Effects of Cyclic Compression and Thermal Aging on Dynamic Properties of Neoprene Rubber Bearings

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ABSTRACT: The dynamic properties of rubber bearings frequently used as isolators in structures could be significantly deteriorated because of the change of microstructure in rubber caused by cyclic compression and thermal aging. As a result, a catastrophic failure of bridges and buildings unexpectedly occurs when they are subjected to earthquake attack. Here, the dynamic properties of neoprene rubber bearings before and after different cycles of compressive loading or various periods of thermal aging were first measured and compared to each other. On the basis of the experimental results, the effects of cyclic compression and thermal aging on the stiffness, energy absorption, and equivalent viscous damping coefficient of neoprene rubber bearings are investigated. It is found that the deterioration of dynamic properties of neoprene rubber bearings caused by either cyclic compression or by thermal aging is significant and should be taken into account in designing rubber bearings. © 2007 Wiley Periodicals, Inc. J Appl Polym Sci 107: 1635–1641, 2008

Key words: rubber; compression; aging; mechanical properties

INTRODUCTION

The functional requirements for rubber bearings used as isolators in buildings and bridges are sufficient stiffness to sustain their own weight and excellent energy absorption to protect them from a seismic damage. In a design of seismic isolated structures, the stiffness and energy absorption of rubber bearings depend on their geometrical dimensions and the dynamic behavior of rubber materials from which they are made.[1–3] When rubber bearings are subjected to severely mechanical and environmental attacks, the degradation of rubber materials is most likely to occur, inevitably, and eventually leading to a catastrophic failure. For example, the fatigue failure of rubber bearings caused by cyclic compression of overloaded vehicles passing through bridges has been frequently found in Taiwan. On the other hand, thermal aging of rubber bearings because of the climate of relatively higher temperature in Taiwan is another possible failure mechanism. Under some circumstances, the deterioration of rubber bearings could cause an unexpected failure of buildings and bridges even they are merely subjected to some earthquakes with an intermediate intensity. Therefore, the effects of cyclic compression and thermal aging on the dynamic properties of rubber bearings should be taken into account in a design of seismic isolated structures when both durability and structural integrity are sought.

In practical applications, fatigue is a typical failure mechanism of rubber materials when they are under cyclic compressive loads. The effects of cyclic stress on the physical properties of a polydimethylsiloxane elastomer were reported by Fitzgerald et al.[4] They concluded that cyclic stress in combination with high temperature accelerated the degradation of the polydimethylsiloxane elastomer. The fatigue failure of rubber materials was found to be faster if they were not perfectly bonded or some intrinsic flaws resulting from manufacturing pre-existed.[5–7] In addition, rubber materials in service are frequently subjected to various environmental attacks such as thermal aging, radiation exposure, and chemical erosion. The effect of thermal aging on the molecular structure of rubber materials was studied by Choi.[8] It was found that the crosslink density of rubber vulcanizates increases continuously with increasing thermal aging time. Meanwhile, the deterioration of mechanical properties of rubber materials caused by thermal aging has been extensively studied by many researchers.[9–11] It was concluded that the deterioration of mechanical properties of rubber materials was attributed to the changes of molecular structure and crosslink density caused by thermal aging.

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When rubber bearings are under compressive loading, their side surfaces expand and the resulting shear stress within them could reach a maximum value at the outmost boundary between rubber materials and steel plates.[2,12] Hence, the intrinsic flaws near the boundary between rubber materials and steel plates accumulate gradually and coalesce eventually to become several macroscopic cracks while rubber bearings suffer from cyclic compression. After some cycles of compressive loading, the protruded portions of rubber bearings are stripped off and lead to the deterioration of their dynamic properties. Similarly, the functional requirement of rubber bearings could be reduced because of the degradation of rubber materials caused by thermal aging. Therefore, it can be said that the deterioration of dynamic properties of rubber bearings caused by cyclic compression and thermal aging plays an important role in preventing bridges and buildings from a seismic damage. The effects of cyclic compression and thermal aging on the dynamic properties of rubber bearings, however, have been paid less attention and should be exploited in detail. In the paper, a series of dynamic tests on neoprene rubber bearings before and after suffering from either cyclic compression or thermal aging were first conducted. Although the temperature in Taiwan is within the range of 10 to 40°C, the thermal aging tests were performed in an oven at the temperature of 70°C to accelerate the oxidation of rubbers according to ASTM standard D573. In conducting dynamic tests, a cyclic compressive stress range between 3.5 and 6.5 MPa as typically requested by the government of Taiwan for a design of bridge, but different loading frequencies of $\omega = 0.5$, 1, 3, and 5 Hz as normally experienced for earthquake in Taiwan were imposed on neoprene rubber bearings. On the basis of the experimental results obtained, the effects of cyclic compression and thermal aging on the stiffness, energy absorption and equivalent viscous damping coefficient of neoprene rubber bearings are then evaluated and discussed.

