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Effects of thermal aging on mechanical properties of laminated lead and natural rubber bearing

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Abstract. Laminated rubber bearing is very popular base isolation of earthquake engineering pertaining to the passive structural vibration control technologies. Rubber used in fabricating NRB and LRB can be easily attacked by various environmental factors such as oxygen, heat, light, dynamic strain, and organic liquids. Among these factors, this study carried out thermal aging test to investigate the effect of thermal aging on the mechanical properties of laminated rubber bearings in accelerated exposure condition of 70℃ temperature for 168 hours. The compressive-shear test was carried out to identify the variation of compressive and shear properties of the rubber bearings before and after thermal aging. In contrast to tensile strength and elongation tests, the hardness of rubber materials showed the increasing tendency dependent on exposure temperature and period. Based on the test results, the property changes of rubber bearing mainly aged by heat are quantitatively presented.

Keywords: laminated bearing; lead rubber bearing; natural rubber bearing; thermal aging

1. Introduction

Base isolation is the most powerful tool of earthquake engineering pertaining to the passive structural vibration control technologies. In practice of seismic base isolation of bridge structures, laminated rubber bearings have been popular since the last century. Among many types of laminated rubber bearings, natural rubber bearing (NRB) which is formed by alternate layers of unfilled rubbers and steel shims has less flexibility and small damping. Also, lead rubber bearing (LRB) which possesses higher damping compared to NRB has been widely used in the seismic isolation practices. LRB is fabricated as a method of inserting lead plugs down the center of rubber bearing to enhance the hysteretic damping (Deb 2004, Xue 2011).

Rubber used in fabricating NRB and LRB is an ideal material to withstand large deformation and absorb energy because of its high elasticity, high damping and large elongation at failure. Due to chemical properties, rubber which is exposed to the air is easily attacked by various

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environmental factors such as oxygen, heat, light, dynamic strain, and organic liquids (Gu and Itoh 2010, Hulme and Cooper 2012).

According to a series of accelerated exposure tests performed by Itoh *et al.* (2006), it was found that the thermal oxidation is the most predominant degradation factor affecting the rubber materials. Very few works are reported in literature regarding the thermal degradation of the rubber bearing. In this regard, the works of Gu and Itoh (2006) and Kalpakidis and Constantinou (2009) can be reported. They studied the degradation effects of a rubber itself by exposing it to different environmental factors like thermal oxidation, ultraviolet irradiation, ozone, low temperature ozone, salt water, and acid rain. From the experiments, Wei *et al.* (2004) investigated the dynamic mechanical properties of rubbers and Itoh *et al.* (2009) performed accelerated thermal oxidation tests on NR and presented aging model under only thermal oxidation. Yang *et al.* (2010) investigated the tensile stiffness and deformation of rubber isolators in tension and tension-shear states. However, the degradation of laminated rubber of NRB and LRB by thermal aging was not addressed by their studies.

Since seismic response of base isolated structures greatly depends on mechanical properties of laminated NRB and LRB, the understanding of the degradation characteristics of the laminated bearing by thermal aging is very essential for the safety and serviceability of structures. Within this purpose, this study was performed in order to characterize time-variant degradation of NRB and LRB and comprehend the dynamic properties of thermally aged-laminated NRB and LRB.

2. Test programs

2.1 Specimen details thermal aging test for rubber materials consisting of laminated bearing

To comprehend the thermal aging of rubber materials tensile strength, elongation, and hardness test were carried out conforming to ASTM D 412 and ASTM D 2240. 100 specimens for tensile strength test were prepared from sheet rubber having the same compositions and mix proportion as rubber in laminated rubber bearing does as shown in Figs. 1 and 2 and the accelerated thermal aging test was performed under the exposure to the temperature of 70°C which is severe condition when compared with the real usage temperature of laminated rubber bearing.

