

Vibration and Sound Damping in Polymers

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Excessive vibrations or loud sounds cause deafness or reduced efficiency of people, wastage of energy and fatigue failure of machines/structures. Hence, unwanted vibrations need to be dampened. This article describes the transmission of vibrations/sound through different materials such as metals and polymers. Viscoelasticity and glass transition are two important factors which influence the vibration damping of polymers. Among polymers, rubbers exhibit greater damping capability compared to plastics. Rubbers reduce vibration and sound whereas metals radiate sound. The damping property of rubbers is utilized in products like vibration damper, shock absorber, bridge bearing, seismic absorber, etc.

Sound is created by the pressure fluctuations in the medium due to *vibration* (oscillation) of an object. Vibration is a desirable phenomenon as it originates sound. But, continuous vibration is harmful to machines and structures since it results in wastage of energy and causes fatigue failure. Sometimes vibration is a nuisance as it creates noise, and exposure to loud sound causes deafness or reduced efficiency of people. So it is essential to reduce excessive vibrations and sound.

We can imagine how noisy and irritating it would be to pull a steel chair along the floor. But when we fix a small rubber bush on each leg of the chair, it reduces noise and facilitates smooth movement (*Figure 1*). Similarly, engine mounts in automobiles help in reducing the vibrations generated by the engine. Several metallic components in vehicles are bonded with rubber to serve the same purpose (*Figure 2*).

Viscous Damping and Hysteretic Damping

In the above examples, *damping* in rubber reduces both vibration

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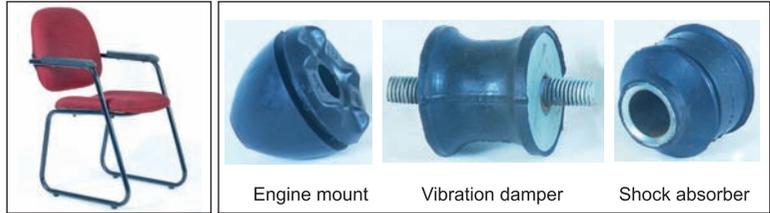
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Figure 1 (left). Chair with rubber bush.

Figure 2 (right). Automobile components which make use of the vibration and sound damping capability of rubber.



and sound. Damping reduces the amplitude of oscillations or prevents oscillations in a system by a mechanism that opposes the changes in it. When an external oscillating force is applied to a material/structure, damping occurs by dissipation of mechanical energy, viz., transformation of mechanical energy into other forms of energy such as heat. Hence, damping represents the capacity for energy absorption.

There are different types of damping: *coulomb*, *viscous* and *hysteretic* damping. Coulomb damping is caused by kinetic friction between sliding dry or insufficiently lubricated surfaces. If the heat is dissipated due to the movement of bodies in a liquid medium, it is called *viscous damping* in which the damping force is proportional to velocity, for example, shock absorbers in automobiles. Viscous damping capacity is characterized by the *damping ratio*, ζ .

But when a solid is deformed, heat is dissipated by internal friction (hysteresis). This is called *hysteretic (solid) damping*, e.g., engineering rubber products used for vibration isolation. In Greek, hysteresis means ‘deficiency’ or ‘lagging behind’. During cyclic loading of a solid, the relation between stress and strain is nonlinear and different. The area of the resulting hysteresis loop represents the energy loss. Hard materials like metals do not show hysteresis under a moderate load, whereas soft materials like rubbers exhibit large hysteresis. Hysteretic damping is characterized by the *loss tangent*, $\tan \delta$.

Keywords

Vibration, sound, damping, polymer, rubber, plastic, viscoelasticity, glass transition, shock absorber.

Passive and Active Dampers: Metals need a damper to reduce the vibration of the system. There are two types of vibration dampers: *passive* and *active*. Passive absorbers do not monitor or react to unwanted vibrations. These can be formed in different



ways: by adding a mass (*mass damper*), by hysteresis properties due to the molecular structure (*material damping*), by friction/rubbing/impact at the structural joints and supports (*structural damping*). Vibrations can be cancelled as in the case of a rubber-mounted *dynamic damper* also. The *active* absorber utilizes some external means such as an actuator for damping. It is more effective as it monitors vibrations and reproduces it out-of-phase so as to cancel the vibrations. This can be accomplished using reverse piezoelectric materials.

