Effect of Ultraviolet Irradiation on Surface Rubber Used in Bridge Bearings

Yoshito Itoh*, Haosheng Gu**

* Dr. of Eng., Professor, Dept. of Civil Eng., Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603
** Dr. of Eng., Dept. of Civil Eng., Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603

Rubber bearings used in bridges are generally exposed to various environment conditions. It is usually known that the sunlight attacks rubber material, and causes it to entirely lose its elasticity and become sticky. In order to obtain the knowledge of the long-term performance of the ultraviolet exposed rubber products, the effect of ultraviolet irradiation on surface rubber of bridge rubber bearing has been examined through accelerated aging tests. Four kinds of rubber materials normally used were subjected to ultraviolet irradiation for a period up to 2 months. The changes in mechanical properties were investigated with different pre-strains. Besides, the influences of the amount of carbon black on the ultraviolet stability of natural rubber (NR) were evaluated. Finally, the long-term performance of surface rubber was estimated in consideration of the location.

Key Words: ultraviolet irradiation, surface rubber, bridge bearing, aging

1. Introduction

Nowadays rubber materials have been widely used as components of structural members. Especially in bridge engineering, more and more rubber bearings are applied to replace steel bearings because of the special advantages related to the excellent properties of rubbers. However, bridge rubber bearings are exposed to air and attacked by various degradation factors, for example, heat, ozone, ultraviolet, low temperature, salt water and acid rain. Based on the research by Itoh et al., the effects of heat and ultraviolet are much more significant than other factors like ozone.

It is well known that rubbers in common use degrade on exposure to light and the deterioration is due to the ultraviolet portion of sunlight reaching the earth. Since the use of rubbers in the outdoor application is increasing, it is important to investigate and understand the degradation behavior of rubber subjected to ultraviolet irradiation. This knowledge will help one to evaluate the product performance and predict the lifetime.

Many studies have been performed to characterize the weatherability of rubbers chemically, physically or mechanically. Dwight et al. reported that many interactions are presumably occurring and counteracting at the same time. Snijders et al. studied the ultraviolet stability of ethylene-propylene-diene (EPDM) elastomers and showed that upon ultraviolet aging crosslinking and chain-scission reactions compete. Since outdoor exposure tests cost too much time and are easily influenced by uncertain factors, the controlled accelerated aging tests are more preferred. Koike et al. conducted accelerated artificial weathering tests on rubber and plastic sheets to estimate the effects of heat and light. Lin made an attempt to study the surfaces of rubbers aged in accelerated tests through scanning Auger microscopy. Besides, the ultraviolet stability of many kinds of rubbers was studied. Ginic-Markovic et al. investigated the weatherability of surface EPDM rubber compound by controlled UV irradiation. Singh and Chandra studied the photodegradation and stabilization of butyl rubbers. And Aslanyan et al. examined the effects of ultraviolet irradiation on chloroprene rubbers.

Nevertheless, most of the studies have focused only on the micro-level. In the civil engineering, the long-term mechanical behaviors of aged rubber materials attract more interests of engineers. Therefore, this study will mainly investigate changes in the mechanical properties. Four kinds of rubbers commonly used as components of bridge rubber bearings are employed in the accelerated aging test. They are natural rubber (NR), chloroprene rubber (CR), ethylene-propylene-diene rubber (EPDM) and high damping rubber (HDR). The ultraviolet irradiation tests lasted for a period up to about 2 months, in
which, we also studied the effects of the pre-strain and the amount of carbon black on ultraviolet stability.

Fig.1 shows an example of commonly used bridge rubber bearing. It is composed of the upper and bottom flange, inner plates, inner rubber layers, and surface rubber. The purpose of the surface rubber is to protect the inner from the attack of degradation factors such as oxidation, ozone, sunlight, oil, and so on. Usually the thickness of the surface rubber is about 10 mm. Since ultraviolet degradation mainly takes place near the outside surface, as the energy gets consumed and the intensity of the ultraviolet decreases on its passage through the rubber layer, in this study only the surface rubber of the bridge bearing is discussed. As for bridge rubber bearings, the existence of cracks in the surface rubber is a problem, which may result in a further deterioration of the inner rubber. Based on the test results, the Arrhenius methodology is applied to predict the long-term performance of surface rubbers. Since the position of the sun varies all the time and the deck of the bridge will shade the rubber bearing, these influences should also be taken into consideration.