At the accelerated thermal aging test, exposure periods to temperature were 24h, 48h, 72h, 120h, 168h, 240h, 360h, 480h, 720h, 1080h, 1440h, 1800h, 2160h, 2880h, 3600h, 4320h, 5760h, and 8760h. At each exposure period 4 specimens were extracted and measured for tensile strength and elongation according to following Eqs. (1) and (2).

$$T_s = \frac{F_{BE}}{A} \tag{1}$$

$$E_f = \frac{L - L_0}{L_0} \times 100 \tag{2}$$

In which, T_s is tensile strength (MPa), F_{BE} is maximum load to fracture (N), A is section area before tensile test (mm^2), E_f is elongation at fracture (%). L_0 and L are initial specimen length (mm) and specimen length at fracture (mm), respectively. Hardness test was performed

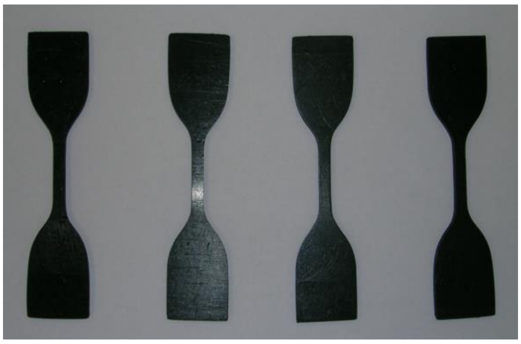


Fig. 1 Tensile test specimens

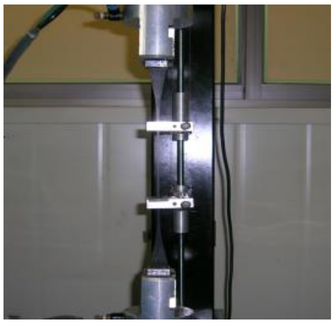


Fig. 2 Accelerated thermal exposure test and tension test

using durometer(hardness apparatus for rubber) on the specimen which was prepared by means of the lamination to be thickness of 12 mm or more.

2.2 Thermal aging test for laminated rubber bearing

2.2.1 Materials and specimens

Among various rubber materials often used as components of bridge rubber bearing, Lead

Table 1 Specifications of two type laminated rubber bearings

Bearing type	Steel diameter (mm)	Hole diameter (mm)	Overall diameter (mm)	Rubber thickness (mm)	Layer No. of Rubber (n)	Steel thickness (mm)	S1	S2	Shear modulus (G)
LRB 1	259	56	279	3	29	3	21.6	2.98	0.4
NRB 1	259	56	279	3	29	3	17.5	2.98	0.4

In which, S1 is first shape factor $\left(\frac{D_s - D_h}{4t_i}\right)$, and S2 is second shape factor $\left(\frac{D_s}{nt_i}\right)$. D_s is the diamter of internal reinforcing steel, D_h is the diameter of internal hole, t_i is the thickness of one layer and n is the number of rubber layer.

Rubber Bearing (LRB) and Natural Rubber Bearing (NRB) were tested in this study. These two rubber bearings have been used in many bridges and building structures.

The test specimens made of these two rubber materials were designed as the same dimensions with a real bridge specification and manufactured with the same chemical compositions in the laboratory. As shown Fig. 3, the diameter of specimen is 279 mm including the 10 mm thickness of outside surrounding rubber and 29 layers of 3 mm rubber thickness were laminated inside a specimen. The detailed dimensions are listed in Table 1.

2.2.2 Test condition and method

The compressive-shear test was carried out to identify the variation of compressive and shear properties by comparing before and after thermal aging. For 168 hours all specimens were exposed to 70ºC which is the same temperature as rubber materials were exposed. This 168h exposure time is equivalent to the estimated life of 60 years according to ISO 11346 (Hulme and Cooper 2012).

The specimens used at this study were prepared with 8 LRB and 8 NRB, respectively. All 16 specimens were prepared. By the bearing type 4 of 8 specimens were deteriorated for 168 hours in the accelerated exposure condition of 70ºC. One of these 4 thermally aged specimens was used for the cyclic loading test and the other was used in the ultimate shear failure tests. In the Table 2 the number of specimens used for each test is listed. Loading test was practiced using compression-shear tester with specification listed in Table 2 and Pic. 1.