EXPERIMENTAL

Materials

All samples of neoprene rubber bearings tested to investigate the effects of cyclic compression and thermal aging on their dynamic properties were manufactured by the Jih-Sheng Rubber Works, Taiwan. The formulation of the neoprene rubber is listed in Table I. Each rubber bearing with a diameter of 6 cm and a height of 4.6 cm is composed of 10 steel plates with a diameter of 6 cm and a thickness of 0.8 mm; the separation distance between any two neighboring steel plates by the introduction of a neoprene rubber layer was set to be constant. Steel plates and neoprene rubber layers were first adhered to each other by using the adhesives of Chemlok 205 and Chemlok 220 manufactured by Lord Elastomer, Taiwan, and then cured at 140°C for additional 30 min in a cylindrical mold. Hence, the dimensionless shape factor S of the resulting neoprene rubber bearings, defined as the ratio of their compressed surface area to their lateral free surface area, was fixed and equal to 4.34.

Cyclic compression tests

In an Instron 8511 dynamic tester, a cyclic compressive stress range between 3.5 and 6.5 MPa was imposed on a cylindrical neoprene rubber bearing under a loading frequency of 5 Hz. Different cycles of the compressive stress range between 3.5 and 6.5 MPa were first performed on the neoprene rubber bearing with a shape factor of 4.34: 3×10^6, 15×10^6, 31×10^6, and 47×10^6 cycles. Later, the dynamic properties of the neoprene rubber bearings before and after suffering from different cycles of compressive loading were measured and then compared to each other.

Thermal aging tests

On the other hand, a series of thermal aging tests on another neoprene rubber bearing were performed at the temperature of 70°C in an air oven. Various periods of thermal aging were considered here: 1, 3, 7 and 12 months. The dynamic properties of the neoprene rubber bearing before and after suffering from different periods of thermal aging were also measured and then compared to each other to evaluate the effect of thermal aging.

Dynamic tests

The dynamic properties of neoprene rubber bearings before and after suffering from either cyclic compression or thermal aging can be obtained from con-

TABLE I
Formulation of the Neoprene Rubber

Sample ingredients	Quantity (phr)
Neoprene W	100
Activator (WH/P)	2
Vulcanizing agent (NA-22)	2
Vulcanizing agent (DM)	2
Vulcanizing agent (S)	1
Antiozonant (OD)	2
Carbon black (N550)	20
Carbon black (N774)	20
Resin (L-80)	5
Zinc oxide	5

ducting a series of dynamic tests. By assuming that neoprene rubber is linear visco-elastic, the relationship between external load F and response displacement Δ for a neoprene rubber bearing subjected to a sinusoidal compression under a loading frequency of ω can be expressed as:[13]

$$F = K\Delta + C\dot{\Delta} = K\Delta_0 \sin \omega t + C\omega\Delta_0 \cos \omega t \qquad (1)$$