2. Accelerated Ultraviolet Irradiation Test

(1) Materials and sample preparation

The specimens made of NR, CR, EPDM and HDR are provided and tested by the main rubber companies in Japan and they almost cover all the rubber materials presently used in bridge rubber bearings. As for NR, three types with different shear modulus are selected. They are NR_G5, NR_G10 and NR_G12, arranged in the increasing order of shear modulus. The suffix “G5” means the static shear modulus of this NR is 0.5 MPa, “G10” stands for 1.0 MPa, and “G12” is 1.2 MPa. The differences in the components of these three types of NR lie in the amount of the carbon black. The more carbon black it contains, the higher the shear modulus is. For a business reason, the details of rubber compound formulations are kept confidential. In fact, NR_G5 is usually used in building rubber bearings that are not subjected to ultraviolet irradiation. For comparison, it is also tested together with the rubbers used in bridge bearings.

All samples to evaluate the deterioration characteristics are prepared with the shape of the No. 3 dumbbell specimens specified by JIS K 6251, as shown in Fig.2. The thickness of the dumbbell-like specimens is 2 mm, and the middle part has a width of 5 mm and a length of 20 mm.

Because rubber is a nearly incompressible material, in practice, the outer surface of the rubber layer between steel plates will bloom outwards when the bearing subjected to compression due to dead and live loads, as shown in Fig.3. Thus, the surface rubber is in tensile state. The shape of the outer surface of the rubber bearing under vertical load is molded and measured. It is found that the tensile strain of the surface rubber varies from 0% to 40%\(^9\),\(^{10}\). And this result is verified by FEM simulation. Therefore, the rubber samples are stretched to 0%, 20% and 40% at room temperature in order to study the ultraviolet stability of rubbers at tensile state. The heat expansion at the test temperature is about 1%, which is ignored because it is comparatively small. The No.3 dumbbell specimens are mounted on special rigs, as shown in Fig.4. In consideration of the scattering feature of rubber material, 12 samples are prepared for each pre-strain state and each measuring time.
(2) Accelerated ultraviolet irradiation test

The accelerated ultraviolet irradiation test is carried out in a machine called Dew Cycle Sunshine Weather Meter (S80D) produced by SUGA Test Instruments Co., as shown in Fig.5. A carbon arc light can produce artificial ultraviolet radiation (267W/m², 300～700nm) covering the main wavelength region of the sunlight ultraviolet reaching the earth. For the purpose of simulating the natural environment in which a rubber bearing is existing, the cycle composed of 60 minutes of irradiation and 30 minutes of pure water spaying is adopted to consider the day-night change. The temperature and humidity in the chamber is controlled automatically. During the irradiation process, the black panel temperature (BPT) is controlled at 63±3°C, the chamber temperature is 50±2°C, and the humidity is 50±3%. During the water spraying process, the irradiation stops. The chamber temperature is kept at 30±2°C, and the humidity is 98±3%. The test conditions conform to JIS K 6266. The samples of EPDM and HDR are exposed to ultraviolet for 360, 720 and 1,440 hours. CR and NR_G5 are tested for 360 and 720 hours. They are withdrawn from the ultraviolet chamber at respective time intervals. For the purpose of comparing different types of NR, NR_G10 and NR_G12 are only tested for 720 hours with the pre-strain of 40%. The details are presented in Table 1, and totally 552 samples are tested.

(3) Methods for mechanical characterization

After the accelerated ultraviolet irradiation test, the mechanical properties are investigated through the uniaxial tensile test. The inspection method follows the quality inspection method specified by Japan Highway Public Corporation (JH) as well as the specifications in JIS K6251 and K6253 about the general rules of physical testing methods for vulcanized rubber. Because the stress-strain relationship of rubber material is highly non-linear, it is difficult to calculate the stiffness using the secant method. For all the aged rubber samples, the stresses at 25%, 50%, 100%, 200% and 300% strain, i.e. M25, M50, M100, M200 and M300, as well as the elongation at break (EB) and tensile strength (TS) are taken as the evaluation indices. Twelve samples are tested for each group. In order to depict the mechanical properties of rubbers as well as their scattering characteristics, the average values with the double of the standard deviations (M±2S) are plotted.