(a) Lead rubber bearing (b) Natural rubber bearing

Fig. 3 Specimen geometry and specification

Pic. 1 Loading tester

Table 2 Loading tester specification

Direction	Maximum load	Maximum displacement	Maximum loading rate
Vertical	±2000kN	±100mm	100mm/sec
Horizontal	±500kN	±200mm	250mm/sec

(1) Compression test

This compression test was carried out to understand the effect of accelerated exposure condition on the vertical stiffness of each laminated rubber bearing. As shown in Fig. 4 this test was vertically 3 times loaded within the range of P_1 and P_2 which are -30 percent and +30 percent of design compressive load of each laminated rubber bearing, respectively. Design compressive load (P_0) of LRB and NRB is 565 kN and 490 kN, respectively. The vertical stiffness (K_v) was obtained by Eq. (3).

$$K_v = \frac{P_2 - P_1}{X_2 - X_1} \tag{3}$$

(2) Shear test

In this test vertical load was uniformly applied. This is intended to maintain the designed in-plane pressure and incur lateral displacement of 0.5 Hz sinusoidal wave. This lateral displacement was 11 times repeated and effective shear modulus and equivalent damping ratio was calculated using measuring data of 2nd to 11th loading history curve. To obtain effective shear modulus (K_h) and equivalent damping ratio ($h_{eq}{}^{i}$) of laminated rubber bearing the loading was applied as shown in Fig. 5. In ith loading cycle effective shear modulus was obtained by Eq. (4).

$$K_h{}^{i} = \frac{Q_2{}^{i} - Q_1{}^{i}}{X_1{}^{i} - X_2{}^{i}} \tag{4}$$

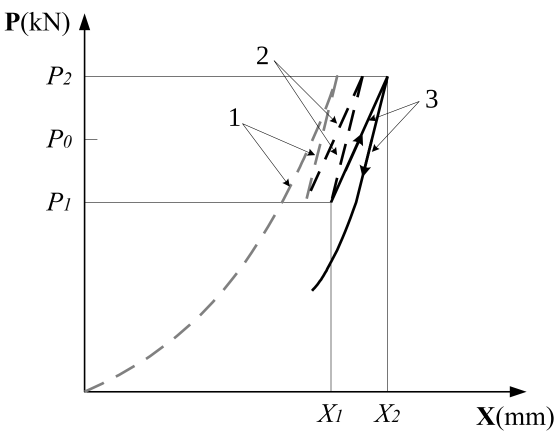


Fig. 4 Compression loading curve

In which Q_1^i and Q_2^i are maximum and minimum shear force in ith loading cycle, respectively and $X_1^{\ i}$ and $X_2^{\ i}$ are also maximum and minimum displacement in ith loading cycle, respectively.

In ith loading cycle equivalent damping ratio was obtained by Eq. (5).

$$h_{eq}^{\ i} = \frac{2\Delta W^i}{\pi K_h^{\ i}\left(X_1^{\ i} - X_2^{\ i}\right)} \tag{5}$$

In which ΔW^i is a area of loading history curve in ith loading cycle.

In this study effective shear modulus (K_h) and equivalent damping ratio ($h_{eq}^{\ i}$) of laminated bearing were obtained from the average of the calculated values in 2nd to 11th loading cycle and can be calculated using the equations shown below.

$$K_h = \frac{1}{10}\sum_{i=2}^{11} K_h^{\ i} \tag{6}$$

$$h_{eq}^{\ i} = \frac{1}{10}\sum_{i=2}^{11} h_{eq}^{\ i} \tag{7}$$

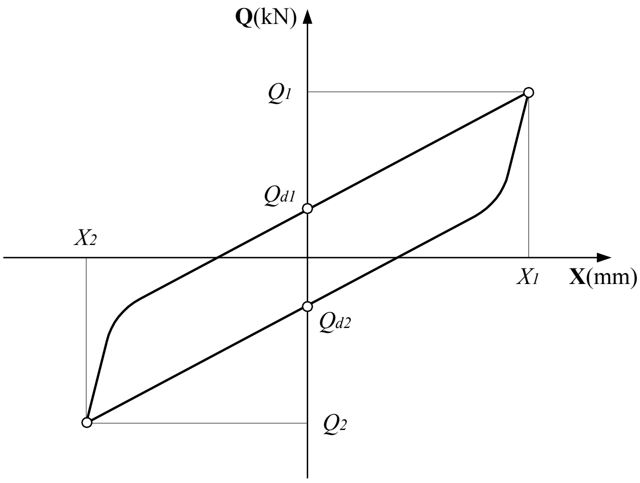


Fig. 5 Compression-shear loading curve

(3) Ultimate shear failure test

In case ultimate shear failure test is loaded in high speed, shear deformation capacity can normally be overestimated. Thus lateral displacement was applied up to maximum deformation with the relative low steady velocity of 0.52 mm/sec. Maximum design compressive load was applied after setting up specimen and shear deformation was applied toward one side direction so that laminated rubber bearing be fractured. Test was to be continued until the load dropped sharply and to be ended when specimen was judged adequately to be failed as shown in Fig. 6.

