Effect of Ultraviolet Irradiation on Surface Rubber Used in Bridge Bearing

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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 bearing has been examined through accelerated aging tests. Four kinds rubber materials normally used in bridge rubber bearings were subjected to ultraviolet irradiation for a period up to 2 months. The changes in mechanical properties were investigated at 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 the steel bearings because of the special advantages related to the excellent properties of rubbers. However, bridge rubber bearings are exposed to the air and attacked by various degradation factors. For example, 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 for 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. Dwright et al.[1)] reported that many interactions are presumably occurring and counteracting at the same time. Snijders et al.[2)] studied the ultraviolet stability of ethylene-propylene-diene (EPDM) elastomers and showed that upon ultraviolet aging crosslinking and chain-scission reactions compete. Since outdoor exposed tests cost too much time and are easily influenced by uncertain factors, the controlled accelerated aging tests are more preferred. Koike et al.[3)] conducted accelerated artificial weathering tests on rubber and plastic sheets to estimate the effects of heat and light. Lin[4)] made an attempt to study the surfaces of accelerated aged rubbers through scanning Auger microscopy. Besides, the ultraviolet stability of many kinds of rubbers was studied. Ginic-Markovic et al.[5)] investigated the weatherability of surface EPDM rubber compound by controlled UV irradiation. Singh and Chandra[6)] studied the photodegradation and stabilization of butyl rubbers. And Aslanyan et al.[7)] examined the effects of ultraviolet irradiation on chloroprene rubbers.

Nevertheless, most of the studies have only focused 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 the changes in mechanical properties. Four kinds of rubbers normally 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 last 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 mainly composed of the upper and bottom flange, inner plates, inner rubber layers, and surface rubber. Usually the thickness of the surface rubber is about 10mm. Since ultraviolet degradation mainly takes place from the surface, as the energy gets consumed and the intensity of the ultraviolet decreases on its passage though the rubber layer[5], in this study only the surface rubber of the bridge bearing is discussed. As for bridge rubber bearings, the existence of the cracks on 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 any 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 bearing. As for NR, three types with different shear modulus are applied. They are NR_G10, NR_G12 and NR_G5, arranged in the decreasing order of shear modulus. The suffix “G5” means the static shear modulus of this NR is 0.5MPa, “G10” stands for 1.0MPa, and “G12” is 1.2MPa. The differences in the components of these three types of NR lie in the amount of the carbon black. The more the carbon black, the higher the shear modulus is. For the business reason, the details of rubber compound formulations are kept confidential. In fact, NR_G5 is usually used in building rubber bearings and not affected by ultraviolet irradiation. For comparison, it is also tested together with the rubbers used in bridge bearings.

All the samples 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 2mm, and the middle part with a width of 5 mm and a length of 20 mm is applied to evaluate the deterioration characteristics.

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 the compressive 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%[8),9)]. And this result is proved by FEM simulation. Therefore, the rubber samples are stretched to 0%, 20% and 40% in order to study the ultraviolet stability of rubbers at tensile state. The No.3 dumbbell specimens are mounted on special rigs, as shown in Fig.4. In consideration of the scattering feature of rubber material, for each pre-strain state and each measuring time, 12 samples are prepared.

(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/m^2, 300～700nm) covering the main wavelength region of the sunlight ultraviolet reaching the earth. The cycle composed of 60 minutes of irradiation and 30 minutes of pure water spaying is adopted. The temperature and humidity inside the chamber can be controlled automatically. During the irradiation process, the black panel temperature (BPT) is controlled as 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