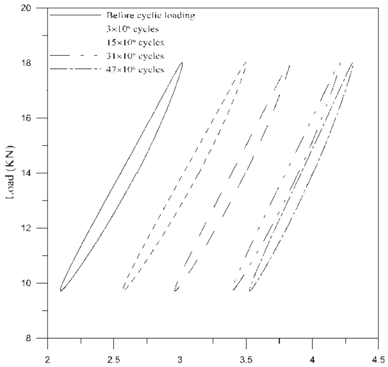
where in, K and C are the stiffness and equivalent viscous damping coefficient of the neoprene rubber bearing, respectively; $\dot{\Delta}$ and Δ_0 are the velocity and amplitude of the neoprene rubber bearing in a dynamic test. Then, the energy absorbed per cycle by the neoprene rubber bearing, equivalent to the area of a hysteretic loop in a load-displacement diagram, can be calculated theoretically:

$$W_D = \int_0^{2\pi/\omega} F(t)\dot{\Delta}(t)dt = \pi C\omega\Delta_0^2 \qquad (2)$$

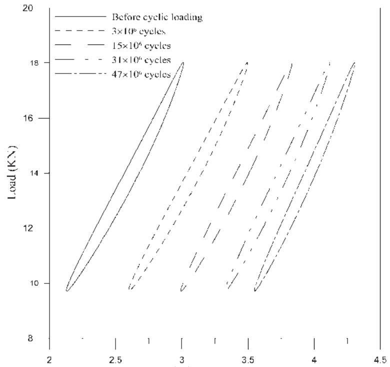
Thus, the equivalent viscous damping coefficient C of the neoprene rubber bearing can be determined from eq. (2) and becomes:

$$C = \frac{W_D}{\pi\omega\Delta_0^2} \qquad (3)$$

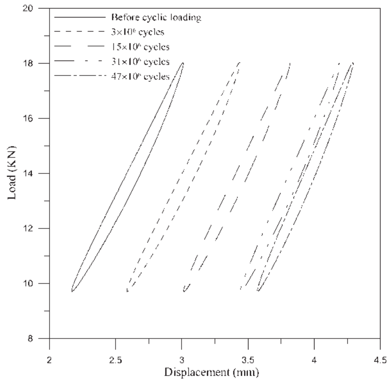
From eq. (3), it is known that the equivalent viscous damping coefficient of a rubber bearing depends on its energy absorption W_D, loading frequency ω and amplitude Δ_0; here, Δ_0 also relies on the stiffness of a rubber bearing. However, both the stiffness and energy absorption of a rubber bearing are affected by the change of microstructure in rubber caused by either cyclic compression or thermal aging. Therefore, it can be expected that the equivalent viscous damping coefficient of a rubber bearing is also influenced by cyclic compression and thermal aging. A series of dynamic tests on neoprene rubber bearings before and after suffering from either different cycles of compressive loading or various periods of thermal aging were conducted. In dynamic tests, the same cyclic compressive stress range between 3.5 and 6.5 MPa but different loading frequencies of ω = 0.5, 1, 3, and 5 Hz were imposed on neoprene rubber bearings. The resulting load-displacement diagrams and hysteretic loops of neoprene rubber bearings before and after suffering from different cycles of compressive loading or various periods of thermal aging were recorded and then utilized to calculate their corresponding dynamic properties



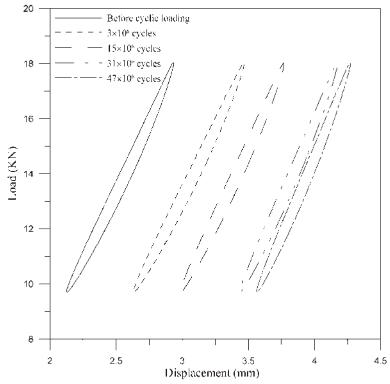
(a)0.5Hz



(b) 1Hz



(c)3Hz



(d)5Hz

Figure 1 The hysteretic loops of neoprene rubber bearings obtained from dynamic tests before and after suffering from 3×10^6, 15×10^6, 31×10^6, and 47×10^6 cycles of compressive loading under a loading frequency of (a) 0.5 Hz (b) 1 Hz (c) 3 Hz and (d) 5 Hz, respectively.

