have higher damping properties. As shown in Fig. 33.7, increased levels of carbon black increase damping and thus decrease the transmissibility at the resonance frequency. Increased levels also increase the compound's stiffness, with a resulting increase in resonance frequency. For further information on the effect of viscoelastic properties on vibration isolation and damping, see Refs. 31 and 32.
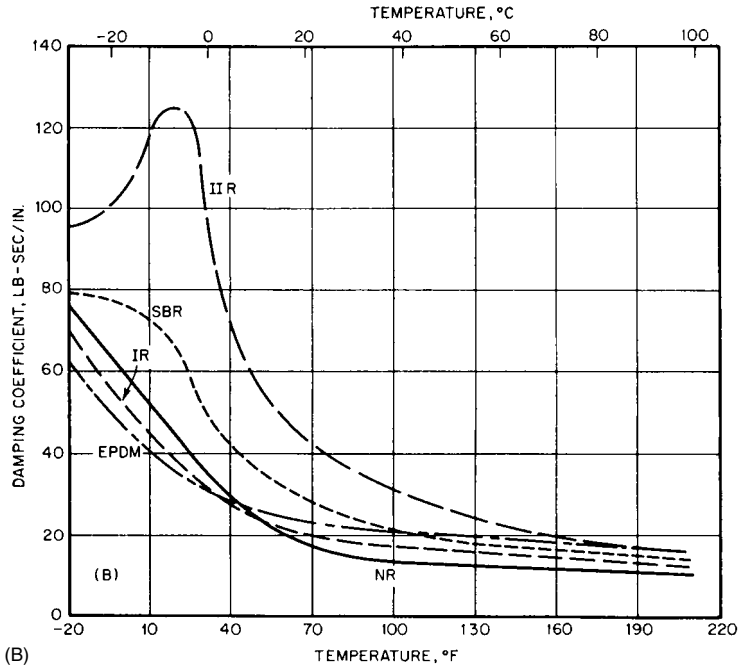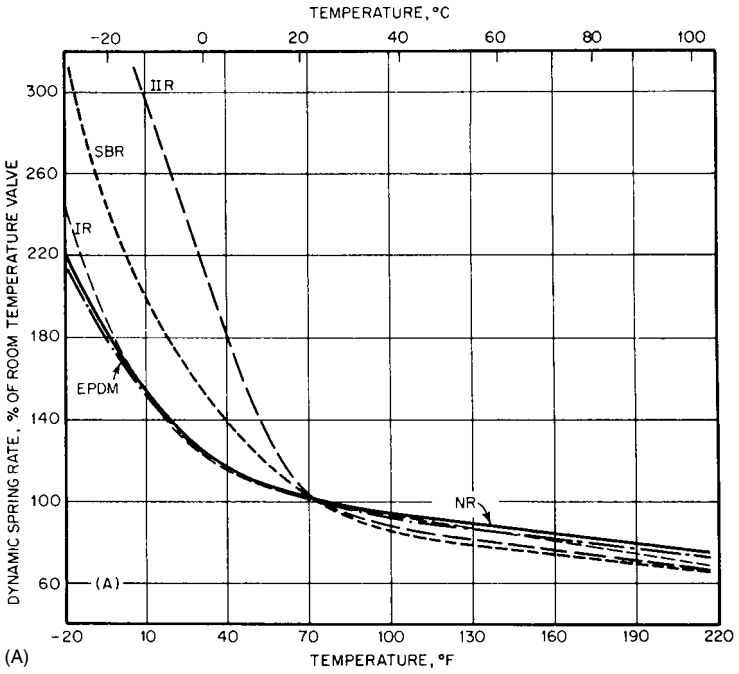
FIGURE 33.4 The effect of temperature on (*A*) the dynamic stiffness (spring rate) and (*B*) the damping coefficient of typical isolating and damping compounds using several elastomers.
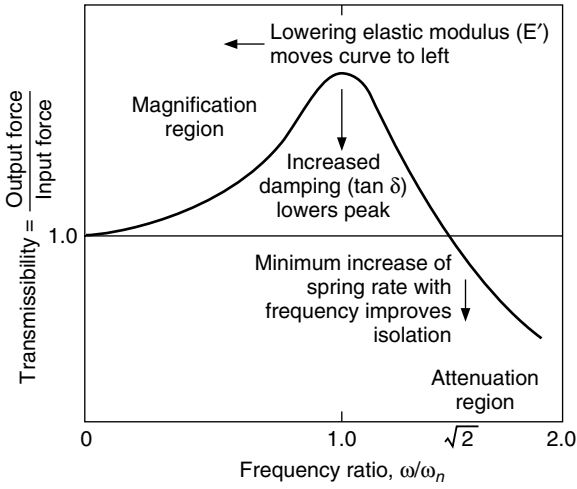
33.13

