Deterioration Assessment of Bridge Rubber Bearings

H. S Gu, Nagoya University, Japan
Y Itoh, Nagoya University, Japan
K Satoh, Nagoya University, Japan

Abstract

Natural rubber (NR) with lead plugs and high damping rubber (HDR) are often used for base-isolated rubber bearings. However, it is usually known that ageing causes rubber performance to drop. This research is to study the deterioration characteristics of these two kinds of bridge rubber bearings through accelerated thermal oxidation tests. The property variations inside the aged rubber blocks are investigated. For natural rubber bearing, the mechanical properties on the surface change the most greatly, but the interior is invariable. On the other hand, as for high damping rubber bearing, not only the surface but also the interior changes. The interior is found to be stable after a rapid change. The time-, temperature- and strain-dependencies of the mechanical properties are studied. Based on the test results, two proper assessment models are established to estimate the property profiles of aged rubber block. Combining with the Arrhenius methodology, the test conditions could be correlated with the real environment. Thus the deterioration of bridge rubber bearings under service conditions can be assessed.

Keywords: deterioration assessment, bridge bearing, natural rubber, high damping rubber

1. Introduction

Since the 1995 Hyogoken-Nanbu earthquake (Kobe earthquake), seismic isolation bridge rubber bearings have been widely adopted in Japan as an effective means to reduce the severe damage of steel and concrete piers due to earthquake. Natural rubber (NR) with lead plugs and high damping rubber (HDR) are often used in horizontal force distributing bearings and base-isolated rubber bearings. However, it is known that ageing causes rubber performance to drop, showing itself by stiffening of the rubber, causing for instance a decrease in tensile strength and elongation at break, and an increase of hardness. In order to evaluate the durability of bridge rubber bearing, it is necessary to develop an approach to the problem of deterioration assessment.

In the previous research, Itoh et al.1), 2) have performed a series of accelerated exposure tests to investigate the degradation effects of different environmental factors on NR and HDR materials. It is known that oxidation plays the most important role among all the degradation factors. In this research, through accelerated thermal oxidation tests on NR and HDR blocks, the deterioration characteristics of both the outer and the interior regions are revealed. Based on the test results, two deterioration assessment models were established to assess the deterioration of NR and HDR bridge bearings.

2. Accelerated thermal oxidation tests

2.1 Specimens and test methods

It is obvious that for thick rubber, the surface is more easily affected by degradation factors than the interior. In order to understand the variation of the material property inside the bridge rubber bearing, accelerated tests were performed on rubber blocks using the most significant factor – thermal oxidation.

Fifteen NR blocks and fifteen HDR blocks were used as test specimens, as shown in **Fig.1**. The dimension is 220×150×50mm (length×width×thickness). The specimens were accelerated aged in a Thermal Ageing Gear Oven. The test conditions are listed in **Table 1**. Three elevated temperatures, 60℃, 70℃, and 80℃ were applied in the oven. For the test under each temperature, the experiment duration were set as 5 stages, with the maximum lasting of 300 days **Fig.2** shows the accelerated thermal oxidation test flow. When the rubber block specimen was taken out from the oven, it was sliced into pieces with a thickness of 2mm. From each slice, four specimens with No.3 dumbbell shape were cut out3). And there are 3,000 specimens in total. Then through the tensile tests on these dumbbell specimens, the stress-strain curves can be obtained, which represent the rubber properties at the corresponding position.

In this research, strain energy was chosen for examination for the reason that it can exhibit the effect of thermal oxidation more remarkably than stresses at certain strains. In the following description, the strain energy corresponding to the strain of 100% is called U100, the strain energy up to the break is called UB, and the modulus of the stress corresponding to the strain of 100% is called M100. Similarly, the distribution of U100 inside rubber blocks is called U100 profile, and the distribution of mechanical properties like modulus, elongation at break (EB) and tensile strength (TS) is called property profile.