3. Test Results and Discussions

(1) Effect of ultraviolet irradiation on mechanical properties of rubbers

Generally, aging drops the performance of rubber, and causes rubber to become harder and more brittle. Fig.6 shows the changes in the stress-strain relationships of NR_G5, CR, EPDM and HDR with the pre-strain of 40%. From Fig.6(a), it is found that although the stiffness of NR_G5 is hardly significantly affected by the ultraviolet irradiation, EB and TS decrease. As for CR, EPDM and HDR, stiffness increases, while EB and TS decrease due to the ultraviolet irradiation. The deviations of these rubbers are relatively small.

The time-dependency of these samples is plotted in Fig.7. The horizontal axis is the aging time, while the vertical axis is the normalized change in the mechanical properties by taking the corresponding properties in the initial state as one. M100 is chosen to represent the stiffness of rubber material in this study. In Fig.7(a), M100 of NR_G5 first increases a little, then decreases. There is only little variation of M100. However, after 720 hours, EB decreases by over 50% and TS by nearly 90%. As for CR, the accelerated aging test finished at 720 hours, as shown in Fig.7(b). It can be seen that M100 increases while EB decreases gradually. By the end of the aging test, M100 increases by about 60%, and EB decreases by about 25%. TS of CR does not change much. The tendency of the change in mechanical properties of EPDM and HDR is very clear, as shown in Figs.7(c) and 7(d). The material properties change rapidly during the early stage. After 720 hours, the variations tend to slow down and eventually become stable. At 1440 hours, M100 of EPDM shows an increase of about 25% at the equilibrium state. And ultraviolet irradiation reduces EB and TS by about 20% and 25%. The increase of M100 of HDR approaches to 50% after 1440 hours, while the reduction of EB and TS approaches to 35% and 20%, respectively.

Table 1 Test specimens and conditions

<table>
<thead>
<tr>
<th>Material</th>
<th>Number of Samples</th>
<th>Pre-Strain</th>
<th>Test Period (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDR</td>
<td>12×3×4=144</td>
<td>0%</td>
<td>0, 360, 720, 1440</td>
</tr>
<tr>
<td>EPDM</td>
<td>12×3×4=144</td>
<td>0%, 20%, 40%</td>
<td></td>
</tr>
<tr>
<td>CR</td>
<td>12×3×3=108</td>
<td>0, 360, 720</td>
<td></td>
</tr>
<tr>
<td>NR G5</td>
<td>12×3×3=108</td>
<td>0, 360, 720</td>
<td></td>
</tr>
<tr>
<td>NR G10</td>
<td>12×1×2=24</td>
<td>40%</td>
<td>0, 720</td>
</tr>
<tr>
<td>NR G12</td>
<td>12×1×2=24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>552</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 6 Effect of ultraviolet irradiation on rubber mechanical properties (pre-strain=40%)

Fig. 7 Time-dependency of rubbers subjected to ultraviolet irradiation (pre-strain=40%)
From a chemical point of view, ultraviolet irradiation shifts the balance between crosslinking and chain-scission reactions. Due to aging, the cross-links between chains break up and the chains re-entangle and form more new cross-links. Therefore, the motions of the chains become more impeded, which results in high hardness and low elongation. With the progress of the competition between the rupture and formation of cross-links, the reaction speed slows down gradually until the saturation is present.

(2) Influence of the pre-strain on ultraviolet deterioration

In the accelerated ultraviolet irradiation test, the rubber samples are stretched to 0%, 20% and 40% and kept throughout the test. The influences of the pre-strain are compared in Fig. 8, in which the normalized variations of properties at 720 hours are illustrated. The existence of the pre-strain reduces the variation of the stiffness of NR_G5 and EPDM, as shown in Figs.8(a) and 8(c). The pre-strain makes both the EB and TS of NR_G5 decrease much more significantly. However, the influences on the EB and TS of EPDM are not very clear. Fig.8(b) indicates that the pre-strain increases the stiffness of CR substantially, and makes EB decrease. After the same aging period, CR becomes stiffer in the tensile state than in the state without pre-strain. Since TS does not change much due to ultraviolet irradiation, the effect of pre-strain is also insignificant. In Fig.8(d), although the relationship between the variation of HDR’s stiffness and the pre-strain is not clear, it is evident that pre-strain accelerates the reduction of EB and TS. HDR becomes more breakable although the stiffness does not change much. Therefore, the effect of the pre-strain is different among kinds of the rubber material.