FIGURE 33.5 The effect of the dynamic properties of rubber on the transmissibility curve. (*After Edwards.*[29])
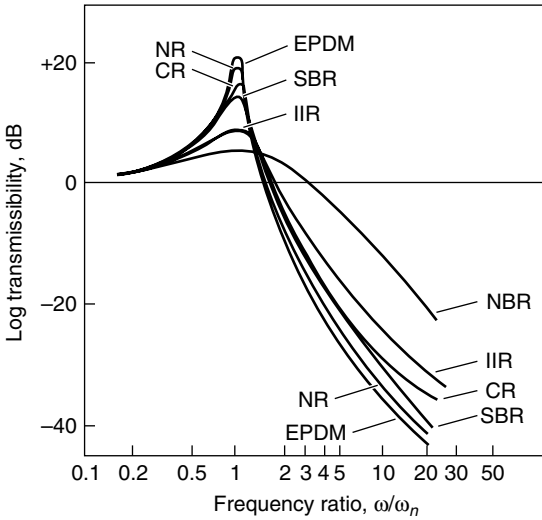

FIGURE 33.6 The dependence of transmissibility on the type of rubber used for the mounting. (*After Freakley.*[30])
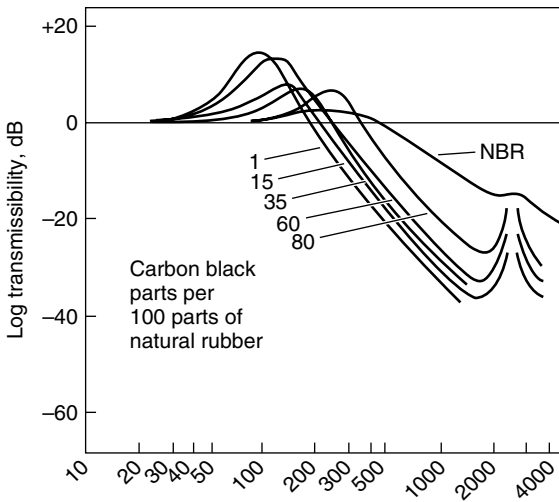
FIGURE 33.7 The dependence of transmissibility-frequency curves on the level of carbon black in natural rubber compounds. (*After Freakley.*[30])

FATIGUE FAILURE

Rubber shock and vibration isolators and dampers fail in service due to either excessive drift (creep) or mechanical fracture as a result of fatigue. Static drift or set testing is described above in the section on compression set. The effect of temperature on the drift of a natural rubber compound is shown in Fig. 33.8.[33] The drift properties of rubber can be tested using static or dynamic methods.
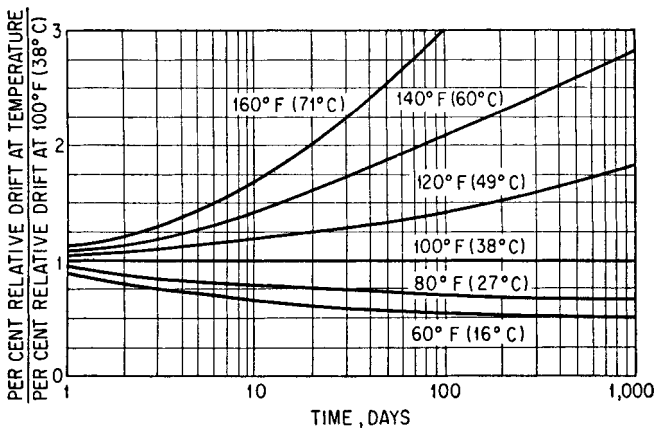