2.2 Test results and examinations

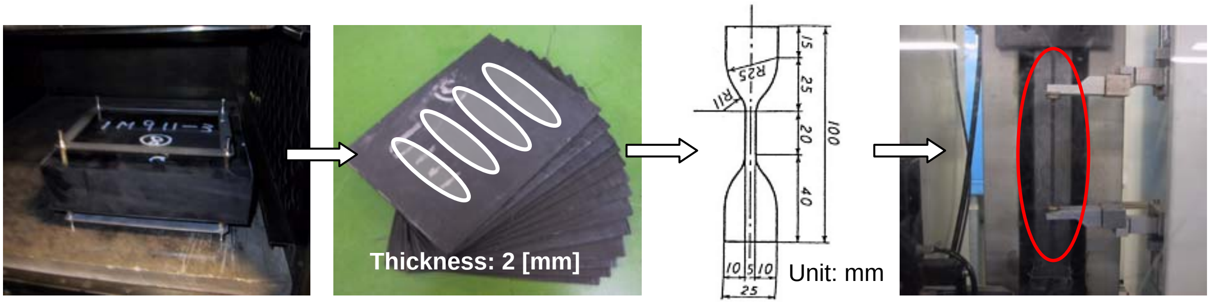
Fig.3 shows the variations of U100 and EB profiles of NR blocks under 60℃. The horizontal axis is the relative position with regard to the thickness of the rubber block. The values 0 and 1 mean the surface of the block. The vertical axis is the normalized change of U100 with the original value equaling one. Every point in the figures is the average value of four specimens with No.3 dumbbell shape. From **Fig.3(a)** and **Fig.3(b**), it can be seen the surface of NR block deteriorates most severely. From the surface to the interior, the property changes become less and less, until to a certain depth, the interior does not deteriorate at all. This depth is called the critical depth d^*, which is found to be the function of temperature. It is about 12.5mm under 60℃, 10mm under 70℃, and 7.5mm under 80℃.

Similar to **Fig.3**, **Fig.4** shows the U100 and EB profiles of HDR blocks at different deterioration time. As to HDR, the changes of U100 and EB are like NR. The change of the outer region is the greatest. However, different from NR, the interior of HDR block also changes. From **Fig. 4(a**), it is discovered that U100 of the interior increases about 15% in 31 days, and almost does not increase any more during the following ageing time. In **Fig.4(b)**, EB of the interior decreases by about 20% soon after the beginning of the thermal oxidation test and keeps stable thereafter. Moreover, compared with NR, the change on the HDR block surface is less. In other words, NR is more vulnerable to oxidation than HDR.

Fig.1 Rubber block specimen

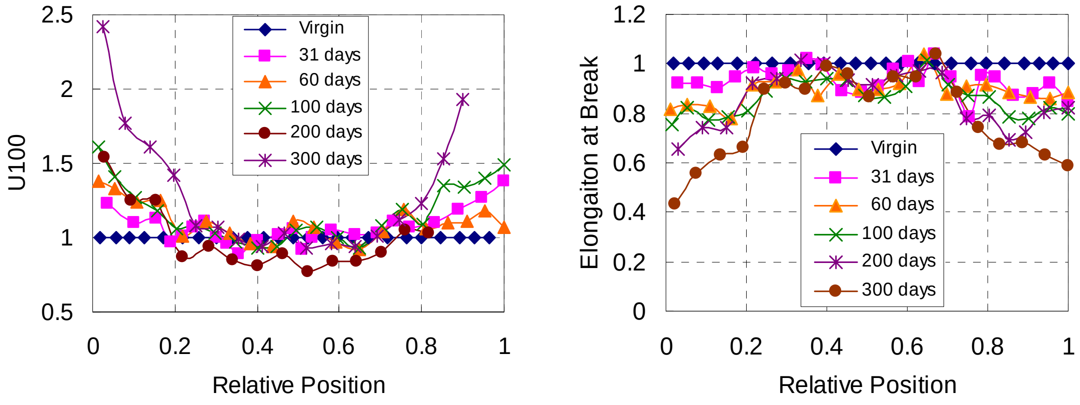
Table 1 Accelerated thermal oxidation test condition

Material	Temperature [℃]	Test Duration [days]
NR, HDR	60	31 , 60 , 100 , 200 , 300
	70	12 , 22 , 38 , 75 , 113
	80	4 , 8 , 14 , 28 , 42