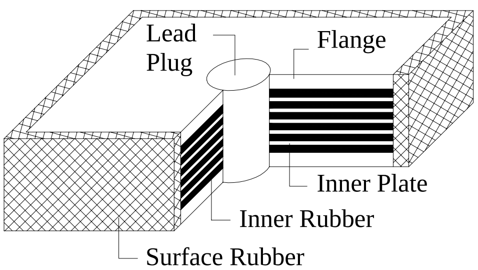


Fig.1 Bridge rubber bearing

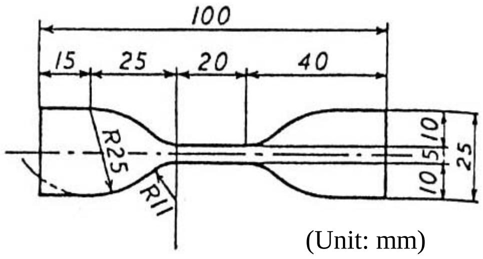


Fig.2 JIS No.3 dumbbell specimen

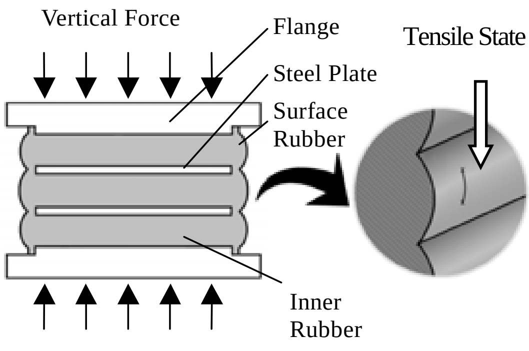


Fig.3 Strain on the bearing surface

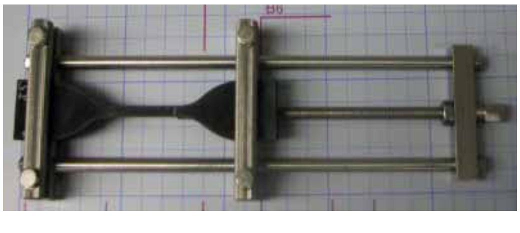


Fig.4 Pre-straining rig

Fig.5 Dew cycle sunshine weather meter

as 30±2℃, 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. And CR and NR_G5 are tested for 360 and 720 hours. They are withdrawn from the ultraviolet chamber at respective time interval. For the purpose of comparing different types of NR, NR_G10 and NR_G12 are only tested for 720 hours with the pre-strain controlled as 40%. The details are presented in Table 1.

Table 1 Test specimens and conditions

Material	Pre-Strain	Test Period (hours)
HDR	0%, 20%, 40%	0, 360, 720, 1440
EPDM		
CR		0, 360, 720
NR_G5		
NR_G10	40%	720
NR_G12		

(3) Methods for mechanical characterization

After the accelerated ultraviolet irradiation test, the mechanical properties are investigated through the uniaxial tensile experiment. The inspection method follows the quality inspection method specified by Japan Highway Public Corporation[8] (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 indexes. Every group is composed of 12 samples. 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

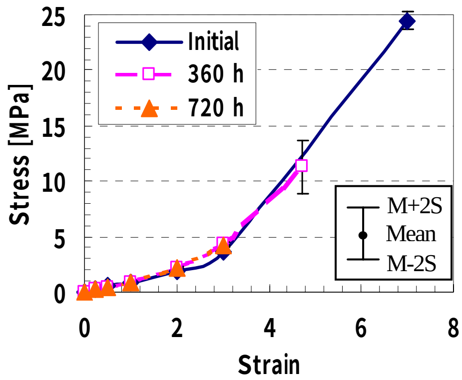
Generally, aging drops the performance of rubber, and causes rubber to become harder and more brittle. Fig.6 shows the changes in the stress-strain relationships of NR_G5, CR, EPDM and HDR with the pre-strain of 40%. From Fig.6(a), it is found that although the stiffness of NR_G5 almost does not affected by the ultraviolet irradiation, EB and TS decrease greatly. As for CR, EPDM and HDR, stiffness increases, while EB and TS drop down due to the ultraviolet irradiation. The deviation of the 12 specimens in each group is very 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 Fig.7(a), M100 of NR_G5 firstly increases a little, then decreases. There is only little variation of M100. However, after 720 hours, EB decreases by nearly 25% and TS by about 50%. 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 adds up by about 60%, and EB falls by about 25%. TS of CR almost does not change. 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 earliest stage. After 720 hours, the variations tend to concentrate. At 1440 hours, M100 of EPDM shows an increment of about 25% at the equilibrium state. And ultraviolet irradiation reduces EB and TS by about 20% and 25%. The increment of M100 of HDR approaches to 50% after 1440 hours, while the reduction of EB and TS approach to 35% and 20%, respectively.