Damping capability is influenced by many factors such as the nature of material, modulus, frequency, temperature and defects like dislocations and phase boundaries. In elastic materials (metals/ceramics), damping occurs mainly due to defects and cracks. But damping is the most sensitive indicator of molecular transitions and structural heterogeneities in *polymers* (plastics and rubbers). Many mechanical properties such as fatigue life, toughness, wear and coefficient of friction are intimately related to damping. Several factors can influence damping in polymers, viz., viscoelasticity, glass transition phenomenon, presence of fillers (compounding ingredients), etc.

Viscoelasticity: Dual Nature of Polymers

The two extremes of the broad spectrum of materials are *perfect elastic solids* and *perfect viscous liquids* (Figure 3). A perfect elastic solid obeys *Hooke's Law*, i.e., within the elastic limit, stress is directly proportional to strain. That is, $\sigma = E \varepsilon$, where σ , E , ε are stress, modulus of elasticity and strain respectively. Strong interaction exists among the constituent units in a solid. Hence these units can only vibrate about their equilibrium without any flow. The energy utilized to deform the elastic solid is stored with no dissipation of energy. Metals and ceramics are predominantly

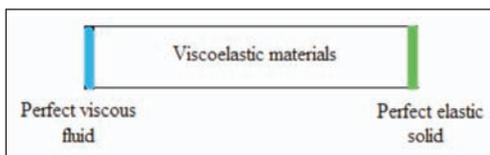
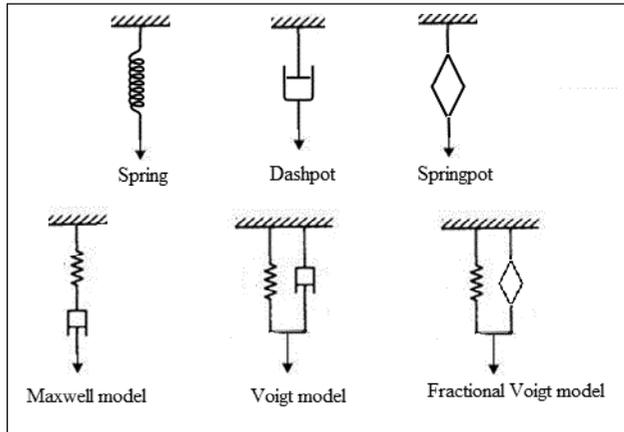


Figure 3. Material spectrum. Real materials show intermediate viscoelastic behaviour.



Figure 4. Mechanical models representing different materials.

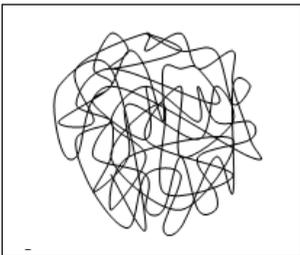


elastic in nature. Elastic solid behaviour is represented by the mechanical model, *spring* (Figure 4).

A perfect viscous liquid obeys *Newton's law*; i.e., for infinitesimal strain rate, stress is directly proportional to strain rate. That is, $\sigma = \eta \dot{\epsilon}$, where σ , η , $\dot{\epsilon}$ are stress, viscosity and strain rate respectively. The work done to deform the viscous fluid is not stored but is dissipated as heat during the irreversible flow (permanent deformation). This reduces the kinetic energy of the system and causes *damping*. The amount of energy dissipated is a measure of the damping capability of the material. *Dashpot* is the mechanical model to represent viscous nature (Figure 4).

However, all real materials exhibit behaviour intermediate to perfect viscous and perfect elastic. These are known as *viscoelastic materials*. Polymer is a typical example for viscoelastic material due to its unique structure. Polymer is a semi-crystalline or amorphous material consisting of a large number of highly entangled, long, chain-like molecules (Figure 5). Its molecular weight is very high, generally in the range of several thousands. The inter chain attraction in most polymers is weak van der Waals forces.

Figure 5. Highly flexible chain-like polymer molecules with large free volume possess the possibilities of many conformations.



Viscoelastic materials are represented by different combinations of spring and dashpot (Figure 4). The Voigt model is used to describe the behaviour of solid viscoelastic dampers, while the Maxwell model is used to represent liquid dampers. Also, both



generalized Voigt model and generalized Maxwell model are used for solid viscoelastic dampers. Another representation uses fractional Voigt and fractional Maxwell models. This uses the springpot (Scott–Blair’s) element which is an interpolation between the spring and dashpot. The fractional Voigt model consists of the spring and the springpot connected in parallel.

