Investigation for crack on base-isolated rubber bearing subjected to environmental degradation factors and external loads

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Summary

For investigating the effect of environmental degradation factors and external loads on the crack occurrence on the surface of rubber bearing and to develop a countermeasure, a series of accelerated exposure experiments was carried out. The accelerated exposure experiment was performed on large size rubber bearing specimens under the condition that the temperature was 40 degrees Celsius and the ozone density was 100 pphm. The crack was observed on the surface of rubber bearing by 384 hours, especially in the large tensile strain region. The crack simulated the actual one observed in the real base-isolated rubber bearing. After the experiments, the load carrying capacity and the stiffness of damaged rubber bearing were examined. However, the performance of damaged rubber bearing was not deteriorated compared with those of virgin state.

Keywords: Base-isolated natural rubber bearing; crack; ozone; temperature; strain.

1. Introduction

Natural rubber is widely used as a material for base-isolated bearings for bridges. The durability of base-isolated bearing is important for the long term performance of bridges. However, the mechanical properties of natural rubber are changed due to several factors such as temperature, solar radiation, and ozone. It is known that the stiffness of natural rubber bearing for bridges increases with the elapsed time [1].

On the other hand, a lot of cracks by ozone attack are actually observed on the surface of base-isolated natural rubber bearings for bridges being used only in a few years. These cracks were observed in the natural rubber bearings used for bridges in cold region in Japan around 2001. The main cause of crack occurrence was estimated as the lack of anti-aging agent like as wax contained in the natural rubber under the low temperature conditions. Therefore, the anti-aging agent with the improved performance under the low temperature conditions was developed and its availability was confirmed [2]. These improved anti-aging agent are generally used for the present natural rubber bearings for bridges.

However, the cracks are still observed in the natural rubber bearings for bridges not only in cold region but also normal temperature region. The feature of these cracks is the linear shape with horizontal direction and the occurrence in the tensile strain region on the surface of rubber bearing by the shear deformation. The load carrying capacity of natural rubber bearing is not decreased even though the cracks occur on the surface of rubber bearing. However, there is a possibility that the load carrying capacity of natural rubber bearing is decreased when the surface cracks reach the rubber layers inside the bearing. Furthermore, the serious damage is anticipated when the large load and uplift force by earthquake are applied on the natural rubber bearing with cracks [3].

It is important that the crack initiation and propagation behaviour is investigated for evaluating the performance of natural rubber bearing. However, the existing evaluation conditions for ozone crack of natural rubber bearing by JIS (temperature from -30 to 40 degrees Celsius, ozone density of 50 pphm and elongation of 20%) [4] are not enough for simulating the actually generated cracks. It is unknown how the crack is initiated and propagated on the surface of natural rubber bearings.

To solve this problem, the large size accelerated exposure experimental system was newly developed for applying the environmental degradation factors (temperature and ozone) and strain on the natural rubber bearing specimens. By using this experimental system, effects of environmental degradation factors and strain on the occurrence of cracks on the surface of natural rubber bearings are investigated.

2. Test specimens

2.1 Dumbbell specimen

In order to identify the experimental conditions for generating cracks of natural rubber used for bridges, dumbbell specimens shown in *Fig. 1* are used [5]. The elongation is applied on the dumbbell specimens by using the metal rig shown in *Fig. 2*. The lengthened dumbbell specimens by the rigs are set in the chamber of accelerated exposure experimental system.

Table 1 shows the compositions of natural rubber materials used in this study. The natural rubber materials are provided by Kawakin Core Tech. Two kinds of natural rubbers with and without the anti-aging agent are used.