Table 2 Crack states in aged NR samples (720 hours)

<table>
<thead>
<tr>
<th>No.</th>
<th>NR_G5</th>
<th>NR_G10</th>
<th>NR_G12</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C-4</td>
<td>B-1</td>
<td>A-1</td>
</tr>
<tr>
<td>2</td>
<td>C-4</td>
<td>B-1</td>
<td>A-1</td>
</tr>
<tr>
<td>3</td>
<td>C-4</td>
<td>A-1</td>
<td>A-1</td>
</tr>
<tr>
<td>4</td>
<td>C-5</td>
<td>B-1</td>
<td>A-1</td>
</tr>
<tr>
<td>5</td>
<td>C-5</td>
<td>A-1</td>
<td>A-1</td>
</tr>
<tr>
<td>6</td>
<td>C-4</td>
<td>B-1</td>
<td>A-1</td>
</tr>
<tr>
<td>7</td>
<td>C-5</td>
<td>A-1</td>
<td>A-1</td>
</tr>
<tr>
<td>8</td>
<td>C-5</td>
<td>A-1</td>
<td>A-1</td>
</tr>
<tr>
<td>9</td>
<td>C-5</td>
<td>A-1</td>
<td>A-1</td>
</tr>
<tr>
<td>10</td>
<td>C-5</td>
<td>B-1</td>
<td>no crack</td>
</tr>
<tr>
<td>11</td>
<td>C-5</td>
<td>no crack</td>
<td>A-1</td>
</tr>
<tr>
<td>12</td>
<td>C-4</td>
<td>B-1</td>
<td>no crack</td>
</tr>
</tbody>
</table>

Number of crack       | Length and depth of cracks
A: Few               | 1: Invisible to naked eyes,
B: Many              | but visible by \( \times 10 \) magnifier
C: Innumerable       | 2: Visible to naked eyes
                    | 3: Deep, length less than 1mm
                    | 4: Deep, length about 1\~3mm
                    | 5: Longer than 3mm or nearly break

Fig. 8 Influence of pre-strain on ultraviolet deterioration (720 hours)
(3) Ultraviolet stability of different types of NR

Even the same kind of rubber, the mechanical properties are different because of the particular components in the rubber. It is also necessary to clarify the aging characteristics of the different type. In this study, three types, NR_G5, NR_G10, and NR_G12 are examined. The static shear modulus is mainly determined by the amount of the carbon black in NR. The amount of the carbon black can be put in the following order: NR_G12>NR_G10>NR_G5. As for each type of NR, two groups of samples are prepared, with 12 specimens in each group. One group is used for the tensile test in the initial state. The other group is stretched to 40% and accelerated aged for 720 hours. Before the tensile test, the appearance of the specimens is first examined.

For example, the appearance of one sample from each group is shown in Fig.9 and Fig.10, in which, NR_G5, NR_G10, and NR_G12 are compared before and after the accelerated aging test, respectively. After 720 hours’ ultraviolet irradiation, many deep and long cracks are found on the surface of NR_G5. However, on the surface of NR_G10 and NR_G12, the cracks are not evident, and are hardly observable by naked eyes. The crack states are evaluated according to the evaluation method specified by JIS K6259. The results are presented in Table 2. This table reveals the performance levels of these three types.
types of NR: NR_G12>NR_G10>NR_G5. The main difference in the components of these rubbers lies on the amount of the carbon black. Therefore, it can be concluded that, the more the amount of the carbon black NR contains, the stronger the NR’s resistance to ultraviolet irradiation is.

The aging characteristics of NR_G5, NR_G10, and NR_G12 subjected to ultraviolet irradiation are plotted in Fig. 11. Due to ultraviolet, the stiffness of all the NR samples increases, while both EB and TS decrease. Especially for NR_G5, its EB and TS decrease most remarkably after 720 hours’ irradiation. The changes in M100, EB and TS are compared in Fig. 12. It is observed that the change in M100 increases with the amount of the carbon black. After 720 hours, M100 of NR_G5 almost does not change, while that of NR_G10 and NR_G12 increases by nearly 20% and about 25%, respectively. However, the tendencies of changes of EB and TS are not clear. The EB and TS of NR_G5 decrease by about 60% and 85%, respectively. NR_G10 decreases by the least amount, with a drop of EB and TS by 15% and 8%. EB and TS of NR_G12 falls by about 20% and 10%, respectively.