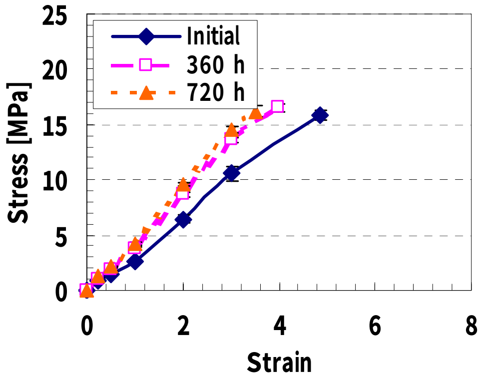
From a chemical point of view, ultraviolet irradiation shifts the balance between crosslinking and chain-scission reactions. Due to aging, usually the cross-link between chains will break up and the chains will re-entangle and form more new cross-links. So the motions of the chains become more impeded, which results in high hardness and low elongation. With the progress of the competition, the reaction speed slows down gradually until the saturation is present.

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

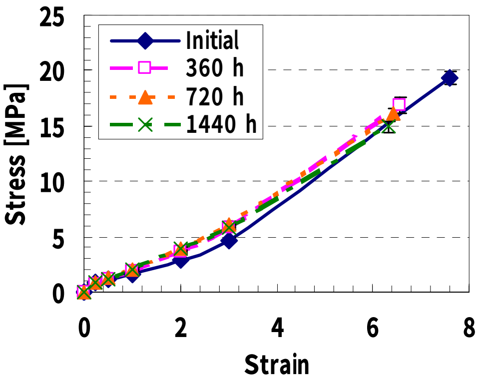
In the accelerated ultraviolet irradiation test, the rubber samples were stretched to 0%, 20% and 40% and kept throughout the test. The influences of the pre-strain are compared in Fig. 8, in which the normalized variations of the properties at 720 hours are illustrated. The existence of the pre-strain reduces the variation of the stiffness of NR_G5 and EPDM, as shown in Figs.8(a) and 8(c). And the pre-strain make both the EB and TS of NR_G5 decrease much more greatly. However, the influences on the EB and TS of EPDM are not clear.



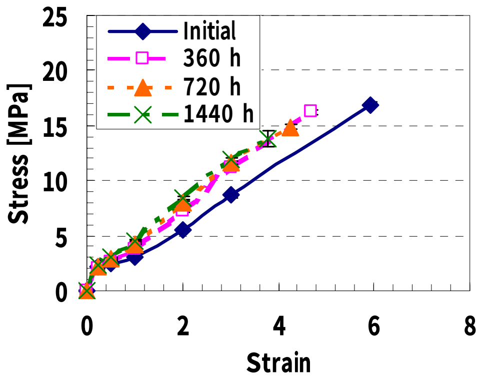
(a) NR_G5



(b) CR

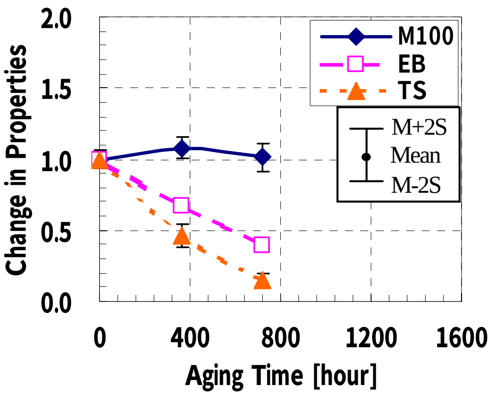


(c) EPDM

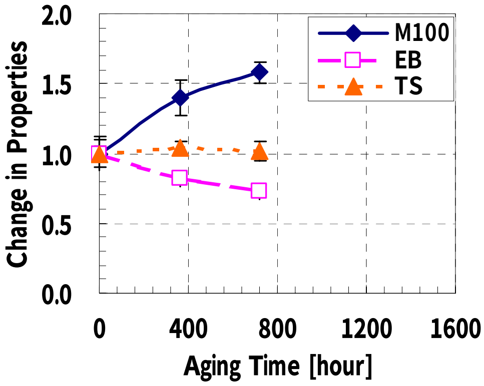


(d) HDR

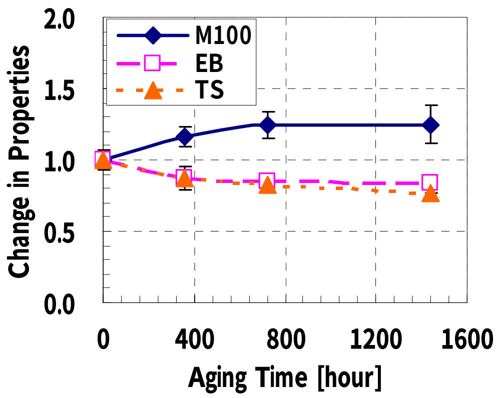
Fig.6 Effect of ultraviolet irradiation on rubber mechanical properties (pre-strain=40%)