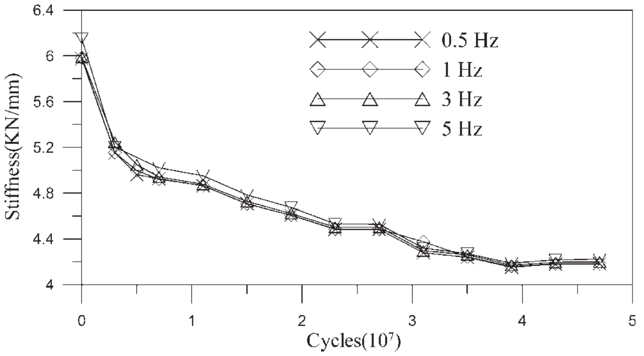


Figure 2 The variation of stiffness plotted against the number of cyclic compression for neoprene rubber bearings under different loading frequencies of ω = 0.5, 1, 3 and 5 Hz.

including stiffness, energy absorption and equivalent viscous damping coefficient. Experimental results were averaged from three times dynamic measurements on neoprene rubber bearings before and after suffering from cyclic compression or thermal aging.

RESULTS AND DISCUSSION

Effect of cyclic compression

The hysteretic loops of the neoprene rubber bearing obtained from dynamic tests before and after various cycles of compressive loading under different loading frequencies of ω = 0.5, 1, 3, and 5 Hz are shown in Figure 1(a–d), respectively. From the figures, it is seen that the resulting vertical displacements of the neoprene rubber bearing after suffering from 3×10^6, 15×10^6, 31×10^6, and 47×10^6 cycles of compressive loading are consistently larger than those before cyclic compressive loading, regardless of the loading frequency ω specified in dynamic tests. Also, the resulting vertical displacements of the neoprene rubber bearing increase significantly as the number of cyclic compression it experienced is increased.

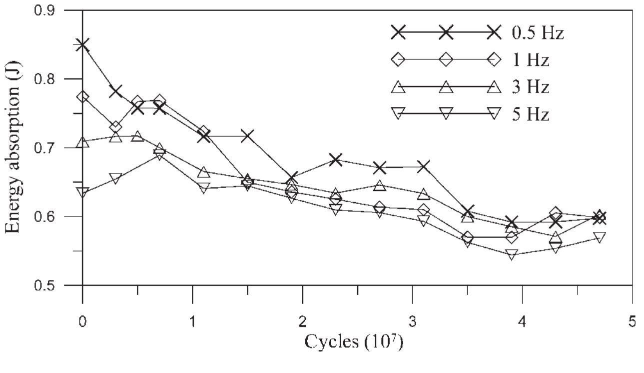


Figure 3 The variation of energy absorption plotted against the number of cyclic compression for neoprene rubber bearings under different loading frequencies of ω = 0.5, 1, 3 and 5 Hz.

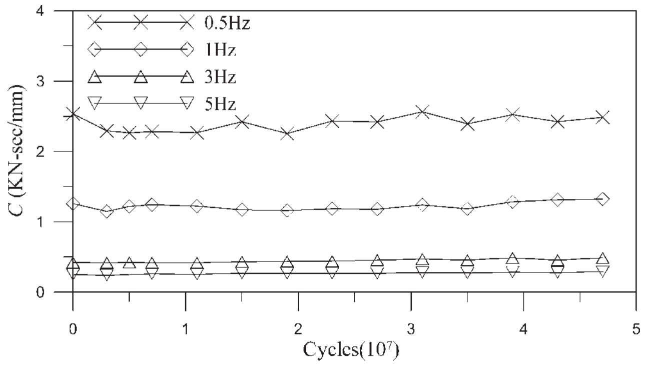


Figure 4 The variation of equivalent viscous damping coefficient plotted against the number of cyclic compression for neoprene rubber bearings under different loading frequencies of ω = 0.5, 1, 3 and 5 Hz.