Glass Transition Phenomenon: Damping in Rubbers and Plastics

Both rubbers and plastics belong to the class of polymers. But they vibrate differently under a force and so the sound generated by them will be different. We hear a sound when we tap our fingers on a plastic table. But we can hardly hear anything if we tap on the rubber cushion of our chair.

The structure of polymers has been discussed in the previous section. Each chain-like polymer molecule has some inherent thermal energy and so it undergoes continuous movement all the time. Such a material undergoes different molecular deformations at various conditions as described below. It is also depicted as the modulus versus temperature curve (*Figure 6*).

- At low temperatures/high frequencies, only straining of bond angles occurs in polymer molecules. This is due to its low thermal energy and lack of sufficient time to undergo permanent deformation. Thus the polymer exhibits *elastic* behavior

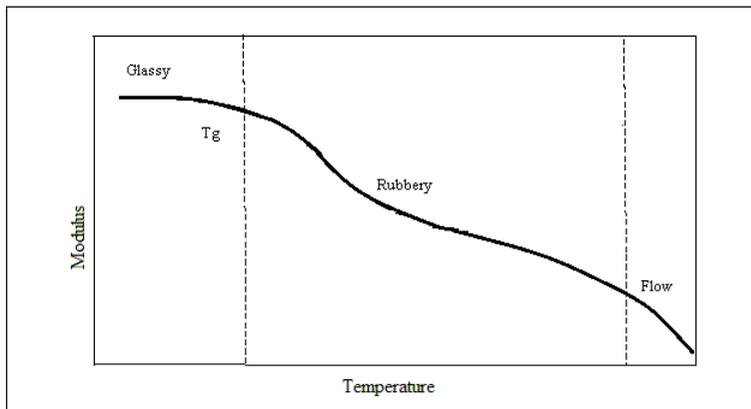
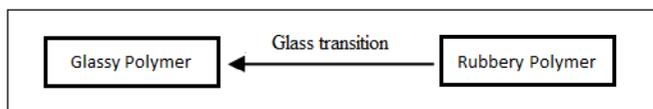


Figure 6. Viscoelastic behaviour of polymer at different temperatures.



Figure 7. High segmental mobility above T_g helps the polymer molecules to relieve the vibration energy.



and is stiff (glassy) under mechanical loading. This is the *glassy plateau*.

- An increase in temperature accelerates *viscoelastic* properties due to both short-range and long-range segmental motion. The change from rubbery to glassy state, known as *glass transition* (Figure 7) occurs at the *glass transition temperature* (T_g). It is the characteristic property of a polymer. Glass transition is the onset of molecular motion involving 10–50 main-chain atoms. At T_g , the chains begin to move back and forth along their length resembling the motion of a snake. The segmental movement will be fast during glass transition.
- At still higher temperatures, molecules slip past one another and sometimes even bond breakage can occur. This results in rapid drop of modulus and thereby permanent deformation. This is the *viscous state*.

In rubbers, the glass transition is easier and it happens at a much lower temperature compared to plastics. This is due to the large free volume, amorphous nature and extremely high flexibility of rubber molecules. Generally, all rubbers have their T_g below room temperature (Table 1). So these are soft and rubbery at room

Table 1. Comparing the T_g of a few rubbers and plastics.

Rubbers	T_g (°C)	Plastics	T_g (°C)
Nitrile rubber	– 40	Poly(vinyl acetate)	30
Styrene butadiene rubber	– 50	Poly(ethylene terephthalate)	70
Neoprene	– 50	Poly(vinyl chloride)	80
Ethylene propylene diene rubber	– 55	Poly(vinyl alcohol)	85
Butyl rubber	– 65	Polystyrene	100
Natural rubber	– 73	Poly(methyl methacrylate)	105
Butadiene rubber	– 100	Polycarbonate	145
Silicone rubber	– 127	Polynorbornene	215



temperature. When rubber is vibrated, it can change into new conformations and can relieve the vibration energy. The damping of a polymer sample is maximum at its T_g . Hence, a polymer is generally selected for the damping purpose if its T_g is in the region of the required temperature. Thus, glass transition is extremely important in damping.