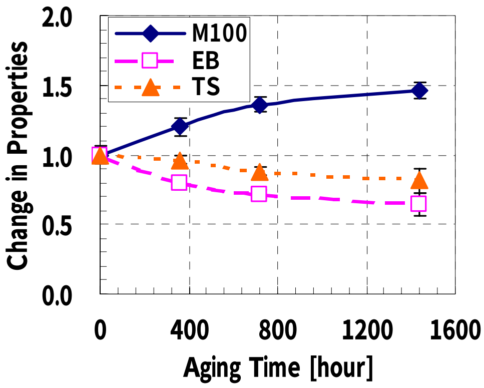
(a) NR_G5



(b) CR



(c) EPDM



(d) HDR

Fig.7 Time-dependency of rubbers subjected to ultraviolet irradiation (pre-strain=40%)

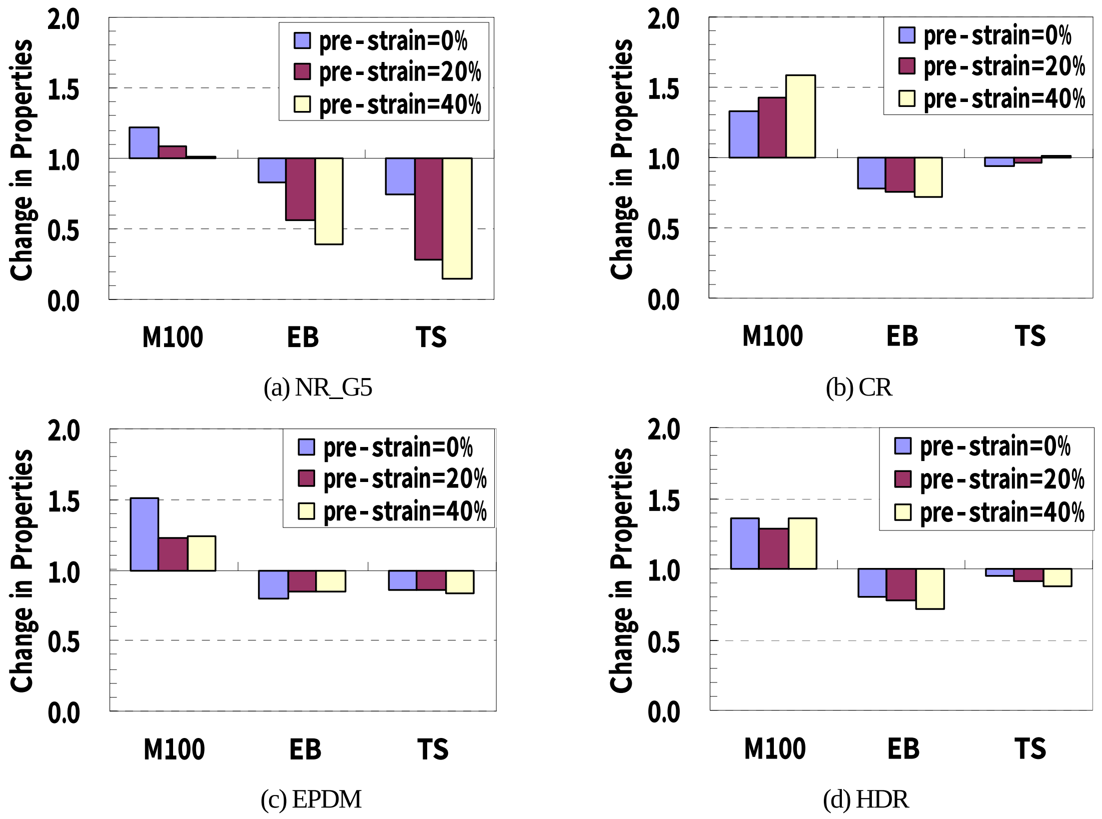


Fig.8 Influence of pre-strain on ultraviolet deterioration (720 hours)

Fig.8(b) indicates that the pre-strain increases the stiffness of CR substantially, and makes EB drop more. After the same aging period, CR will appear harder in the tensile state. TS increases with pre-strain, or in other words, due to the pre-strain, the effect of ultraviolet irradiation on TS is lessened. 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 according to the kind of the rubber material.