From the hysteretic loops in load-displacement diagrams obtained from dynamic tests, the vertical stiffness of the neoprene rubber bearing and its amplitude Δ_0 can be easily calculated because the imposed compressive stress range between 3.5 and 6.5 MPa is previously specified in conducting dynamic tests. At the same time, the energy absorption per cycle can be determined by computing the area contained in each hysteretic loop. Once the vertical stiffness, amplitude and energy absorption per cycle of the neoprene rubber bearing are given, its corresponding equivalent viscous damping coefficient can be calculated directly from eq. (3). The cal-

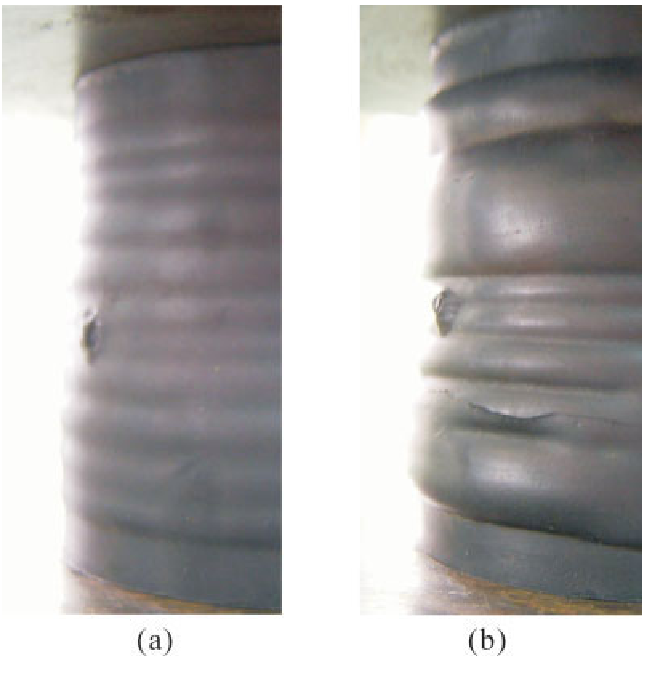


Figure 5 The appearances of neoprene rubber bearings with a shape factor $S = 4.34$ (a) before and (b) after some cycles of compressive loading. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

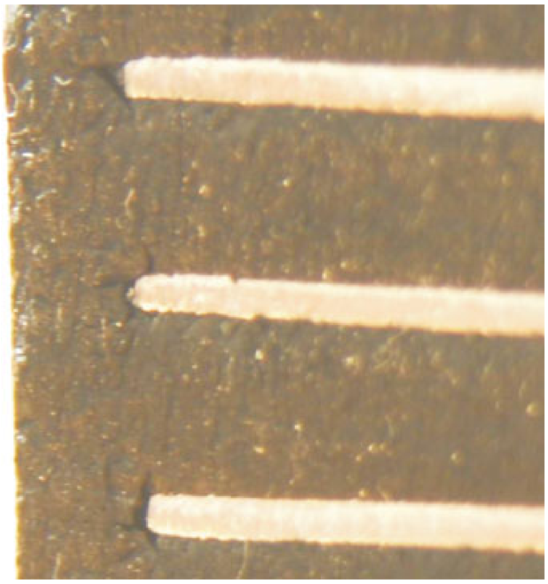
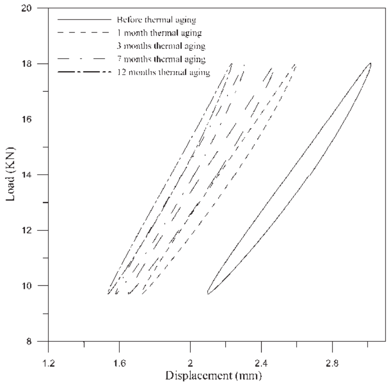