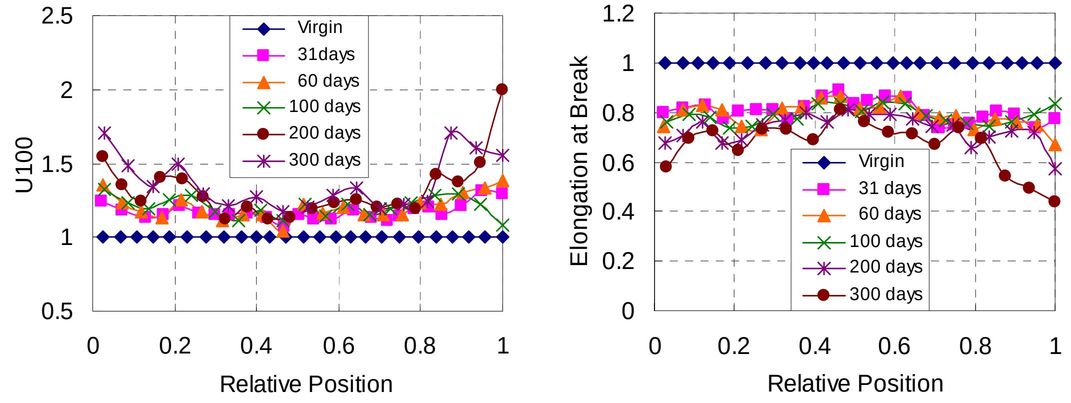
(a) Accelerated test (b) Rubber slices (c) No.3 dumbbell specimen (d) Tensile test

Fig.2 Accelerated thermal oxidation test flow



(a) U100 profile (b) EB Profile

Fig.3 Test results of NR (60℃)



(a) U100 profile (b) EB Profile

Fig.4 Test results of HDR (60℃)

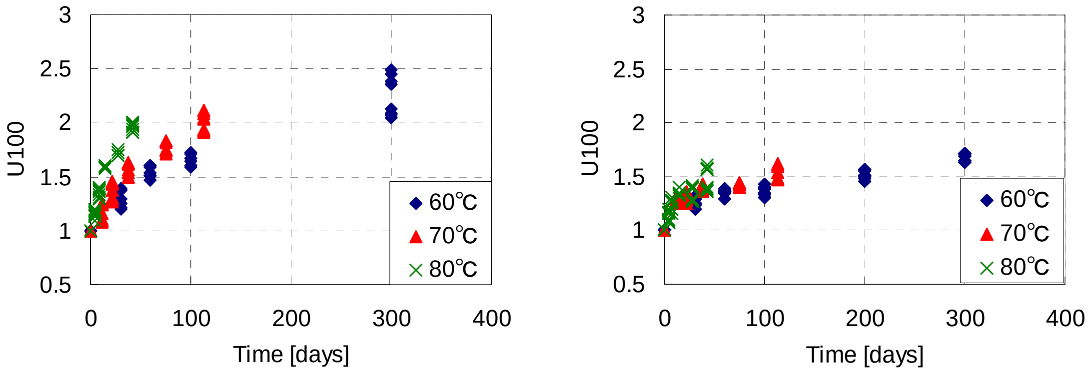
Fig.5～Fig.8 show the time-dependency of U100 and EB on the surface and in the interior of NR and HDR blocks. The horizontal axis is the deterioration time, and the vertical axis is the normalized value of the material property variations. From **Fig.5** it is found that U100 on both the NR and the HDR block surfaces changes nonlinearly over the time. The property change speed under higher temperature is faster than under lower temperature. With the passage of time, the property change speed decreases gradually. Comparing **Figs.5(a)** and **5(b)** it is clear after the same time the surface of NR changes faster than HDR. In **Fig.6(a),** U100 in the interior region of NR block does not change at all. However, in **Fig.6(b)**, U100 of HDR increases in very short time, then keep invariable after U100 increases by about 20～40%. Under higher temperature, the increase of U100 is larger. The variations of EB on the block surfaces are shown in **Fig.7**. EB of both NR and HDR decreases about 50% by the end of the accelerated thermal oxidation tests, and decreases faster under higher temperature. As to the interior region, in **Fig.8(a)**, EB of NR almost does not change much. On the other hand, EB of HDR experiences a sudden decrease by about 20% and then keeps the equilibrium state, as shown in **Fig.8(b)**. There's no clear relation between the change of EB and temperatures.

It is known due to the diffusion-limit oxidation effect4), it becomes more difficult for oxygen to propagate into the block, so that the ageing of the interior region may not be caused by oxidation. It is assumed that there are two factors causing the HDR material to deteriorate. One is temperature, which might cause the polymer structure to change and this reaction completes in relatively short time; the other is oxidation, which only deteriorates the outer region of HDR blocks combining with temperature.