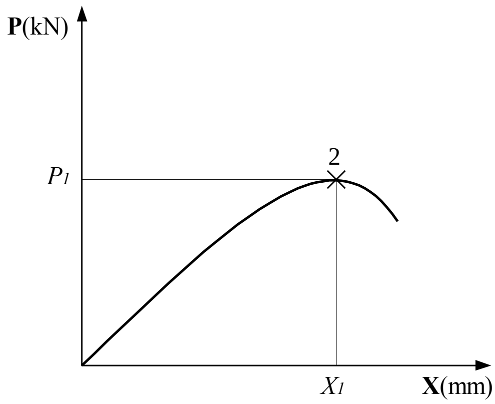


Fig. 6 Ultimate shear properties of laminated rubber bearing

(4) Cyclic loading test

Cyclic loading test was performed on one laminated rubber bearing specimen to investigate the change in the stiffness property and damping ratio of LRB and NRB with and without thermal aging and the test is repeated up to 50 times. The lateral loading was applied by the same magnitude as a design shear displacement with a 5 Hz sinusoidal wave under the design in-plane pressure toward the vertical direction. The change ratios of shear modulus and equivalent damping ratio by cyclic loading test were measured in 3, 5, 10, 30 and 50 times, respectively.

3. Result and discussion

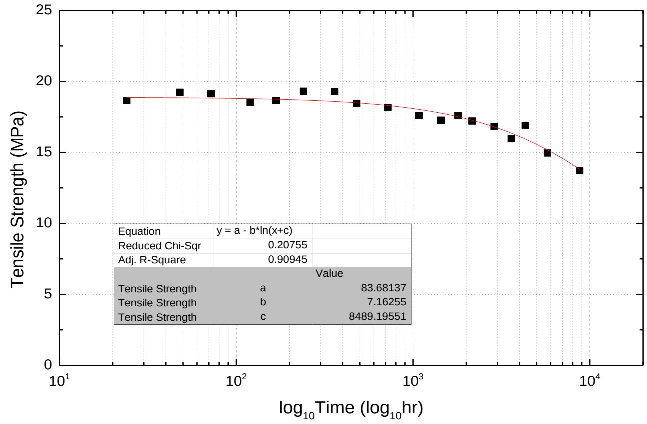
3.1 Properties of thermally aged-rubber materials for laminated bearing

Test results of rubber materials exposed to accelerated thermal condition for 8760 hours (365days) are represented in Fig 7. The tensile strength of rubber materials exposed to heat showed the tendency to slightly increase with the increase in time in case of relatively early term exposure and after that significantly decreased with the increase in exposure time. Elongation of rubber materials showed the similar tendency with tensile strength. Compared with the tensile strength, the elongation of rubber was more remarkably decreased with the increase in exposure time. Unlike tensile strength and elongation test the hardness of rubber materials increased with increase in exposure time. This may be attributed to the hardening of rubber material by heat and accordingly the change to brittle material.

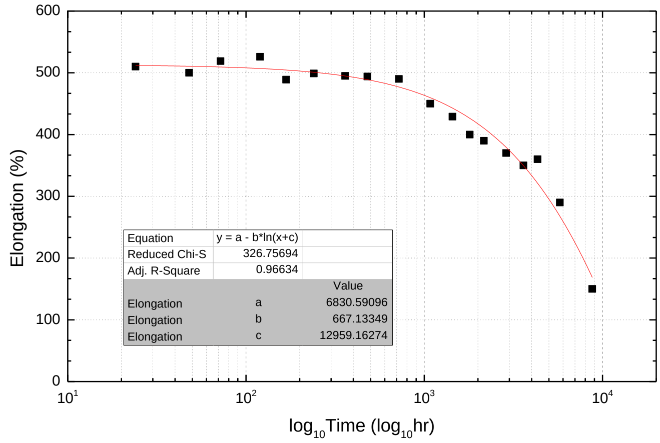
3.2 Properties of thermally aged-Laminated rubber bearing