(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, we investigated NR_G5, NR_G10, and NR_G12. 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 were prepared, with 12 specimens in each group. One group is used for the tensile test in the initial state. The other group was stretched to 40% and accelerated aged for 720 hours. Before the tensile test, the appearance is firstly examined.

For example, the appearance of one sample in 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

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

No.	NR_G5	NR_G10	NR_G12
1	C-4	B-1	A-1
2	C-4	B-1	A-1
3	C-4	A-1	A-1
4	C-5	B-1	A-1
5	C-5	A-1	A-1
6	C-4	B-1	A-1
7	C-5	A-1	A-1
8	C-5	A-1	A-1
9	C-5	A-1	A-1
10	C-5	B-1	no crack
11	C-5	no crack	A-1
12	C-4	B-1	no crack

Number of crack
A: Few
B: Many
C: Innumerable

Length and depth of cracks
1: Invisible to naked eyes,
but visible by ×10 magnifier
2: Visible to naked eyes
3: Deep, length less than 1mm
4: Deep, length about 1～3mm
5: Longer than 3mm or nearly break

are not evident, almost cannot be observed 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 order of these three 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, 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, both EB and TS decrease. Especially 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 NR_G10 increases nearly 20% and NR_G12 grows by about 25%. However, the tendencies of EB and TS are not clear. The EB and TS of NR_G5 decrease by about 60% and 85%, respectively. NR_G10 decreases least, with a drop of EB and TS by 15% and 8%. EB of NR_G12 falls by about 20% and TS reduces by 10%.

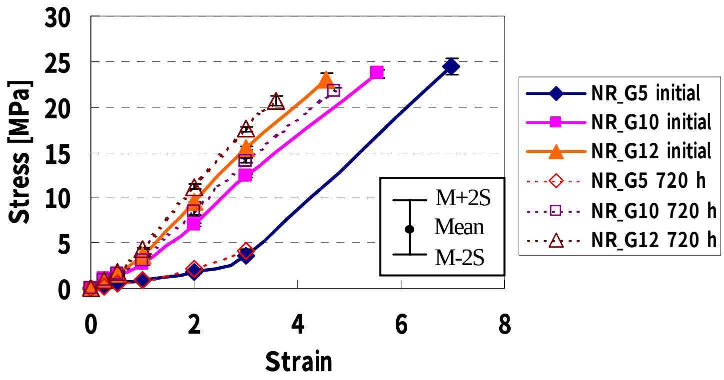
Generally speaking, less cracks appear on the surface of NR with more amount of carbon black. Usually ultraviolet irradiation results in an increment in the stiffness of rubber material. However, in NR_G5, it is thought that the existence of the cracks offsets the stiffness increment. Meanwhile, the cracks drop 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 mounted under basement. As for NR_G10 and NR_G12 used in bridge rubber bearings, the behavior is fairly good under ultraviolet irradiation.

(a) NR_G5 (b) NR_G10 (c) NR_G12

Fig.9 Appearance of NR samples in the initial state

(a) NR_G5 (b) NR_G10 (c) NR_G12

Fig.10 Appearance of NR samples after 720 hours' ultraviolet irradiation



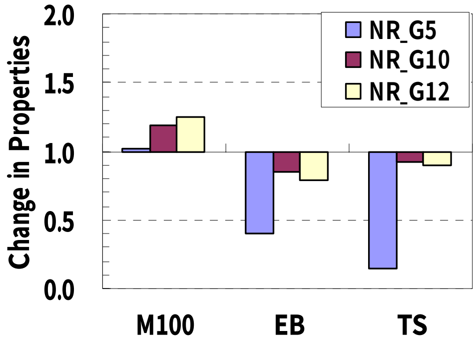


Fig.11 Aging characteristics of NR subjected ultraviole irradiation (pre-strain=40%)