3. Deterioration assessment model for bridge rubber bearings

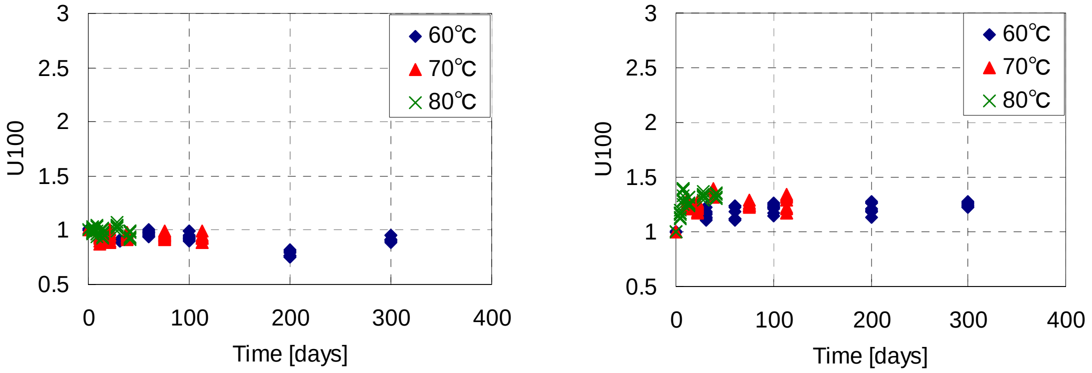
3.1 Deterioration pattern

To predict the long-term deterioration of bridge rubber bearing, it is needed to quantify the deterioration characteristics. From the accelerated thermal oxidation test results, the deterioration pattern of the NR and HDR blocks can be schematically expressed by **Fig.9**. The vertical axis U/U_0 means the relative property change, which is the current material property U comparing with the original