3.2.1 Compressive properties

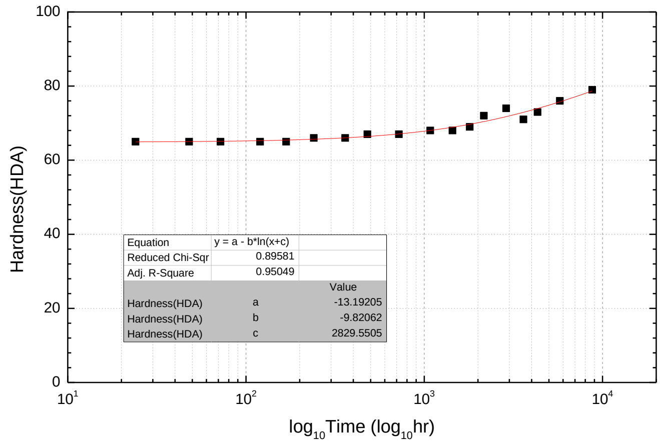
When compressive loading was applied as previously mentioned method, as summarized in Table 3, in case of LRB compressive stiffness was measured to be 478 kN/mm before the accelerated thermal exposure and 462 kN/mm after exposure. Compressive stiffness of LRB was decreased by an extent of 3.3%. NRB also showed a similar tendency with LRB and was measured to be 195 kN/mm before exposure. After exposure compressive stiffness was measured to be



(a) Tensile strength according to heating exposure time



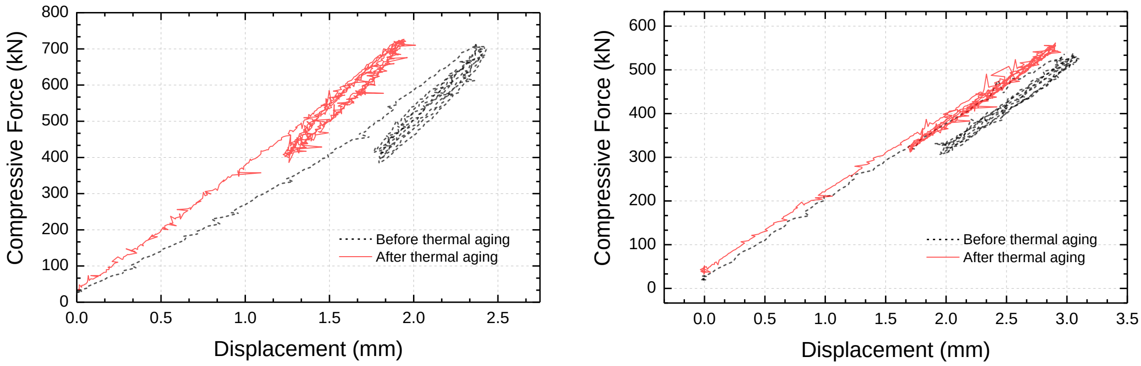
(b) Elongation according to heating exposure time



(c) Hardness according to heating exposure time

Fig. 7 Test results of rubber materials exposed to heat according to time

191 kN/mm and was decreased by an extent of 2% compared with before exposure. Fig. 8 describes compression-displacement curve of LRB and NRB. From these curves it was revealed that compressive load carrying capacity after aging (accelerated thermal exposure) became a bit higher than before aging. The ratio of compressive force to displacement of LRB and NRB became higher after thermal aging. In other words the displacements of LRB and NRB to applied direction were decreased compared with before aging when each laminated rubber bearing was thermally aged. For these phenomena LRB showed more obvious differences than NRB. The reason is that heat must make rubber materials thermal-hardening. Consequently, it makes bearing materials more solid and not flexible. Normally, physical change due to thermal aging causes the elongation decreased.