Table 1: Components of rubber material (weight ratio)

	With ant-aging agent	Without ant-aging agent
Natural rubber	100.0	100.0
N330 Carbon	40.0	40.0
Naphthenic oil	10.0	10.0
Anti-aging agent (TMDQ)	1.5	-
Anti-aging agent (IPPD)	1.5	-
Wax	1.5	-
Oxide zinc	5.0	5.0
Stearic acid	1.0	-
Accelerator (CBS)	1.5	1.5
Accelerator (TMTD)	1.0	1.0
Sulphur	0.5	0.5
Total	163.5	158.0

2.2 Bearing specimen

Fig. 3 shows the shapes and dimensions of natural rubber bearing specimen used in this study. The length and width of the bearing specimen is 220 mm. The height of the bearing specimen is 108 mm. 6 sheets of the natural rubbers with 8 mm thick and 5 sheets of steel plates (SS400) with 3.2 mm thick are layered alternatively. The steel plates (SM490A) with 22 mm thick are set on the top and bottom of the bearing. The surface of bearing is covered by the natural rubber with 10 mm thick. Two bearing specimens are made by the natural rubbers with and without the anti-aging agent.

The bearing specimens with shear deformation are set in the chamber of accelerated exposure experimental system. For applying and locking the shear deformation on the bearing specimen, the steel frame shown in *Fig. 4* is used. The

Thickness: 2 mm

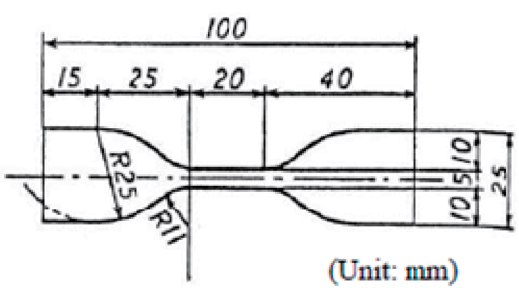


Fig. 1: Dumbbell specimen

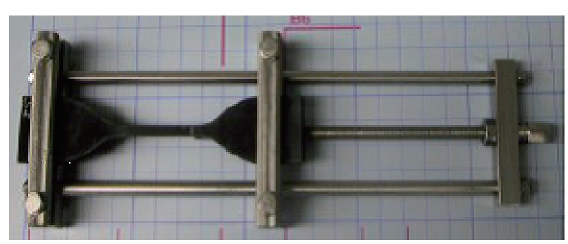


Fig. 2: Dumbbell specimen with pre-strain

bearing specimen is set in the steel frame with bolt holes. The specified horizontal deformation is applied on the top of the steel frame. And then, the vertical pressure is applied and the bolts are fixed for locking the horizontal deformation. The horizontal deformation applied is 72 mm. That corresponds to 150 % of the total thickness of rubber layers (8 mm x 6 sheets). The vertical pressure is 6 MPa.

3. Accelerated exposure experiment under the low temperature conditions

3.1 Experimental system

Fig. 5 shows the developed accelerated exposure experimental system. The dimension of the inside of chamber is 1500 mm wide, 1000