On the other hand, T_g of plastics is above room temperature. Hence, it is hard and brittle at room temperature and so it is less efficient in accommodating the vibration energy. Hence, sound is radiated and plastic may even break with a snapping sound as in the case of polystyrene, which is a typical plastic.

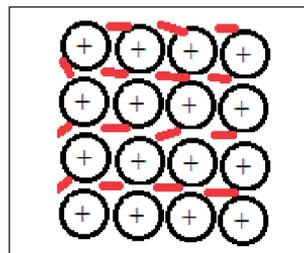
Metallic Bells Ring, but Rubber Bells Don't; Why?

When we strike a metal bell by its clapper inside, the metallic parts collide and the bell rings. We can listen to and enjoy the celestial, melodious bell ring only if it is a metal bell. A rubber bell will be of no use except as a showcase piece.

The speed of sound in a material depends upon its structure (*elasticity* and *density*) and temperature. When an object vibrates, the molecules bump one another in a wave pattern and the kinetic energy is passed from molecule to molecule. This transmission is faster if the molecules are closer and the bonds are stronger. Hence, sound travels fast in solids, but it is slow in liquids and gases since the molecules are not closely connected. The speed of sound is 4600 m/s in copper; but it is 1482 m/s and 355 m/s in water and air respectively.

Metals contain a 3-dimensional crystalline lattice of positive ions in a sea of electrons with strong electrostatic bonding (*Figure 8*). Due to this strong metallic bond, large forces are required to produce even a small deformation. Thus elastic nature predominates in the metal bell. It has only little chance for viscous flow and no dissipation of energy. Hence its damping ratio (ζ) is very small, viz., in the range of 0.001 to 0.004. On vibration, the basic constituents in metal can return to their equilibrium position quickly and are ready to vibrate again. Hence the bell continues to vibrate and the

Figure 8. Cations in a sea of electrons form strong metallic bond, which restricts freedom of movement.



Box 1. Vibration Damping in Rubbers

This is due to the following reasons:

- Long chain-like molecule needs more energy to vibrate.
- Large free volume, lack of close packing of molecules, amorphous nature and weak intermolecular attraction retard the transmission of vibration in rubber.
- Highly flexible molecules can accommodate vibration energy and adopt new conformations easily.
- Low T_g makes the rubber soft at room temperatures.
- Rubber is viscoelastic and a part of the vibration energy is dissipated as heat.

sound is transmitted fast. Thus, the characteristic metallic ringing sound is radiated.

In contrast, since polymers contain large, chain-like molecules, they need more energy to vibrate than that required by small molecules. Moreover, in rubbers there are many factors which favour damping, viz., high free volume, no dense packing of molecules, weak intermolecular attraction, amorphous nature, extremely flexible molecules, etc. Each rubber molecule has a multitude possibilities of conformation. When rubber is vibrated, molecules will be able to adopt new conformations easily so as to relieve the vibration energy. Thus, rubbers can accommodate an external force and therefore vibrations and sound are reduced.

In addition to these factors, polymers exhibit both elastic and viscous properties simultaneously and are viscoelastic. So, when a polymer is vibrated, part of the energy is stored (elastic) and part is dissipated as heat (viscous) within the polymer. This viscous nature results in loss of vibration energy as heat rather than being radiated as airborne noise. Thus rubbers have high damping ratio, viz., in the range of 0.01 to 0.5 depending upon their structure. Hence sound travels very slowly in rubber (60 m/s) and these are used as coatings or sheets to dampen vibrations and sound (*Box 1*).

Characterization of Damping

Damping represents the ability for energy absorption. Hence, the techniques used to determine the damping of polymers can be



classified into two: *direct* methods (measure energy dissipation directly) and *indirect* methods (measure amplitude and frequency which are related to the energy dissipated). Examples for direct methods are energy method, thermal method, hysteresis loop method, etc. The indirect methods include the method of free damped vibrations and the resonance curve/half-power bandwidth method. In the vibration method, logarithmic decrement is measured, which is defined as the natural logarithm of the ratio of any two successive amplitudes.