(a) Lead rubber bearing (b) Natural rubber bearing

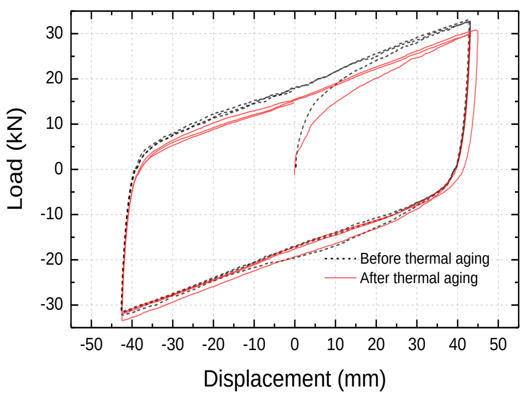
Fig. 8 Compressive properties

Table 3 Compression test result summary

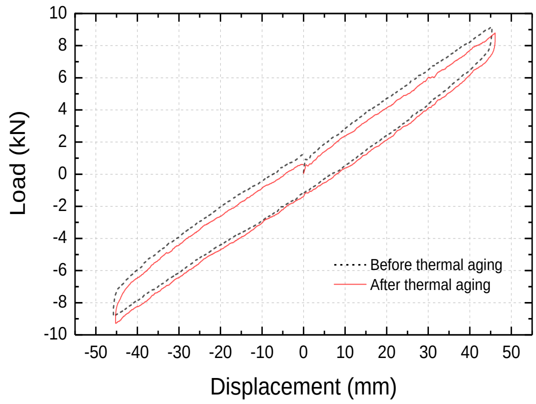
Bearing type	Compressive stiffness(kN•mm)		
	Before aging	After aging	Change ratio (%)
LRB	478	462	-3.34
NRB	195	191	-2.05

3.2.2 Shear properties

As summarized in Table 4, in case of LRB shear stiffness was measured to be 0.73 kN/mm before the accelerated thermal exposure and 0.70 kN/mm after exposure. That means shear stiffness of LRB was decreased by an extent of 4% after aging. NRB also showed a similar tendency with LRB and was measured to be 0.196kN/mm before exposure. After exposure shear stiffness was measured to be 0.195 N/mm and was decreased by an extent of 0.5% compared with before exposure. Equivalent damping ratio of LRB was measured to be 35.28% before aging and to be 35.16% after aging and decreased by an extent of 0.34%. Similar to LRB, equivalent damping ratio of NRB also decreased from 7.56 % to 7.35% by a 0.27%. Differences in shear properties before and after aging are compared in Fig. 9. It can make it be understood that shear properties is less sensitive than compressive properties when bearing materials are aged by heat.



(a) Lead rubber bearing



(b) Natural rubber bearing

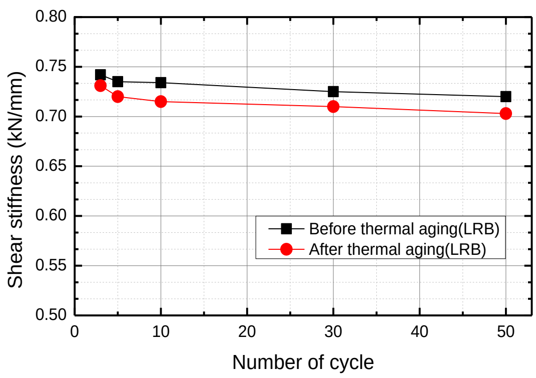
Fig. 9 Compression-shear properties

Table 4 Compression-shear test result summary

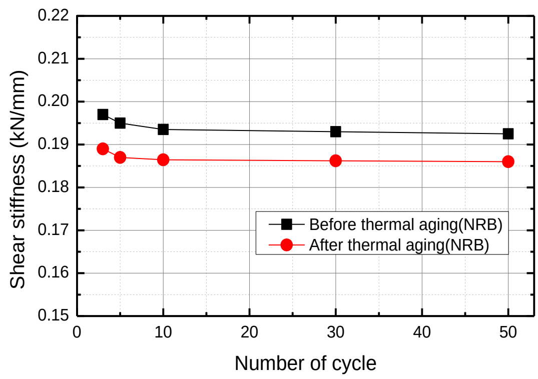
Bearing type	Thermal aging	Shear stiffness(kN•mm)		Equivalent damping ratio (%)	
LRB	Before	0.73	-4.10%	35.28	-0.34%
	After	0.70		35.16	
NRB	Before	0.196	-0.51%	7.56	-0.27%
	After	0.195		7.35	

3.2.3 Cyclic loading properties

Figs. 10 and 11 describe the effect of cyclic load on shear modulus and equivalent damping ratio of LRB and NRB before and after the accelerated thermal exposure (thermal aging). In case