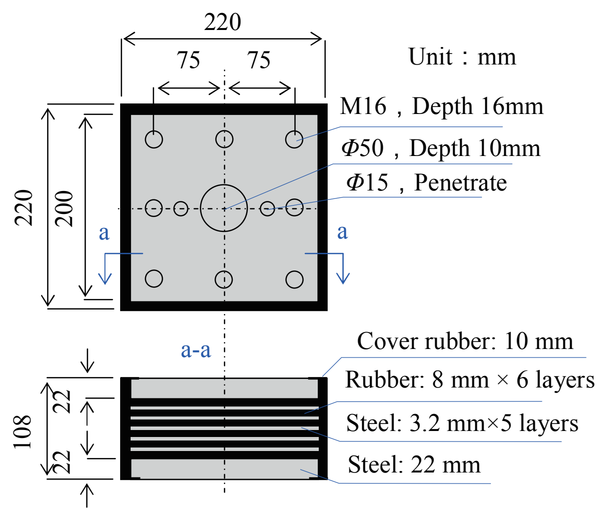
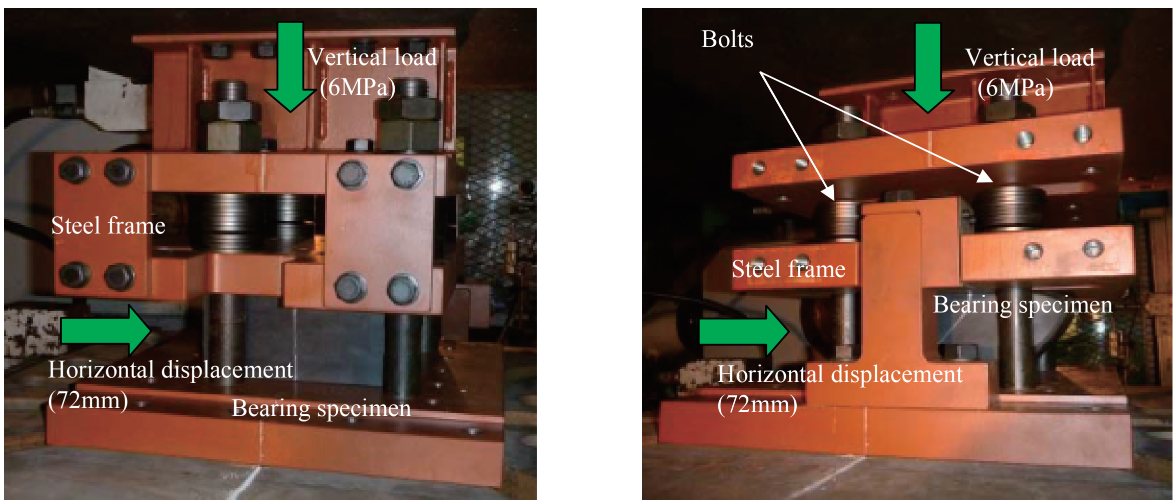
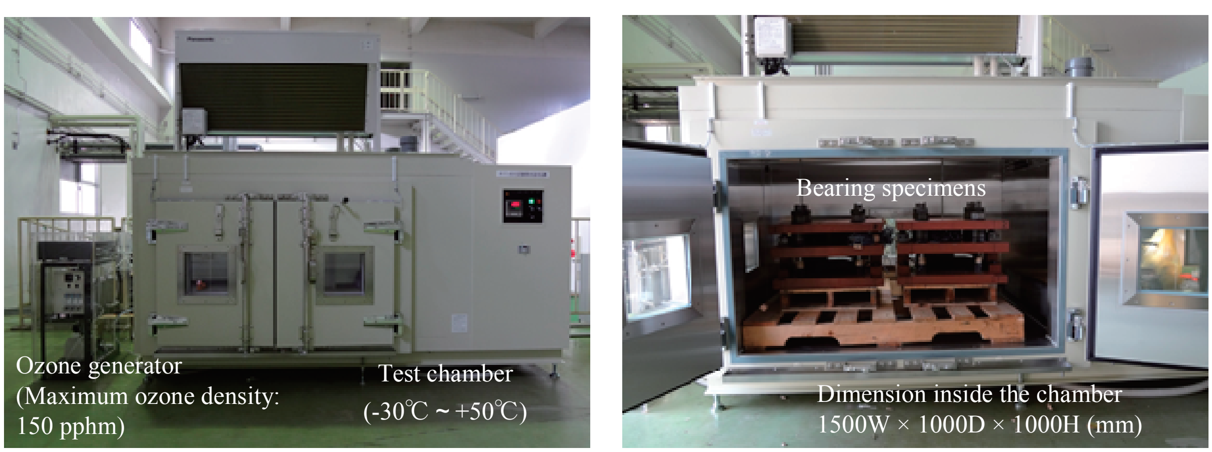


Fig. 3: Bearing specimen



(a) Initial state (b) After deformation

Fig. 4: Deformation of bearing specimen by steel frame



(a) Closed (b) Open

Fig. 5: Accelerated exposure experimental system

mm long and 1000 mm high. Two of the bearing specimens applied shear deformation by the steel frames can be set in the chamber. The number of the dumbbell specimens set in the chamber is 150. The temperature range of this experimental system is from -30 to 50 degrees Celsius. The maximum ozone density of this experimental system is 150 pphm.