Fig.12 Change in properties of NR (pre-strain=40%, 720 hours)

4. Performance Estimation of Surface Rubber

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:

$$\ln\frac{y_h}{y_0} = C(It)^a \tag{1}$$

where, y_h is the rubber material properties such as the elongation at the break point, the stiffness and so on. And y_0 indicates the original value of y_h, C, a are constants of rubber material, t is deterioration period, and I represents the ultraviolet intensity. In the light emitted by the carbon arc light[10)], the ultraviolet (300～400nm) intensity is 77.5W/m^2.

In the aging test of ultraviolet irradiation, the environment temperature is 50 ℃. With the influence of heat eliminated[11)], the relationship between ultraviolet intensity and the change in EB of CR is shown in Fig. 13.

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 ground level the received solar radiation is quite different because of the diffusion by atmosphere and the reflection by clouds and ground. On the earth, the global solar radiation is the sum of the direct, diffuse and reflect radiation. 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 a constant. All the time the earth is rotating, so that 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 solar radiation received by the surface rubber[12)].

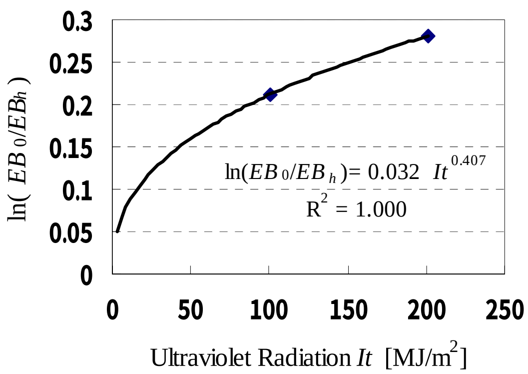
Using Fig. 14, the direct solar radiation flux H_i to a vertical surface can be expressed by the solar radiation to the normal surface H_n using the expression[13)]:

$$H_i = H_n \cos i \tag{2}$$

$$\cos i = \cos\alpha \cdot \cos\bar{Z} \tag{3}$$

where, α is the solar altitude, $\bar{Z} = Z - P$, where P is the azimuth of the plane, and Z is the sun's azimuth from the south. α and Z can be determined from the following equations.