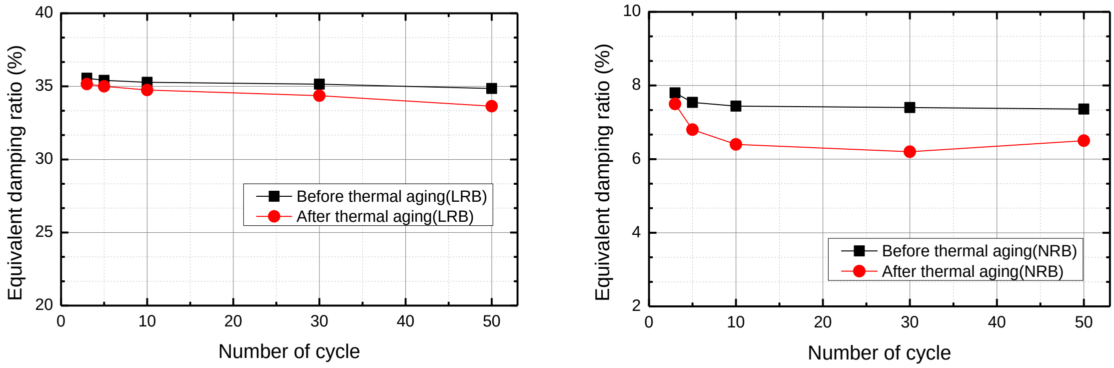


(a) Lead rubber bearing



(b) Natural rubber bearing

Fig. 10 Shear modulus according to cyclic loading



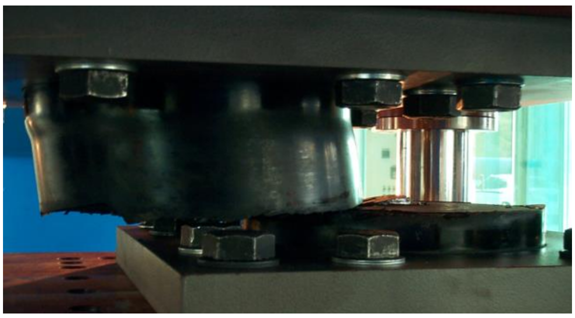
(a) Lead rubber bearing (b) Natural rubber bearing

Fig. 11 Equivalent damping ratio according to cyclic loading

of LRB shear stiffness was changed as an about 2.7% from 0.731 kN/mm before thermal aging to 0.715 kN/mm after thermal aging as shown in Fig. 10 and equivalent damping ratio was decreased as an about 1.9% from 32.25% before thermal aging to 34.2% after thermal aging as shown in Fig. 11 when 50 times cyclic load were applied. NRB also showed a similar results with LRB and its shear stiffness was changed as an about 3.6% from 0.194 kN/mm before thermal aging to 0.187 kN/mm after thermal aging as shown in Fig. 10. Equivalent damping ratio of NRB was decreased by an about 10.9% from 7.5% before thermal aging to 6.68% after thermal aging. According to the experimental results before and after thermal aging it is found that NRB shows markedly higher performance loss caused by thermal aging than LRB.

3.2.4 Ultimate limit shear failure properties

Shear force test of specimen (laminated bearing) is shown in Pic. 2. Shear force tests of laminated LRB and NRB specimens are described in Figs. 12 and 13, respectively. From test result of LRB summarized in Table 5, ultimate shear displacement of LRB specimen aged by heat is 112.9mm decreased by a 17.2% compared to specimen before aging. The different curve gradients and the different displacements at completely failure before and after thermal aging are considered to be an evidence of rubber material hardening due to thermal aging even if the difference seems to be slight in the graph of Fig. 13 in comparison with Fig. 12. Like shear displacement, in case of



Pic. 2 Photograph for ultimate shear failure

LRB shear displacement at failure decreased as an about 17.4% after thermal aging and NRB decreased as an about 2.0% compared to the case before aging.

Additionally, both LRB and NRB bearing are failed in remarkably low shear displacement ratio when compared to Yasaka *et al.* (1991)'s test results. This reason is judged to be why second shape factor of bearing material used in this study is very low as 2.1%. Considering the low second shape factor of 2.1%, these test results are identical to Yasaka *et al.* (1991) study result which carried out the experiment for investigating limit properties of laminated rubber bearing according to the variable of a shape factor. Through their test it was revealed that the lower shape factor of laminated rubber bearing resulted in the remarkably lower shear strength and shear displacement.