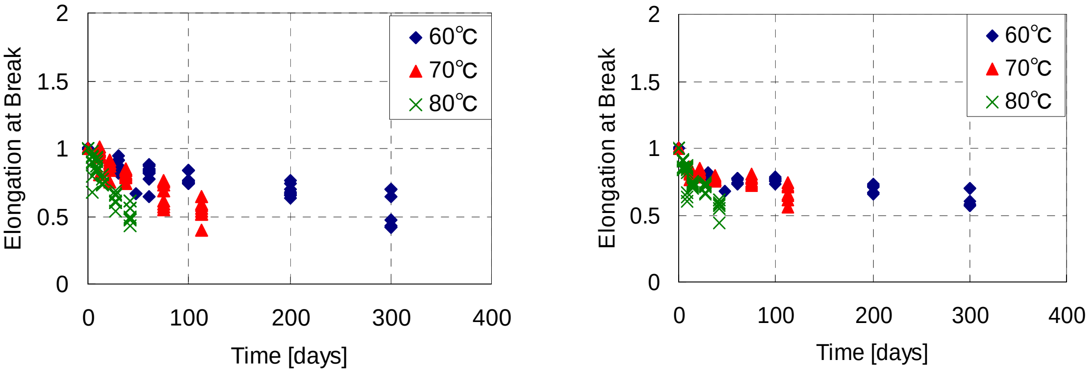
(a) NR (b) HDR

Fig.5 U100 variation on block surface



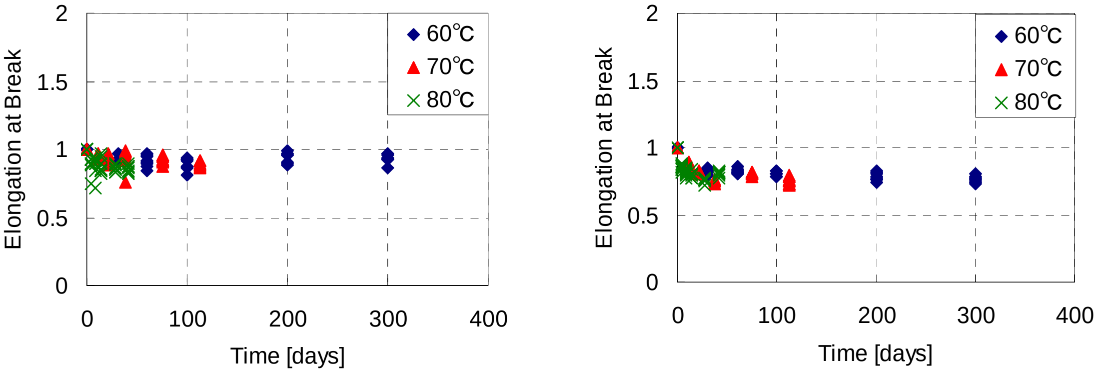
(a) NR (b) HDR

Fig.6 U100 variation in the interior



(a) NR (b) HDR

Fig.7 EB variation on block surface



(a) NR (b) HDR

Fig.8 EB variation in the interior

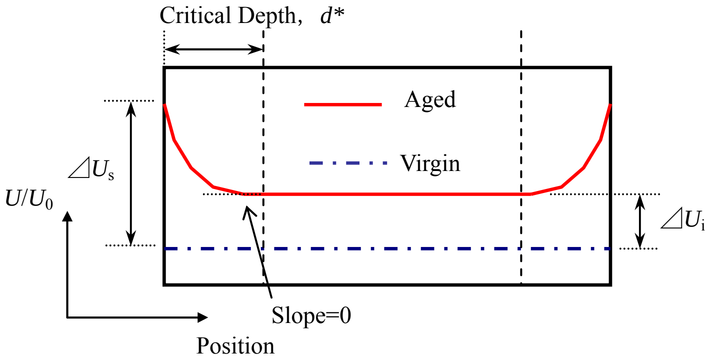


Fig.9 Property profile pattern

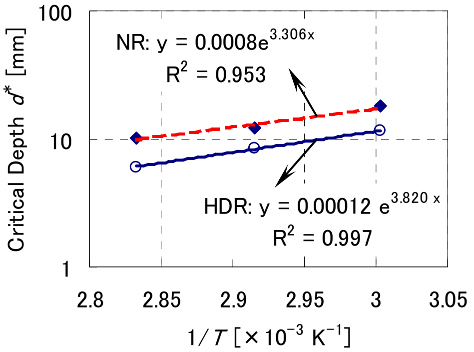


Fig.10 Critical depth

value U_0. And the horizontal axis is the relative position inside the rubber block. As to HDR, the interior region beyond the critical depth d^* is only affected by temperature, and the relative property change is ΔU_i. For NR the interior does not deteriorate and ΔU_i is zero. The outer region from surface to the critical depth d^* is influenced by both temperature and oxidation, and the property on the block surface changes the most greatly. The relative property change on the block surface is represented by the symbol of ΔU_s. When proceeding into the block, because of the decrease of the amount of oxygen, the oxidation effect becomes weaker and weaker, so that the property change declines. While exceeding the critical depth, the slope of the property profile becomes zero.

3.2 Critical depth

Muramatsu et al.[5)] has discovered that the critical depth is the exponential function of the reciprocal of the absolute temperature. And the following formula was proposed to express the relationship between the critical depth and the temperature.

$$d^* = \alpha \exp\left(\frac{\beta}{T}\right) \tag{1}$$

where, d^* is the critical depth, T is the absolute temperature, and the symbols α and β are coefficients determined by the ageing test.

The exponential relationship between the critical depth and the temperature is verified in **Fig.10**.

3.3 Property variation in the interior region

For NR, the properties of the interior region are invariable, so that ΔU_i is zero. However, for HDR, the test results show that the interior region changes in relatively very short time, and then keeps stable. It changes so rapidly that the time-dependency may be neglected. EB decreases about 20% no matter under what temperature. However, the equilibrium state of strain energy is correlated with temperature, as shown in **Fig.11**. The relationship between the temperature and the strain energy variation in the interior region may be expressed by an exponential function as follows:

$$\Delta U_i = A \exp\left(\frac{B}{T}\right) \tag{2}$$

where, ΔU_i is the relative strain energy variation of the interior region, T is the absolute temperature, and the symbols A and B are coefficients.

The symbols A and B in Eq.(2) are found to be related to the nominal strain. The strain-dependency is observed in **Fig.12**, in which the coefficients A and B versus the strain from 25% to 500% are drawn. So they can be calculated approximately using the following equations.

$$\ln A = b_1 \ln \varepsilon + b_2 \tag{3a}$$

$$B = c_1 \ln \varepsilon + c_2 \tag{3b}$$

where, ε is the nominal strain, the symbols b_1, b_2, c_1, and c_2 are factors determined by the tests.

3.4 Property variation on block surface

The rubber block surface is the most greatly affected by deterioration. The normalized variations of strain energy U_s and EB on the surface of NR block are shown in **Fig.13**. Although the properties change nonlinearly over the time, the property variations of NR are discovered to be linear to the square root of time. And the slopes of the regression lines of different strain energy are also different,