A very common method to measure the damping of polymers is dynamic mechanical analysis (DMA). It measures the modulus (stiffness) and damping (energy dissipation) properties of materials. The polymer sample is subjected to an oscillating stress and the resulting strain is recorded continuously. The ratio of dynamic stress to dynamic strain is the *complex modulus*, E^* , which can be resolved into the *storage modulus*, E' , and the *loss modulus*, E'' . The storage modulus represents the ability of a material to store energy for every oscillation and it is related to the stiffness of the material. The loss modulus represents the heat dissipated by the material due to its molecular motions and this reflects the damping characteristics of the polymer.

It is surprising to observe that polymer sample, though being a viscoelastic material, behaves entirely different from both perfect elastic and perfect viscous materials. In the case of polymers, the output strain lags behind the input stress by a *phase angle*, δ , whose value varies between 0 and 90°. The values of phase angle for elastic and viscous materials are 0 and 90° respectively. The $\tan \delta$ value, known as *loss tangent*, is the ratio of E'' and E' .

The $\tan \delta$ or E'' is plotted against temperature or frequency. Information on damping can be obtained from the area, peak value, width and height of the curve. Stiff materials, like metals, have low damping whereas compliant rubbers possess high damping. But the figure of merit for damping materials can be represented by a combination of stiffness and compliance. However, materials possessing high damping and high modulus at the same time are not



common. But, this can be achieved by making composites containing stiff and compliant materials.

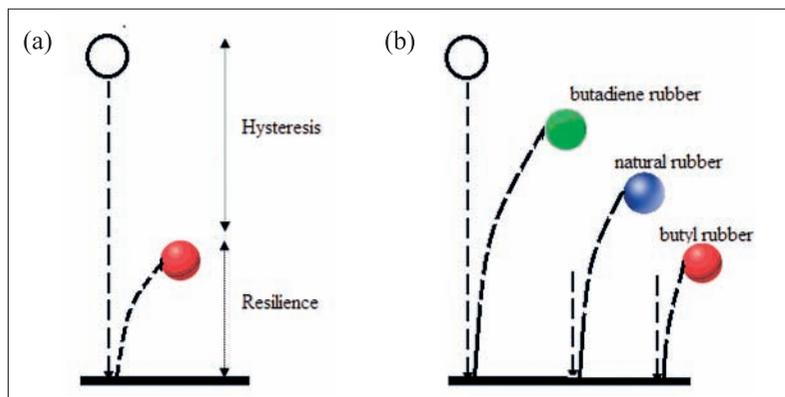
Hysteresis in Rubber Balls

The bouncing of a ball involves gravitational potential energy (PE), kinetic energy (KE) and elastic potential energy. When the ball falls, its gravitational PE transforms into KE. Let us ignore the small heating caused by air resistance. Then the PE lost is equal to the KE it gained. Immediately before it hits the ground, its KE is equal to the PE it had initially. The moment it touches the floor, it remains stationary for a very short time. Then the ball is compressed and the energy is stored as elastic PE. When this compressive force is released, it bounces up with the same KE as it had before hitting the ground. It will rise until all the KE is transformed into PE and so it will rise to its initial height.

Unfortunately, this does not happen. A rubber ball bounces when we drop it onto the ground from a height, but not completely (*Figure 9a*). During deformation, elastic energy is stored in the rubber ball, which is released upon the removal of the deforming forces. Rubber ball bounces due to this elasticity. But, being viscoelastic, rubber possesses inherent viscous nature as well and some energy is dissipated as heat. Hence complete recovery of the ball is impossible. Thus, the ball actually heats up during the collision.

In *Figure 9b*, we can see that rubber balls bounce to different levels based on their molecular structure. The more resilient a rubber ball

Figure 9(a). Bouncing of a rubber ball. **(b)** Damping of different types of rubber. Butyl rubber shows the highest damping.