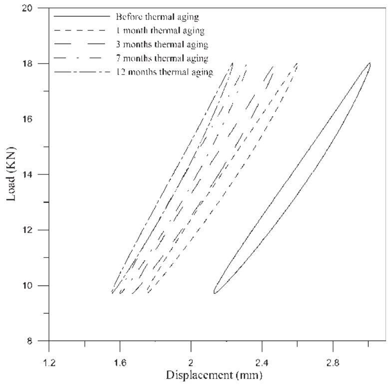
Figure 6 The propagation and coalescence of intrinsic flaws near the boundaries of neoprene rubber and steel plates in a rubber bearing with a shape factor $S = 4.34$ under cyclic compression. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

culated vertical stiffness, energy absorption per cycle and equivalent viscous damping coefficient of neoprene rubber bearings plotted against the number of cyclic compression are shown in Figures 2–4 respectively. From Figure 2, it is seen that the vertical stiffness of neoprene rubber bearings decreases consistently as the number of cyclic compression is increased, regardless of the loading frequency ω specified in dynamic tests. From Figure 3, it is found that the energy absorptions per cycle of neoprene rubber bearings before cyclic compression tests depend on the loading frequency ω. But, the effect of the loading frequency ω on the energy absorption per cycle becomes insignificant when the number of cyclic compression is much larger. The reduction of energy absorption per cycle of neoprene rubber bearings after suffering from different cycles of compressive loading can be more than 30% when they are measured under a lower loading frequency ω = 0.5 Hz in dynamic tests. From Figure 4, it is noted that the effect of cyclic compression on the equivalent viscous damping coefficient of neoprene rubber bearings is insignificant because of the simultaneous decreases of their energy absorption and amplitude. As a result of those, the equivalent viscous damping coefficient is substantially dominated by the loading frequency ω specified in dynamic tests.

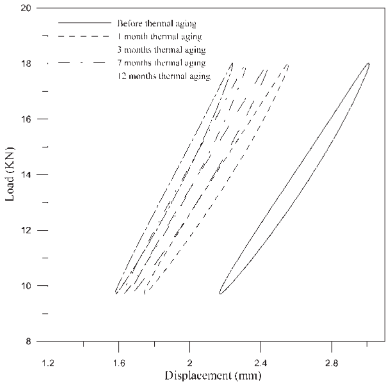
The reason for the deterioration of dynamic properties of neoprene rubber bearings after some cycles of compressive loading could be due to the propagation of intrinsic flaws pre-existed around the bound-



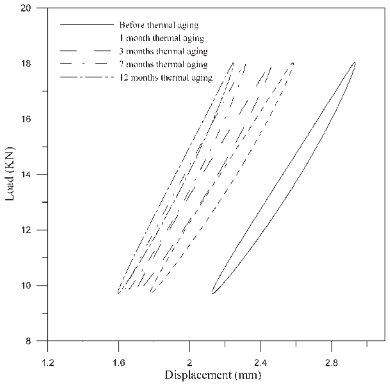
(a) 0.5Hz



(b) 1Hz



(c)3Hz



(d)5Hz

Figure 7 The hysteretic loops of neoprene rubber bearings obtained from dynamic tests before and after suffering from 1, 3, 7 and 12 months thermal aging under a loading frequency of (a) 0.5 Hz (b) 1 Hz (c) 3 Hz and (d) 5 Hz, respectively.

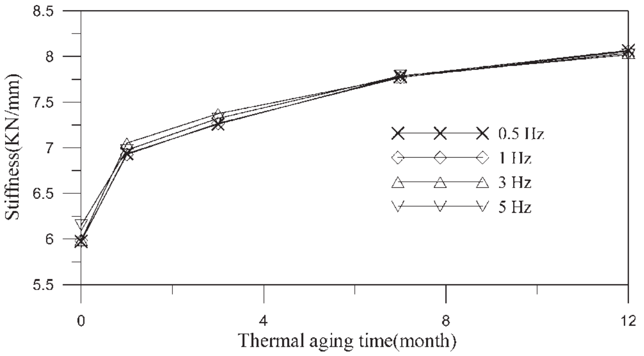


Figure 8 The variation of stiffness plotted against the thermal aging time for neoprene rubber bearings under different loading frequencies of ω = 0.5, 1, 3 and 5 Hz.