3.2 Experimental condition

It was estimated by the previous study that the main cause of crack occurrence was the lack of anti-aging agent contained in the natural rubber under the low temperature condition [2]. Therefore, the lowest temperature (-30 degrees Celsius) and the highest ozone density condition is examined for investigating whether the cracks occur on the surface of natural rubber bearing specimens.
75 dumbbell specimens with and without anti-aging agent are used respectively. Different pre-strains are applied on 3 groups of the dumbbell specimens. The number of specimens in one group is 25. The applied pre-strains are 0 %, 40 % and 75 %. The experimental period per one cycle is 96 hours. 5 cycles of the experiments are carried out (480 hours). The crack occurrence of the dumbbell specimens and the bearing specimens is observed when the every cycle of experiment is finished.

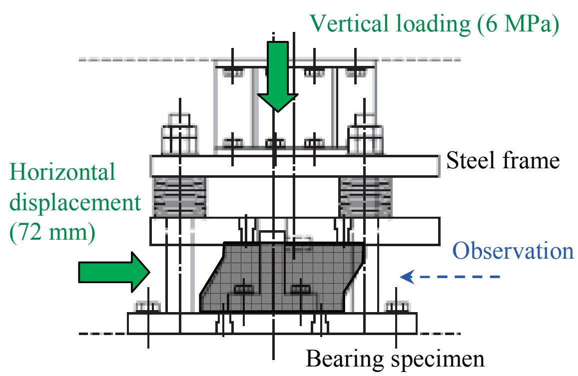
3.3 Experimental results

3.3.1 Crack observation in dumbbell specimens

Cracks could not visually be observed in the dumbbell specimens with and without anti-aging agent in each cycle until finishing the five cycles. By using a microscope of which the magnification was 100, fine cracks could be found in the dumbbell specimens without anti-aging agent from the first cycle regardless of the magnitude of pre-strain. Although the cracks partially occurred in the dumbbell specimens without pre-strain, cracks were observed in the overall surface of the specimens with large pre-strain. The tendency was not confirmed that the cracks propagated with the increase of experimental cycles.
On the other hand, no crack could be observed in the dumbbell specimens with anti-aging agent regardless of the pre-strain and the experimental cycles.

3.3.2 Experimental results of bearing specimen

Fig. 6 shows the appearances of the bearing specimens after finishing 5 cycles of the accelerated exposure experiment. The surfaces crossing to the shear deformation direction of the bearing specimen are shown.
A lot of cracks were generated on the surface of the bearing specimen without anti-aging agent during 2 hours from the start of experiment. The number of cracks increased with time



(a) Observed position

(b) Bearing specimen without anti-aging agent

(c) Bearing specimen with anti-aging agent

Fig. 6: Experimental results under the low temperature condition

passage after that. The cracks observed in not only surfaces crossing to the shear deformation direction, but also all surfaces. That is, the cracks were generated regardless of the strain distribution on the surfaces of bearing specimens. On the other hand, no crack could be observed in the bearing specimen with anti-aging agent during 5 cycles of the accelerated exposure experiment. The results indicated that the effectiveness of anti-aging agent used in the natural rubber bearings under the low temperature condition. In other words, the reason of crack occurrence recently reported in the actual natural rubber bearings of bridges is not the lack of anti-aging agent. Therefore, the accelerated exposure experiment is performed under the different temperature conditions for identifying the condition by which cracks are generated on the surface of the bearing specimen.

4. Accelerated exposure experiment under the high temperature conditions

4.1 Accelerated exposure experiment on dumbbell specimens

The same accelerated exposure experiment as in the chapter 3 was performed under the different temperature and ozone density to investigate the conditions for crack occurrence. *Table 2* shows the experimental conditions. The temperature conditions were -15, 0 and 23 degrees Celsius which occur in the general situations. The crack occurrence was examined at every 24 hours by visual check and observation with microscope.