$$\sin\alpha = \sin L \sin\delta + \cos L \cos\delta \cos h \tag{4}$$



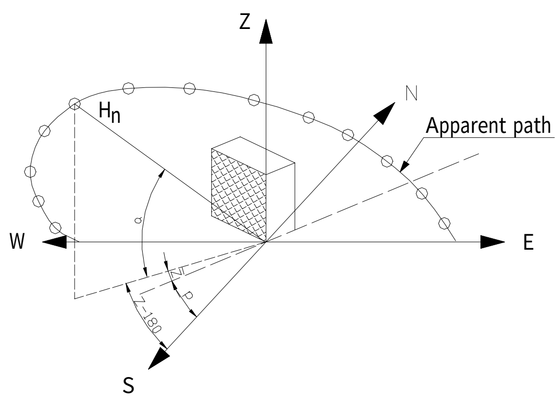


Fig.13 Relationship between EB change in CR and ultraviolet intensity

Fig.14 Angle diagram for finding solar radiation on vertical surfaces

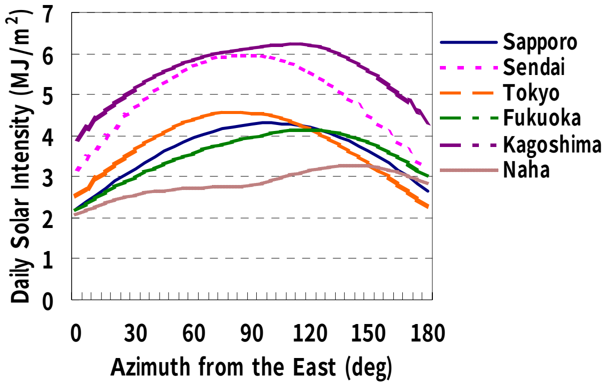


Fig.15 Average daily direct solar intensity of various oriented vertical planes

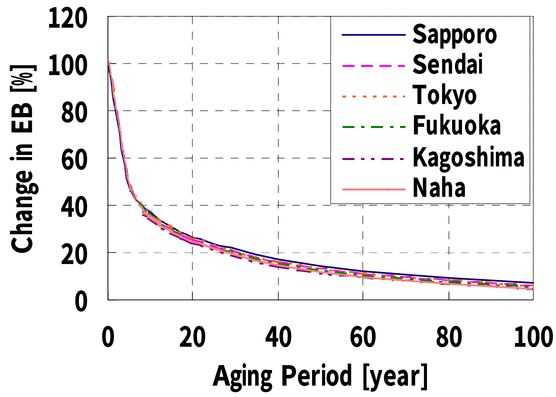


Fig.16 Long-term performance estimation of CR in the worst cases

Table 3 Maximum radiation and the corresponding azimuth

Location	Azimuth from the east (deg)	Maximum average daily radiation (MJ/m^2d)	Average daily diffuse radiation (MJ/m^2d)	Maximum daily global radiation (MJ/m^2d)
Sapporo	100	4.30	3.47	7.77
Sendai	85	5.95	2.04	7.99
Tokyo	80	4.57	2.64	7.21
Fukuoka	120	4.14	3.76	7.94
Kagoshima	110	6.23	2.15	8.38
Naha	145	3.27	4.42	7.78

$$\cos Z = (\sin L - \cos L \tan \delta)/\sinh \qquad (5)$$

$$\sin Z = (\cos \delta \sinh)/\cos \alpha \qquad (6)$$

where, L is the northern latitude of the place, δ 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 Observatory[14], are used and the direct solar radiation on various oriented vertical planes are accumulated, 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. Firstly, the worst case is considered. In other words, the vertical surface of the surface rubber is assumed to face the direction 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 of the visible sky hemisphere, and the diffuse radiation falling on an inclined plane can be calculated by the following equation.

$$D_i / D_0 = (1 + \cos b)/2 \qquad (7)$$

where, D_i and D_0 are the diffuse radiation on inclined and horizontal plane, respectively. For a vertical plane, b equals

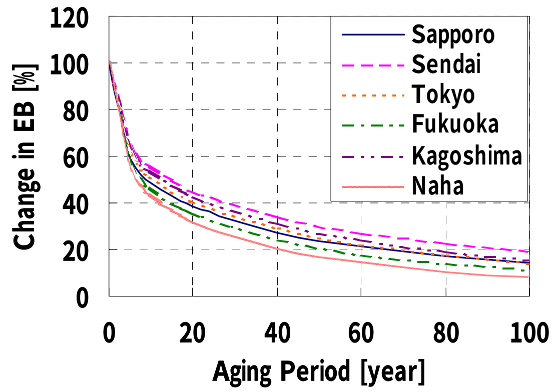


Fig.17 EB degradation of CR coating in the shadow

$\pi/2$ 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 also different. The ultraviolet irradiation accounts for 15.9% of the total solar energy[15].

Based on the above knowledge, it is possible to estimate the long-term performance of surface rubber in bridge bearing. 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 considered[11]. It is found that ultraviolet irradiation causes EB to drop greatly. 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 might initiate cracks in tensile state. The discrepancies of the decreasing speed among various locations are small because the global radiation is similar, as shown in Table 3.

Practically, since bridge bearings are installed between the pier and the superstructure, in most cases they are in the shadow of the deck. If 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.

5. Summary and Conclusions

Through accelerated ultraviolet irradiation test, the degradation behaviors of NR, CR, EPDM and HDR, which are used as the surface rubber in bridge bearings, are investigated. The influences of the pre-strain and the carbon black are also examined. Based on the test results, the long-term performance of CR is estimated considering the location and 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 harder and more brittle.
2. Pre-strain may accelerate or decelerate the ultraviolet irradiation, and its influences are different with the rubber.
3. As for NR, cracks are more easily appear on the rubber with less carbon black, which result in a remarkable drop of EB and TS. However, for rubbers used in bridge rubber bearings, cracks are not easily to appear.
4. Using the Arrhenius methodology, the change in EB of CR is predicted. When exposed to the sunlight directly, EB drops very fast and the discrepancies of the locations are very small. If in the shadow, EB also decreases by about 40% in 5 years.

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