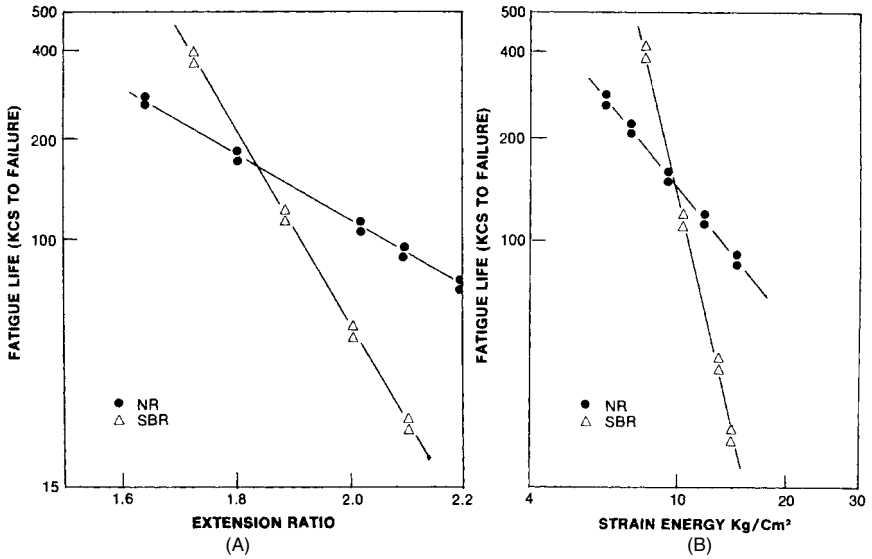**FIGURE 33.8** The effect of temperature on the drift of natural rubber. (*After Morron.*[33])

FIGURE 33.9 Fatigue curves of carbon-black-filled natural rubber and SBR plotted as a function of extension ratio (*A*) and strain energy (*B*). (*After Babbit.*[36])

Mechanical fractures occur when a rubber part is subjected to a cyclic stress or strain. The initial crack usually originates in an area of high stress concentration and grows until complete fracture occurs. Both the time until initial crack appearance and the growth rate increase with increasing temperature and increased stress or strain amplitudes.

Several procedures are available for the dynamic testing of laboratory-prepared samples. The most common is the DeMattia flex machine which can test for crack initiation or the growth of an induced cut.[34] The Ross Flexer machine also tests for cut growth.[35] Although the data can be used for relative comparisons, all of these procedures show poor correlation with product performance. Dynamic fatigue testing is therefore frequently performed on the actual part. Because of time constraints, the applied energy input (cyclic stress and strain amplitudes) is increased to much larger values than what the part experiences in actual service. The effect of energy input on fatigue life is shown in Fig. 33.9.[36] At low-energy input the SBR compound has better fatigue resistance than the NR compound. However, when the strain and resulting input energy is increased, the curves cross over, and the NR compound has the better fatigue resistance.[37] Therefore, caution must be exercised when interpreting such data.

Reinforcing fillers and vulcanization systems also have definite effects on fatigue properties.[38] Smaller particle-size carbon blacks typically give increased reinforcement and improved fatigue resistance. Vulcanization systems that produce high levels of polysulfide crosslinks give optimum fatigue resistance.

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