Generally speaking, less cracks appear on the surface of NR with a more amount of carbon black. Usually ultraviolet irradiation results in an increase in the stiffness of rubber material. However, in NR_G5, it is thought that the existence of the cracks offsets the stiffness increase. Meanwhile, the cracks decrease the EB and TS to a great degree. Although NR_G5 is very sensitive to the ultraviolet irradiation, it is not necessary to consider this deterioration since NR_G5 is usually used in building rubber bearings, which are installed in the basement. As for NR_G10 and NR_G12 used in bridge rubber bearings, the ultraviolet aging behavior is fairly good, and cracks are few.

4. Performance Estimation of Surface Rubber

The accelerated ultraviolet irradiation test simulated the environmental condition of sunlight by taking the day-night change into consideration. The Arrhenius methodology is commonly used to correlate the accelerated aging results with the aging under service conditions. Through accelerated artificial weathering tests on rubber and plastic sheets, Koike et al.3) gave the following equation to express the relationship between the property variation and the ultraviolet irradiation received:

\[ \ln \left( \frac{y_h}{y_0} \right) = C (I^\alpha t) \]  

where, \( y_h \) is the rubber material properties such as the elongation at break, stiffness and so on, \( y_0 \) indicates the original value of \( y_h \), \( C \) and \( \alpha \) are constants of rubber material, \( t \) is a deterioration period, and \( I \) represents the ultraviolet intensity. In the light emitted by the carbon arc light11), the ultraviolet (300~400nm) intensity is 77.5W/m².

In the aging test of ultraviolet irradiation, the environment temperature is 50°C during the irradiation process, and 30°C during the water spraying process. The average temperature at the surface of rubber samples is 44°C. With the influence of heat eliminated1), the relationship between ultraviolet intensity and the change in EB of CR is shown in Fig. 13.

It is clear that the equation presented by Koike et al.3) agrees well with the test results. The decrease of EB is the function of the ultraviolet radiation received, shown as follows:

\[ \ln(EB_0/EB_t) = 0.032(I^\alpha t^{4.07}) \]  

where, \( EB_0 \) and \( EB_t \) are elongation at break before and after aging, respectively.

In the service environment, the ultraviolet intensity should be calculated from the sunlight falling on the surface of the surface rubber. Energy received outside the atmosphere has a degree of constancy. But at the ground level the received solar radiation is quite different because of the diffusion by atmosphere and the reflection by the clouds and the ground. On the earth, the global solar radiation is the sum of the direct, diffuse and reflect radiations. Since reflection is uncertain and its proportion in solar radiation is comparatively very small, the impact of reflection is neglected in this study. The direct radiation is not constant. The position of the sun in the sky
varies throughout the day and season due to the spin of the earth around its axis and to its orbiting around the sun. Moreover, as for rubber bearing, only the vertical surface is needed to consider. The orientation of the vertical surface also affects the amount of solar radiation received by the surface rubber12).

Using Fig. 14, the direct solar radiation flux $H_i$ to a vertical surface can be expressed by the solar radiation to the normal surface $H_n$ using the expression13).

$$H_i = H_n \cos i$$  \hspace{1cm} (3)

$$\cos i = \cos \alpha \cdot \cos Z$$  \hspace{1cm} (4)

where, $\alpha$ is the solar altitude, $Z = Z_0 - P$, where $P$ is the azimuth of the plane, and $Z_0$ is the sun’s azimuth from the south. $\alpha$ and $Z$ can be determined from the following equations.

$$\sin \alpha = \sin L \sin \delta + \cos L \cos \delta \cos h$$  \hspace{1cm} (5)

$$\cos Z = (\sin L - \cos L \tan \delta) / \sin h$$  \hspace{1cm} (6)

$$\sin Z = (\cos \delta \sin h) / \cos \alpha$$  \hspace{1cm} (7)

where, $L$ is the northern latitude of the place, $\delta$ is the declination of the sun, and $h$ is the hour angle.

The solar radiation data of 2002 at Sapporo, Sendai, Tokyo, Fukuoka, Kagoshima and Naha, published by the National Astronomical Observatory14), are used. The direct solar radiation on various oriented vertical planes are accumulated, and the average values of which in a day are shown in Fig. 15. From this figure, the maximum direct radiation on a vertical plane and the corresponding azimuth in each place can be determined. First, the worst case is considered. In other words, the vertical surface of the surface rubber is assumed to be facing in the direction that it can receive the maximum solar radiation.