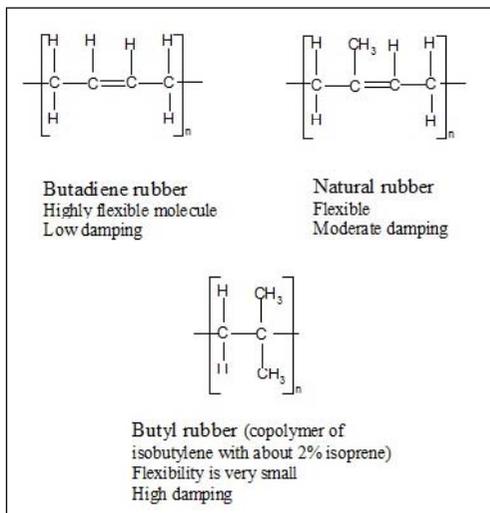


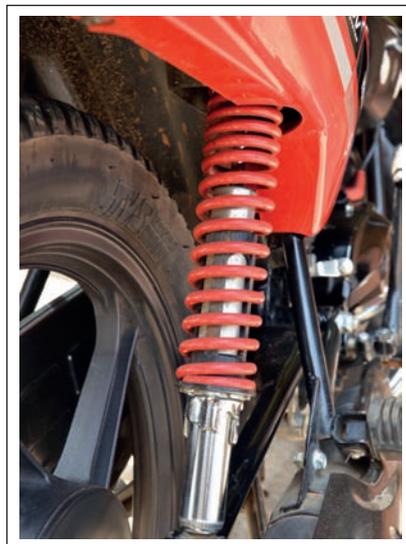
Figure 10. Flexibility of rubber depends on molecular structure.

is, the less damping it is. When rubber is deformed, its molecules are uncoiled and straightened. This happens only if its segments are sufficiently flexible. Butyl rubber is a polymer of mainly isobutylene and a small amount of isoprene. In its molecule, there are two bulky methyl side groups on every repeating unit, which hinder free movement of the chain (*Figure 10*). Therefore, its resilience is less and the damping is high. It is a popular material used for making shock absorbers. The repeating unit of natural rubber also contains methyl group, but only one. Hence, it is more resilient. In butadiene rubber, bulky side group is not present and the hydrogen atoms do not cause any hindrance to the chain movement. Therefore, it shows the highest resilience and the lowest damping.

Role of Damping in Polymer Products

Many materials are used to make dampers. Apart from the excellent damping capacity, rubbers have several advantages such as light weight, low cost, design flexibility, easy processing, non-corrosive nature, variation in properties by adding other ingredients, etc. Hence, dampers based on polymers and their composites replace the traditional dampers in many applications, for example, the *shock absorber* used in a motor cycle (*Figure 11*). Shock absorber in a

Figure 11. Shock absorber.



vehicle is a mechanical device to damp the shock impulse. It improves ride quality by controlling unwanted spring motion and reduces the effect of travelling over rough ground. Vehicle suspension has both dashpot and spring/torsion bars. In this combination, ‘shock absorber’ is actually the hydraulic piston that absorbs and dissipates vibration energy of suspension movement as heat, by pumping a fluid through orifices that resist high-velocity flow. Recently, gas-based shock absorbers are also being used. Suppose that the vehicle suspension does not contain a damper. Then the spring will absorb and release the energy it receives from a bump in an uncontrolled manner and the spring will continue to bounce at its natural frequency until all of its energy is used up.

Surprisingly, rubbers possess the dual function of springing and damping. This uniqueness renders it a suitable material for making the small shock absorber used in an autorickshaw (*Figure 2*). Unlike metal springs, rubber has high hysteresis and does not release the absorbed compression energy completely on the rebound.

Most often, damping in polymer products is considered as a boon. For example, high damping is an essential requisite for products like vibration dampers, bridge bearings, seismic absorbers, building/engine mounts, etc. These reduce the amplitude of undesirable vibrations in various structures from aerospace applications to bridges. Damping is an important factor in electronic goods also. For example, we drop and abuse our mobile phones frequently. This can damage its soldering connections, and leads to loss of data and unsatisfactory performance. Hence, these devices need to withstand shocks. Damping enhances the performance and increases the service life of such products.

However, in certain products, high damping is advantageous but it is a drawback at some other occasions. For instance, high damping in a rubber tyre gives better friction to the road surface (*Figure 12*). This makes riding easier when roads are bumpy. But, at the same time, damping reduces the capability to store energy. This reduces springiness of the tyre

Figure 12. Damping in tyres enhances the road grip. However, damping accelerates tyre abrasion and reduces riding comfort.



and thereby the riding comfort. Damping also causes heat build-up due to the low thermal conductivity of rubbers, which degrades the tyre more rapidly (*Figure 12*). The most undesirable factor of high damping is the excessive distortion in shape and dimensions of structures carrying loads for long time.

Suggested Reading

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