Table 2 and *Fig. 7* show the experimental results. X in *Table 2* means the obvious crack occurrence or break of dumbbell specimens. On the other hand, the bar means that cracks could not be observed by visual checks and even the microscope.

No crack could be observed after finishing 96 hours of the experiment under the condition (1), of which the temperature was a little higher than that examined in the chapter 3. When the temperature was a little rose up by the condition (2), cracks were generated and the dumbbell specimens were broken at 24 hours in the cases with pre-strain of 75 %. That is to say, cracks easily occur under the not so low temperature condition such as 0 degrees Celsius rather than the low temperature condition of -30 degrees Celsius when the high ozone density and the pre-strain are applied. However, in the case that the temperature was more rose up to 23 degrees Celsius and the ozone density was decreased to 50 pphm, cracks did not occur regardless of the magnitude of pre-strain after the experiment of 192 hours (the condition (3)). Based on these results, the

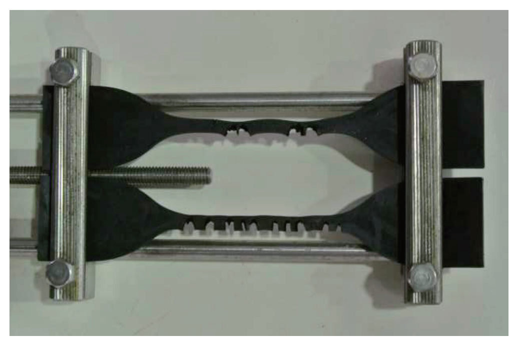


Fig. 7: Damaged dumbbell specimen (23 degrees Celsius, Ozone 100 pphm, pre-strain 80%)

Table 2: Experimental conditions under the high temperature and their results

Condition	(1)			(2)			(3)			(4)		
Temperature (degrees Celsius)	-15			0			23			23		
Ozone density (pphm)	150			150			50			100		
Pre-strain (%)	0	40	75	0	40	75	0	40	80	0	40	80
Time (hour)	96	96	96	96	96	24	192	192	192	192	144	24
Crack or break	-	-	-	-	-	X	-	-	-	-	X	X

X: Crack occurrence

(a) Front side (b) Back side

Fig. 8: Cracks of bearing specimen with anti-aging agent

experiment was performed by the condition (4), of which the temperature was 23 degrees Celsius and the ozone density was 100 pphm. As a result, cracks or breaking occurred earlier according to the magnitude of pre-strain.

4.2 Accelerated exposure experiment on bearing specimens

The accelerated exposure experiment was performed on the bearing specimen with anti-aging agent under the condition of which the temperature was 23 degrees Celsius and the ozone density was 100 pphm. However, cracks did not occur on the surface of specimen after the experiment of 96 hours. It might be thought that the resistance toward ozone attack of the bearing specimen was higher than that of the dumbbell specimens of which the thickness was just 2 mm and which is subjected to ozone attack from the both surfaces. Therefore, the temperature was rose up to 40 degrees Celsius and the experiment was carried out again. As a result, cracks were observed as shown in *Fig. 8* after the experiment of 384 hours. The position of crack occurrence corresponded to the region in which the high tensile strain was applied. The features of cracks were almost the same as that observed in the actual rubber bearing used during 10 or more years in the general temperature sites. The maximum length and depth of crack obtained by this experiment were around 30 mm and 6 mm respectively. The cracks stopped in the surface cover rubber and they did not reach the rubber layers inside the bearing specimen.