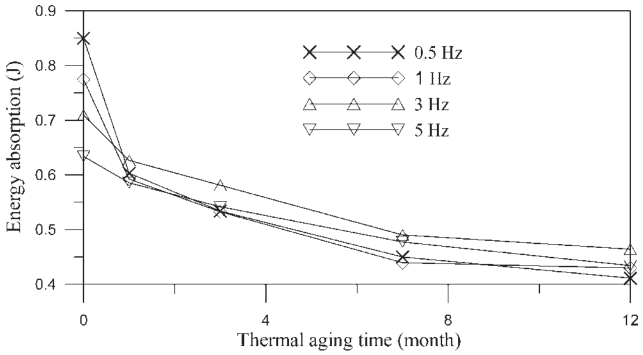


Figure 9 The variation of energy absorption plotted against the thermal aging time for neoprene rubber bearings under different loading frequencies of ω = 0.5, 1, 3 and 5 Hz.

ary of neoprene rubber and steel plates. Photographs for the appearances of neoprene rubber bearings before and after suffering from cyclic compression are shown in Figure 5; the microstructural observation of a particular cross-section by cutting the neoprene rubber bearing after suffering from cyclic compression is shown in Figure 6. From Figure 5, it is seen that the side surfaces of the neoprene rubber bearing expand when it is under cyclic compression. Since the maximum shear stress occurs at the outmost boundaries between neoprene rubber and steel plates,[12] the intrinsic flaws pre-existed near the boundaries are likely to propagate and coalesce to become several macroscopic cracks as can be seen in Figure 6. After some cycles of compressive loading, some of the boundaries between neoprene rubber and steel plates could be no longer perfectly bonded, leading to the reduction of dynamic properties of neoprene rubber bearings. On the basis of the earlier findings, it can be said that the reductions of stiffness and energy absorption of neoprene rubber bearings are attributed to the propagation and coalescence of intrinsic flaws near the outermost boundaries between neoprene rubber and steel plates. As a result of that, the dynamic properties of neoprene rubber bearings are significantly reduced.

Effect of thermal aging

The hysteretic loops of neoprene rubber bearings before and after suffering from various periods of thermal aging are shown in Figure 7(a–d) for different loading frequencies of ω = 0.5, 1, 3, and 5 Hz, respectively. From the figures, it is seen that the resulting vertical displacement of neoprene rubber bearings becomes smaller as the thermal aging time is increased. Meanwhile, the corresponding slope of each hysteretic loop in load-displacement diagrams of neoprene rubber bearings increases gradually as the thermal aging time is increased, consequently giving a lower value of amplitude Δ_0. The earlier findings can be attributed to the increase of crosslink density in rubber after suffering from thermal aging as reported in existing literatures.[8,9] Consequently, the increase of crosslink density in neoprene rubber could further change the dynamic properties of neoprene rubber bearings.

The resulting vertical stiffness, energy absorption per cycle and equivalent viscous damping coefficient under different loading frequencies of ω = 0.5, 1, 3, and 5 Hz are plotted against the thermal aging time and shown in Figures 8–10 respectively. It is seen that the vertical stiffness of neoprene rubber bearings increases with increasing thermal aging time. But, the energy absorption per cycle of neoprene rubber bearings after 1, 3, 7, and 12 months thermal aging is decreased substantially. When neoprene rubber bearings are subjected to 1 year thermal aging, the increase of vertical stiffness can be up to 35% while the reduction of energy absorption per cycle is more than 50%. From Figure 10, it is seen that the equivalent viscous damping coefficient of neoprene rubber bearings under lower loading frequencies ω = 0.5 and 1 Hz decreases first and then

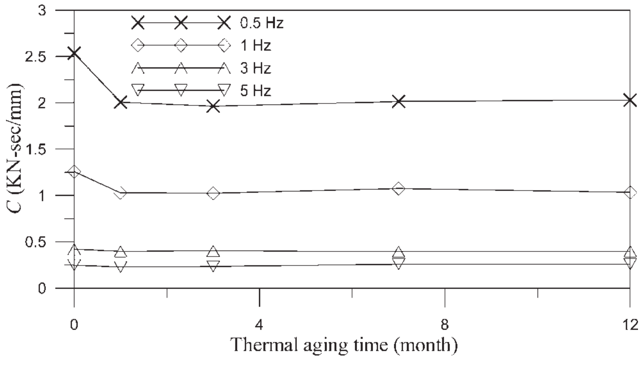


Figure 10 The variation of equivalent viscous damping coefficient plotted against the thermal aging time for neoprene rubber bearings under different loading frequencies of ω = 0.5, 1, 3 and 5 Hz.