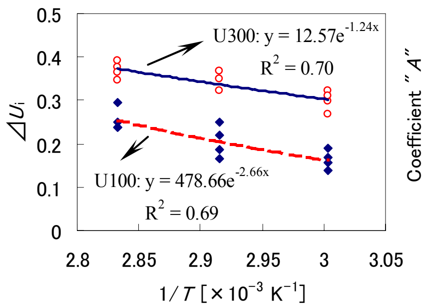
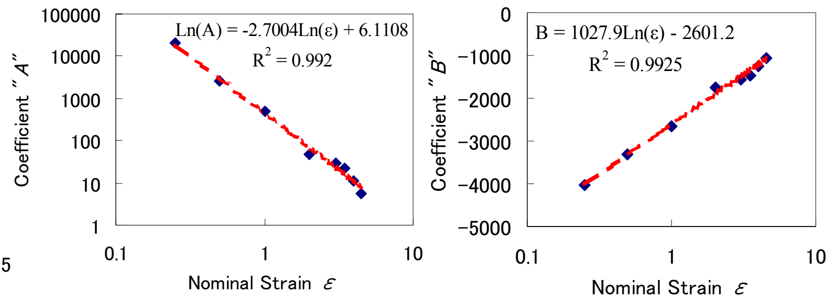


Fig.11 Relations between inner Strain energy change and temperature (60℃)



(a) Coefficient "*A*" **(b)** Coefficient "*B*"

Fig.12 Relations between coefficient "*A*", "*B*" and nominal strain ε

which means the variation of strain energy is not only time-dependent, but also strain-dependent. The relationship between the slopes of the regression lines and the nominal strains are depicted in **Fig.14**. The time-dependency and strain-dependency can be expressed by the following equations:

$$\Delta U_s = U_s - 1 = k_s\sqrt{t} \tag{4a}$$

$$k_s = a_1\varepsilon^3 + a_2\varepsilon^2 + a_3\varepsilon + a_4 \tag{4b}$$

where, ΔU_s is the relative strain energy variation on the NR bearing surface, t is the ageing time and k_s is the function of nominal strain ε. Factors $a_1 \sim a_4$ are determined by the tests.

As for HDR, the property variations on block surface can be deemed as the combined effect of temperature and oxidation. Temperature not only causes HDR properties to change, but also accelerates the oxidation reaction. The property variation due to the temperature is reflected by ΔU_i. **Figs.15(a)** and **15(b)** show the relative change of strain energy and EB on the HDR block surface with the property variations due to the temperature eliminated. The property variation of HDR contacting with the air is found to be time-dependent and the increase of strain energy and the decrease of EB are linear with the ageing time, as expressed by the following equation:

$$U'_s = k_s \cdot t + 1 \tag{5a}$$

where, U'_s is the relative strain energy on the HDR bearing surface only due to the oxidation, t is the deterioration time and k_s is coefficient related to the nominal strain, which can be obtained through Eq.(4b).

The strain energy variation on the bearing surface is strain-dependent too, as shown in **Fig.16.** Since the relative property variation on HDR bearing surface ΔU_s is the combination of the deterioration effects due to temperature and oxidation, the following equation is achieved.

$$\Delta U_s = U'_s \cdot (1 + \Delta U_i) - 1 \tag{5b}$$

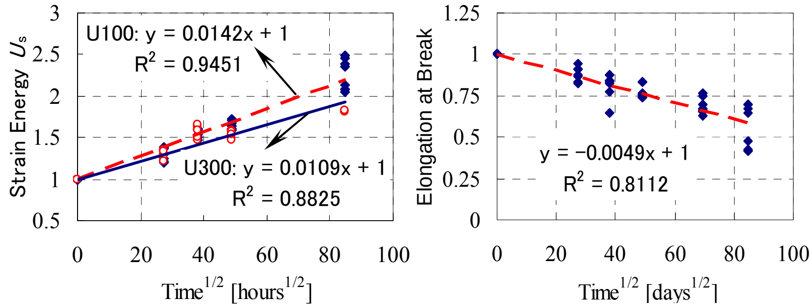
3.5 Shape model of property profile

From rubber bearing surface to the critical depth, the property variation decreases gradually and is nonlinear to the relative depth. It is assumed the relative strain energy variation is a square relation to the relative position from the surface to the critical depth, and can be expressed as follows:

$$\frac{U(t)}{U_0} = 1 + \left[w\Delta U_s + (1-w)\Delta U_i\right] \tag{6}$$

where, U(t) and U_0 are strain energy at time t and the initial state, respectively. w is the coefficient correlated with the position x, the critical depth d^* and the thickness l of the HDR bridge bearing, which can be calculated by Eq.(7).

$$w = \begin{cases} \left(\dfrac{x-d^*}{d^*}\right)^2 & \left(0 \le x \le d^*\right) \\ 0 & \left(d^* \le x \le l-d^*\right) \\ \left(\dfrac{x-\left(l-d^*\right)}{d^*}\right)^2 & \left(l-d^* \le x \le l\right) \end{cases} \tag{7}$$