5. Loading experiment on bearing specimens

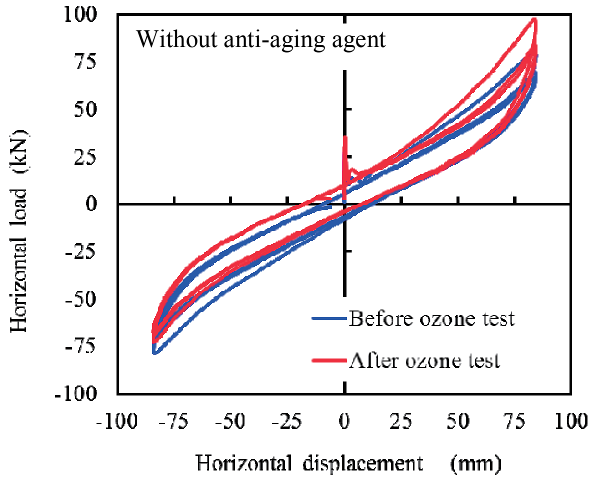
5.1 Experimental procedure

A series of loading experiments was performed on the bearing specimens after the accelerated exposure experiments for investigating the influence of cracks on the mechanical performances of the bearing specimens.

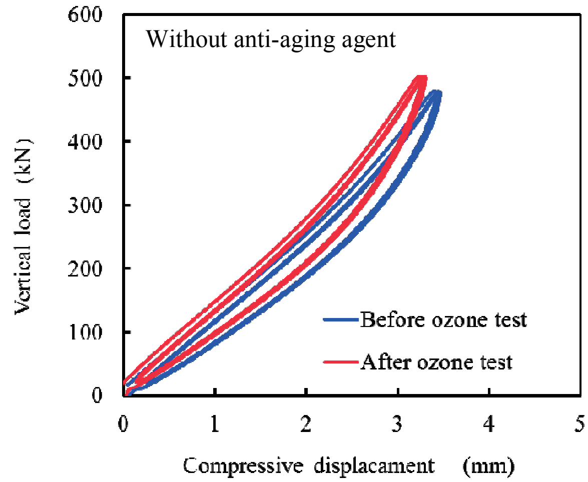
A cyclic compressive load from 0 MPa to 12 MPa was applied by 3 times during 20 seconds on the bearing specimens. On the other hand, a cyclic horizontal displacement of ±84 mm, which corresponded to ±175 % of shear deformation, was applied by 3 times on the bearing specimens with vertical pressure of 6 MPa. The loading frequency was 0.5 Hz.

5.2 Experimental results

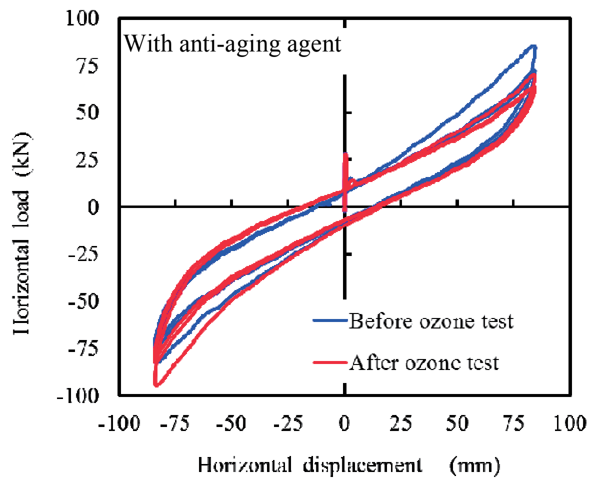
Fig. 9 shows the results of loading experiments. The vertical displacement of the bearing specimen without anti-aging agent, in which a lot of cracks occurred by the accelerated exposure experiment under the low temperature condition, decreased by 6 % from that of the virgin situation. The horizontal stiffness of it increased by 8 % compared with that of the virgin situation. The vertical displacement of the bearing specimen with anti-aging agent, in which some cracks occurred by the accelerated exposure experiment under the high temperature condition, increased by 4 % from that