reaches a constant value as the thermal aging time is increased. But, the variation of equivalent viscous damping coefficient is insignificant when neoprene rubber bearings are under higher loading frequencies ω = 3 and 5 Hz. The deterioration of dynamic properties of neoprene rubber bearings can be attributed to the changes of molecular structure and crosslink density in neoprene rubber caused by thermal aging.[8–11] However, the effect of thermal aging on the dynamic properties of neoprene rubber is expected to be nonuniform and location-dependent because of the introduction of steel plates in rubber bearings. Therefore, the changes of molecular structure and crosslink density in neoprene rubber caused by thermal aging should be investigated thoroughly in further research.

On the basis of the experimental results obtained here, it is confirmed that the effects of cyclic compression and thermal aging on the dynamic properties of rubber bearing can not be neglected and should be taken into account in designing a rubber bearing used in bridges and buildings. Once the effects of either cyclic compression or thermal aging on the dynamic properties of rubber bearings are known, the dynamic response of a rubber bearing with any dimension and a specified shape factor after suffering from different cycle of compressive loading or different period of thermal aging can be easily estimated from a structural dynamic analysis.[1–3]

CONCLUSIONS

By conducting a series of dynamic tests on neoprene rubber bearings before and after suffering from different cycles of compressive loading or various periods of thermal aging, their vertical stiffness, energy absorption and equivalent viscous damping coefficient are measured and compared to each other. After some cycles of compressive loading, the vertical stiffness and energy absorption per cycle of neoprene rubber bearings are significantly reduced. Here, the deterioration of dynamic properties of neoprene rubber bearings is attributed to the propagation and coalescence of intrinsic flaws in neoprene rubber caused by cyclic compression. On the other hand, the stiffness of neoprene rubber bearings after suffering from various periods of thermal aging increases but their energy absorption and equivalent viscous damping coefficient decrease substantially. The change of dynamic properties of neoprene rubber bearings is due to the changes of molecular structure and crosslink density in neoprene rubber caused by thermal aging. Therefore, it is said that the deterioration of dynamic properties of neoprene rubber bearings caused by either cyclic compression or by thermal aging is significant and can not be neglected. The design goal of preventing bridges and buildings from a seismic damage for neoprene rubber bearings can be achieved if the effects of cyclic compression and thermal aging are taken into account.

References

1. Gent, A. N. Engineering with Rubber, How to Design Rubber Components; Oxford University Press: New York, 1992.
2. Kelly, J. M. Earthquake-Resistant Design with Rubber; Springer-Verlag: London, 1997.
3. Naeim, F.; Kelly, J. M. Design of Seismic Isolated Structures, from Theory to Practice; Wiley: New York, 1999.
4. Fitzgerald, J. J.; Martellock, A. C.; Nielsen, P. L.; Schillace, R. V. Polym Eng Sci 1992, 32, 1350.
5. Dizon, E. S.; Hicks, A. E.; Chirco, V. E. Rubber Chem Technol 1974, 47, 231.
6. Hamed, G. R. Rubber Chem Technol 1983, 56, 244.
7. Fielding-Russell, G. S.; Rongone, R. L. Rubber Chem Technol 1983, 56, 838.
8. Choi, S. S. J Appl Polym Sci 2000, 75, 1378.
9. Hamza, S. S. Polym Test 1998, 17, 131.
10. Abdel-Aziz, M. M.; Basfar, A. A. Polym Test 2000, 19, 591.
11. Ha-Anh, T.; Vu-Khanh, T. Polym Test 2005, 24, 775.
12. Horton, J. M.; Tupholme, G. E.; Gover, M. J. C. J Appl Mech 2002, 69, 836.
13. Kelly, J. M.; Quiroz, E. Mechanical Characteristics of Neoprene Isolation Bearings, UBC/EERC-92/11, University of California, Berkeley, 1992.