(a) Strain energy (b) Elongation at break

Fig.13 Time dependency of NR block surface (60℃)

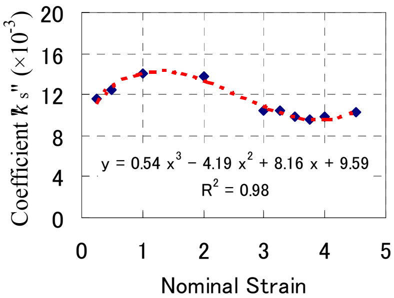
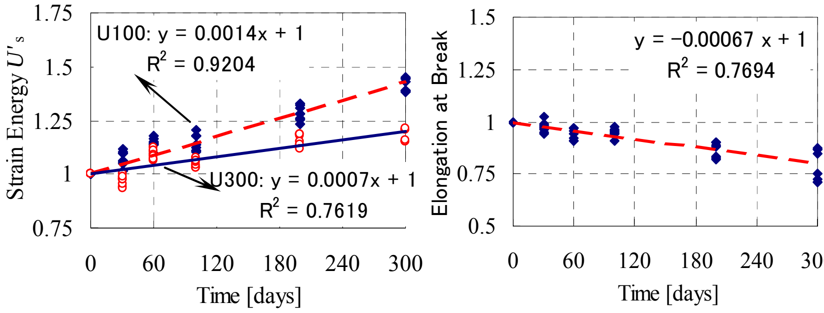


Fig.14 Relations between strain and coefficient "k_s" (NR, 60℃)



(a) Strain energy (b) Elongation at break

Fig.15 Time dependency of HDR block surface (60℃)

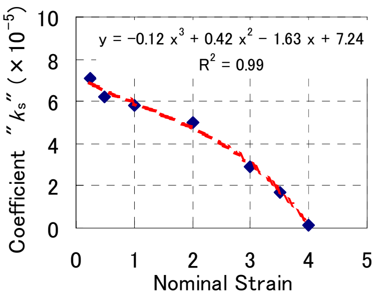


Fig.16 Relations between strain and coefficient "k_s" (HDR, 60℃)

3.6 Verification of the deterioration assessment model

Based on the test results, the coefficients in the equations mentioned above are deduced and presented in **Table 2**. Through the comparisons shown in **Fig.17**, it is found that the simulations of the critical depth, the property variation on the block surface and in the interior agree well with the test results. Thus the feasibility of the deterioration assessment method is verified.

In the thermal oxidation test the temperature is much higher than the temperature in the real environment because high temperature can accelerate the deterioration. Using the Arrhenius methodology, the accelerated ageing results could be correlated with ageing under service conditions6). The deterioration time in the accelerated exposure tests can be converted into the service conditions through Eq.(8), then the deterioration of bridge rubber bearing under service conditions can be assessed based on the accelerated thermal oxidation tests.

$$\ln(\frac{t_r}{t})=\frac{E_a}{R}(\frac{1}{T_r}-\frac{1}{T}) \tag{8}$$

where, E_a is the activation energy of rubber (NR: 9.94×10^4J/mol; HDR: 9.04×10^4J/mol), R is the gaseous constant (=8.314[J/mol· K]), T_r indicates the absolute temperature in the service condition, and T is the absolute temperature in the thermal oxidation test. The symbols t_r and t are the actual time and test time, respectively.

4. Summary and conclusions

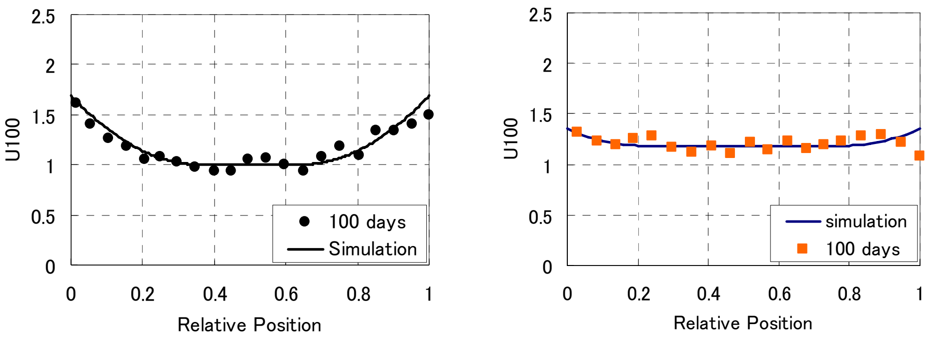
In this research, accelerated thermal oxidation tests were performed on natural rubber (NR) and high damping rubber (HDR) blocks. The deterioration characteristics inside the blocks are investigated. Based on the test results, two deterioration assessment models are proposed for NR and HDR bearings. The major findings and conclusions are summarized as follows:

1) The material properties of both NR and HDR blocks display the features of a diffusion-limited oxidation: initially the profiles are relatively homogeneous, but strong heterogeneity develops with ageing. The outer region changes more than the interior region.
2) From the block surface to the interior, the property variations decrease gradually until to the critical depth. For NR, the interior region does not deteriorate. For HDR, the interior becomes invariable after a sudden change. On the block surface, NR deteriorates faster than HDR.
3) Based on the test results, the relationships among property change, temperature, position, and strain are quantatified. A deterioration assessment model is proposed, which can estimate the property profiles of aged bridge rubber bearings. Combined with the Arrhenius methodology, the deterioration characteristics under service conditions may be predicted.

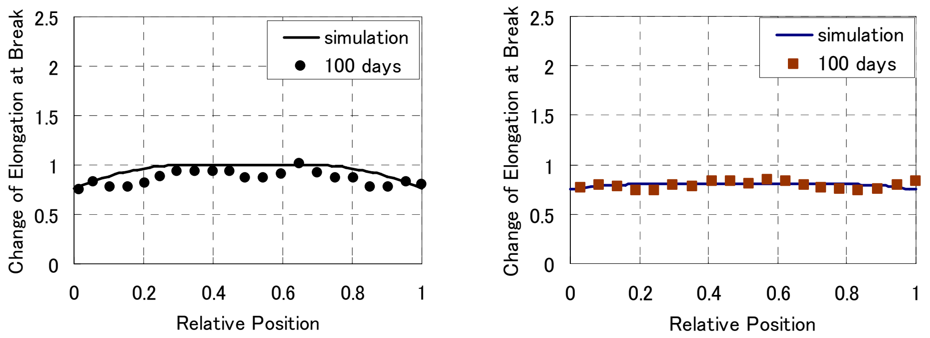
Table 2 Parameters of deterioration prediction model (60℃)

	α [10^{-4}mm]	β [10^{3}K^{-1}]	a_1 [10^{-5}]	a_2 [10^{-5}]	a_3 [10^{-5}]	a_4 [10^{-5}]	b_1	b_2	c_1 [10^{3}]	c_2 [10^{3}]	k_{bs} [10^{-3}]	$\varDelta E_{bi}$
NR	8.0	3.31	54	419	816	959	—	—	—	—	-4.9	—
HDR	1.21	3.82	-0.12	0.42	-1.63	7.24	-2.70	6.11	1.03	-2.60	-0.67	-0.20

*k_{bs}: Change rate of EB on block surface **$\varDelta E_{bi}$: Change of EB in the interior



(a) NR· U100 (b) HDR· U100



(c) NR· EB (d) HDR· EB

Fig.17 Comparison between test results and simulation (60℃)

References:

[1] Itoh Y., Yazawa A., Satoh K., Gu H. S., Kutsuna Y., and Yamamoto Y.: Study on environmental deterioration of rubber material for bridge bearings, *Journal of Structure Mechanics and Earthquake Engineering*, JSCE, No.794/I-72, pp.253-266, 2005 (in Japanese).

[2] Itoh Y., Gu H. S., Satoh K., and Kutsuna Y.: Experimental investigation on ageing behaviors of rubbers used for bridge bearings, *Journal of Structure Mechanics and Earthquake Engineering*, JSCE (tentatively accepted).

[3] Japanese Standards Association: *JIS handbook - rubber*, Japanese Standards Association, pp.284-287, 1999 (in Japanese).

[4] Celia M., Wise J., Ottesen D. K., Gillen K. T. and Clough R. L.: Correlation of chemical and mechanical property changes during oxidative degradation of neoprene, *Polymer Degradation and Stability*, Vol. 68, pp.171-184, 2000.

[5] Muramatsu Y. and Nishikawa I.: A study for the prediction of the long-term durability of seismic isolators, *Showa electric wire review*, Vol. 45, No.1, pp. 44-49, 1995 (in Japanese).

[6] Wise J., Gillen K. T., and Clough R. L.: An ultrasensitive technique for testing Arrhenius extrapolation assumption for thermally aged elastomers, *Polymer Degradation and Stability*, Vol. 49, Issue. 3, pp.403-418, 1995.