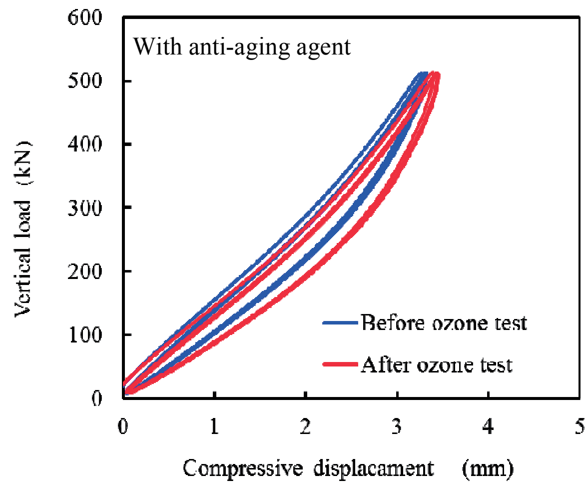
(a) Horizontal loading on bearing specimen without anti-aging agent



(b) Vertical loading on bearing specimen without anti-aging agent



(c) Horizontal loading on bearing specimen with anti-aging agent



(d) Vertical loading on bearing specimen with anti-aging agent

Fig. 9: Results of loading experiment on bearing specimens

of the virgin situation. The horizontal stiffness of it was almost the same as that of the virgin situation. Both of the specimens satisfied the design specifications of vertical displacement and horizontal stiffness. No crack propagation could be observed by the loading experiment. It might be thought that the influence of cracks generated by the accelerated exposure experiments on the mechanical performances of bearing specimens was not so large because the cracks did not reach the rubber layers inside the specimens.

6. Conclusions

A series of accelerated exposure experiments was performed for identifying the conditions which cause cracks on the surface of natural rubber bearing for bridges.

The main conclusions obtained are as follows.

(1) Cracks could be found in the dumbbell specimens and the bearing specimen without anti-aging agent under the low temperature (-30 degrees Celsius) and high ozone density (150 pphm) conditions regardless of the magnitude of pre-strain. On the other hand, no crack could be observed in the dumbbell specimens and the bearing specimen with anti-aging agent regardless of the pre-strain and the experimental cycles.

(2) Cracks occurred in the dumbbell specimens with anti-aging agent under the high temperature (23 degrees Celsius) and high ozone density (100 pphm) condition. Furthermore, the larger the magnitude of pre-strain was, the earlier the cracks or breaking occurred.
(3) Cracks occurred on the surface of bearing specimen with anti-aging agent under the high temperature (40 degrees Celsius) and high ozone density (100 pphm) condition. The cracks occurred in the region which the high tensile strain was applied on. The features of cracks were almost the same as that observed in the actual rubber bearing used during 10 or more years in the general temperature sites.
(4) The influence of cracks generated by the accelerated exposure experiments on the mechanical performances of bearing specimens was not so large because the cracks did not reach the rubber layers inside the specimens. No crack propagation could be observed by the loading experiment.

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References

[1] ITOH Y., GU H., SATOH K. and KUTSUNA Y., ‘‘Experimental Investigation on Aging Behaviors of Rubbers Used for Bridge Bearings’’, *JSCE Journal of Japan Society of Civil Engineers*, No.808/I-74, 2006, pp.17-31.

[2] SUGIMOTO H., MIZOE M., YAMAMOTO Y. and IKENAGA M., ‘‘Research on Low Temperature Resistance of The Natural Rubber Bearing’’, *JSCE Journal of Japan Society of Civil Engineers*, No.693/VI-53, 2001, pp.73-86.

[3] YAMADA K., SODA N., KIMIZU T., HIROSE T., NAGOYA K. and SUZUKI M., ‘‘An Analytical Investigation into Causes of Ruptures of The Elastomeric Bearings Used on The East Viaduct Due to The 2011 Off The Pacific Coast of Tohoku Earthquake’’, *JSCE Journal of Structural Engineering*, Vol.59A, 2013, pp.527-539.

[4] Japanese Standards Association, *Rubber, vulcanized or thermoplastic – Determination of ozone resistance*, JIS K 6259, 2004.

[5] Japanese Standards Association, *Rubber, vulcanized or thermoplastic – Determination of tensile stress-strain properties*, JIS K 6251, 2010.