For a clear sky, the diffuse radiation component of solar radiation depends mostly on air mass and atmospheric turbidity, water vapor, dust content, and aerosols. For simplicity, it is assumed that the distribution of the diffuse radiation is uniform over the whole visible sky hemisphere, and the diffuse radiation falling on an inclined plane can be calculated by the following equation.

$$D_i / D_0 = (1 + \cos b) / 2$$  \hspace{1cm} (8)

where, $D_i$ and $D_0$ are the diffuse radiation on inclined and horizontal plane, respectively. For a vertical plane, $b$ equals $\pi/2$, and the diffuse radiation $D_i$ is $D_0/2$.

The solar spectrum consists of the ultraviolet region, the visible region and the infrared region. The energy in each region is different. The ultraviolet irradiation accounts for 15.9% of the total solar energy15).

With all the information described above, it is possible to estimate the long-term performance of surface rubber in a bridge bearing. First, the maximum solar radiation is calculated based on the astronomical information. The maximum average daily direct radiation and the average daily diffuse radiation at some typical location in Japan are shown in Table 3. Then, only the energy in the ultraviolet region is considered. Using Eq.(2), for instance, the EB of CR vs. aging time in various places of Japan is plotted in Fig. 16. The influence of heat is also considered11. It is found that ultraviolet irradiation causes EB to decrease significantly. In the worst case, EB decreases by about 50% in less than 5 years, and by about 80% in 30 years. The reduction of EB to a certain degree might initiate cracks in the
rubber in a tensile state. The discrepancies of the decreasing speed among various locations are small because the global radiation is similar.

Practically, since bridge bearings are installed between the substructure and the superstructure, in most cases they are in the shadow of the deck. For the case where it is assumed that the side surface of the rubber bearing is in the shadow all the time, the degradation of EB is shown in Fig.17. In this case, only the diffuse radiation is counted. Ultraviolet irradiation reduces EB by about 40% within 5 years. It is clarified that the smaller the diffuse radiation, the less EB decreases.

However, it should be noted that ultraviolet irradiation is thought to merely affect the surface rubber that receives the sunlight directly. A typical thickness of the surface rubber is 10mm, which is 5 times the thickness of the specimens in this test. It is difficult for ultraviolet irradiation to pass through this thickness. As for the inner rubber, even oxidation can only progress to a certain depth\(^{16}\). Therefore, the horizontal stiffness of a rubber bearing will not distinctly be influenced by the ultraviolet irradiation.

Up to now, there’s no specific standard for the long-term performance of surface rubber in bridge bearing. This paper provides a method to predict the drop of surface rubber’s performance due to ultraviolet irradiation. The information will be useful in design and maintenance. The required performance and the evaluation criteria will be studied in the following research.

5. Summary and Conclusions

This study evaluated the long-term property changes in NR, CR, EPDM and HDR, which are used as the surface rubber in bridge bearings, through accelerated ultraviolet irradiation tests. The influences of the pre-strain and the carbon black are also examined. Based on the test results, the long-term properties of CR are estimated considering the location and the deck shadow. The major findings are summarized as follows:

1. Ultraviolet irradiation increases the stiffness of rubber, and decreases its elongation at break and tensile strength. As a result, rubber becomes hard and brittle.

2. Pre-strain may accelerate or decelerate property changes due to the ultraviolet irradiation, depending on the kind of the rubber.

3. As for NR, c more cracks are found on the rubber with less carbon black, which consequently result in a remarkable decrease of EB and TS.

4. Although there are many cracks on NR_G10 usually used in building bearings, less cracks are found on NR_G10 and NR_G12, which are more commonly used in bridge rubber bearings.

5. Using the Arrhenius methodology, the change in EB of CR is predicted. When exposed to the sunlight directly, EB decreases very fast, and the variations resulting from the locations are very small. When in the shadow, EB decreases by about 40% in 5 years.
6. Ultraviolet irradiation changes the mechanical properties of the surface rubber; however, it is not thought to influence the general performance of the bridge rubber bearings.

Acknowledgement

The authors wish to express their gratitude to Kawaguchi Metal Industries Co., Ltd., Tokai Rubber Industries, Ltd., Bridgestone Co., and Yokohama Rubber Co., Ltd. for support with the long-term accelerated exposure tests. The authors also thank Prof. Takeda Kunihiko of Nagoya University for his precious advice. The study presented in this paper was supported by the Grants-in-Aid for Scientific Research of Ministry of Education, Culture, Sports, Science and Technology, Grant No.1560237, and the research leader is Prof. Yoshito Itoh. The support is gratefully acknowledged.

References


(Received September 10, 2006)