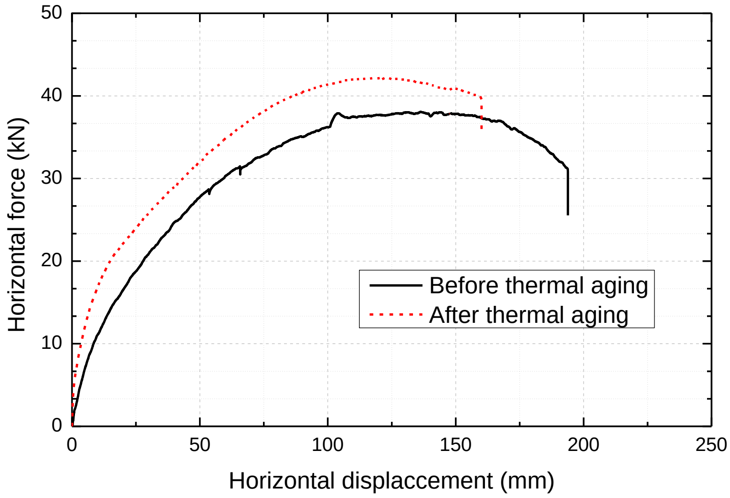


Fig. 12 Ultimate limit shear failure test of LRB

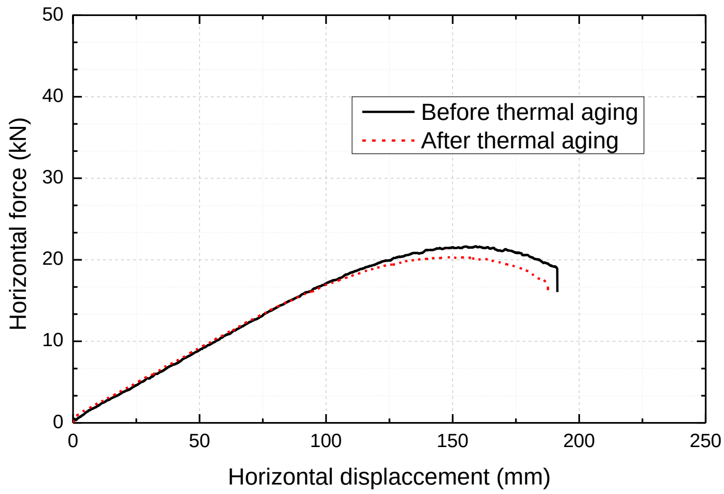


Fig. 13 Ultimate limit shear failure test of NRB

Table 5 Comparison of ultimate shear failure properties before and after aging

Type		Ultimate shear displacement (mm)		Ultimate force (kN)	Stiffness (kN•mm)		Shear displacement at failure(mm)	
LRB	Before aging	136.4	-17.2%	38.1	5840.7	-5.7%	193.8	-17.4%
	After aging	112.9		42.2	5508.6		160.1	
NRB	Before aging	159.2	-2.1%	21.7	2741.3	-5.4%	191.4	-2.0%
	After aging	155.9		20.3	2593.1		187.6	

4. Conclusions

This study carried out thermal aging test to investigate the effect of thermal aging on the mechanical properties of laminated rubber bearing prepared with lead rubber bearing and natural rubber bearing in accelerated exposure condition of 70℃ temperature. The test results of this study can be summarized as follows.

- Tensile strength and elongation of rubber materials consisting of laminated rubber bearing decreased with the increase in thermal aging period when aged in accelerated exposure condition of 70℃ temperature for 8760 hours. In contrast to tensile strength and elongation test, the hardness of rubber materials showed the increasing tendency dependent on exposure temperature and period.
- Compressive stiffness of rubber bearing decreased as an about 2 to 3% after thermal aging. Especially, lead rubber bearing showed the clear tendency that the gradients in load-displacement curve and vertical displacement increased. In the compressive-shear properties test, shear modulus and equivalent damping ratio of all specimens decreased and the change in shear modulus of LRB appeared to be clear. In the 50 times cyclic loading test, shear modulus of LRB and NRB decreased as a 2.7 % and 3.6%, respectively and it was found that NRB was much more deteriorated than LRB in thermal exposure condition because the change of equivalent damping ratio of LRB is 1.9% and NRB is 10.9%.
- In ultimate limit shear failure test, in case of LRB shear displacement ratio decreased as an about 17.2% after thermal aging and NRB decreased as an about 2.1%.
- Based on the test results, the property changes of rubber bearing mainly aged by heat are quantitatively presented. It was revealed that the mechanical properties of the LRB are more significantly affected by thermal aging than those of NRB.

Acknowledgments

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