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MECHANICAL CHARACTERISTICS OF HIGH DAMPING RUBBER BEARINGS UNDER LOW TEMPERATURE ENVIRONMENT

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Abstract

Laminated rubber bearings have been widely used as seismic isolation devices in bridges. Lead rubber bearing (LRB) and high damping rubber bearing (HDRB) are widely used for these devices. According to past researches, the mechanical characteristics of these rubber bearings depend on temperature. To use the devices in cold region, it is important to evaluate about the temperature dependency of the mechanical characteristics of rubber bearings. And it is necessary for the evaluation to examine for cyclic loading tests by loading facility in constant temperature room.

Therefore, this study discusses the mechanical characteristics of HDRBs by dynamic loading tests under the low temperature environment. Fundamental cyclic loading tests at different temperatures were conducted using 2 types of HDRBs (HDReX and HDR-S). The specimens were tested under shear deformation with a constant vertical compressive stress of 6MPa. Sine waves were applied in the horizontal direction to the specimens. The period of the sine wave was 2.0 sec, and the shear strain was 175%. In these tests, Equivalent stiffness and energy absorption of all specimens increased under low temperature and its ratio depended on type of rubber. Especially equivalent stiffness of HDR-S was significantly larger than HDReX because of its material characteristic. In the case of increasing shear strain, the temperature dependencies of the equivalent stiffness and energy absorption were lower than the result of the fundamental tests. And in the case of decreasing vertical compressive stress, the temperature dependencies were equivalent to the fundamental tests. In cyclic loading tests under allowable design displacement (250%), the rate of change of the equivalent stiffness and energy loss of HDR-S significantly increased specially in -30 degrees in Celsius. Finally, all specimens did not break under cyclic loading test of 120% allowable design displacement under any temperature cases.

Keywords: high damping rubber bearing; temperature dependency; cyclic loading test

1. Introduction

Seismic isolation bearings using laminated rubber are one of the leading options for improving the seismic performance of bridges and are widely used. According to the specifications for highway bridges in Japan [1], some seismic isolation rubber bearings have characteristics such as strain level dependence, vertical compressive stress dependence, and temperature dependence. Therefore, it is important to evaluate its properties under various conditions. In particular, it is important to evaluate the temperature dependence in cold regions such as Northern Pacific area including Hokkaido, Japan.

Seismic isolation rubber bearings absorb energy by deforming by shaking and converts it to heat. Takaoka et al. [2] studied the effect on mechanical properties when the internal temperature rose due to the rubber bearing absorbing energy. Nguyen et al. [3] conducted loading experiments at low temperature and examined a model representing the hysteresis characteristics. According to past researches, the mechanical characteristics of these rubber bearings depend on temperature. To use the devices in cold region, it is important to evaluate about the temperature dependency of the mechanical characteristics of rubber bearings. And it is necessary for the evaluation to examine for cyclic loading tests by loading facility in constant temperature room.

Therefore, this study discusses the mechanical characteristics of HDRBs by dynamic loading tests under the low temperature environment. In this study, two types of experiments are performed. One is the experiment to confirm the temperature dependence of mechanical properties, and the other is the ultimate limit experiment.

2. Experiments to confirm the temperature dependence

2.1 Experimental equipment

The experiments were carried out with a loading facility (Figs. 1 and 2) in the cold room of the Kitami Institute of Technology. In this laboratory, the cooling device can control the room temperature of the entire laboratory including the loading facility within the range of -30 to +50 degree in Celsius, and the loading test can be performed on the specimen without being affected by the ambient temperature. The loading facility is a biaxial loading facility that applies shear deformation to the specimen by applying horizontal pressure to the specimen while applying a downward vertical compressive stress to the specimen. The horizontal actuator has a dynamic loading capacity of 200kN and a displacement of 100mm, and the sine wave with a vibration frequency of 0.5Hz used in this study can excite with 40mm. The actuator for vertical force has a static loading capacity of 200kN.

2.2 Experimental method

In this study, after confirming the basic temperature dependence, we focus on temperature dependences for differences in strain level and vertical compressive stress. For this purpose, experiments are performed under 4 conditions. Table 1 shows the experimental conditions. No. 1 performs a basic temperature dependent experiment, No. 2 and 3 compare experiments with different strain levels, and No. 1 and 4 compare experiments with different vertical compressive stresses.

First, perform preloading before the experiment. The preloading conditions were as follows: the temperature of +23°C, the vertical compressive stress of 6MPa, the sine wave with an excitation period of 2.0 sec, and the constant amplitude of 175% of shear strain, 11 cycles.

After the preloading, more than 24 hours have passed before the experiment and keep the specimens in the room at normal temperature. Before the experiment, place the specimen in the laboratory and bring it to the specified temperature.

In all experiments, sine waves were applied in the horizontal direction to the specimens. The sine waves were period 2.0 sec and 11 cycles.

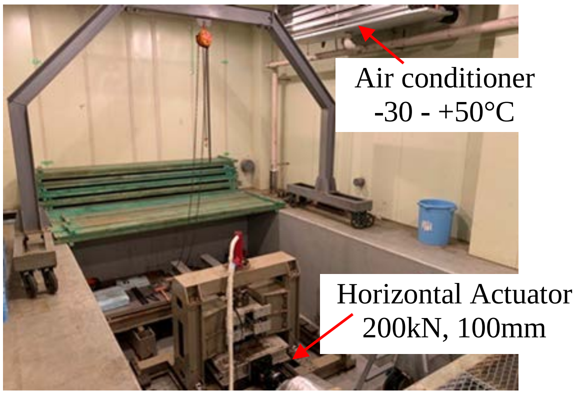


Fig. 1 - Experimental equipment

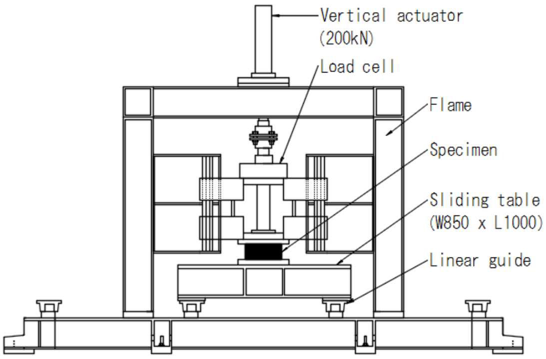


Fig. 2 - The losding facility

Table 1 - The experimental conditions

No.	Rubber type	Size (mm)	Thickness (mm)	layer	Total thickness (mm)	Shear strain (%)	Vertical compressive stress (MPa)	Temperature (℃)
1	HDReX HDR-S	□170	7	3	21	175	6	-30, -20, -10, +23, +40
2	HDReX HDR-S	□120	5	3	15	175	6	-30, -20, -10, +23
3	HDReX HDR-S	□120	5	3	15	250	6	-30, -20, -10, +23
4	HDReX	□170	7	3	21	175	1	-30, -20, -10, +23

Differences in experimental conditions are temperature, shear strain, and vertical compressive stress. The temperatures are +23, -10, -20 and -30°C respectively. In addition, No. 1 is performed at + 40 °C. The shear strain is set to 175% in No. 1, 2, and 4, and to 250% in No. 3. The vertical compressive stress is set to 6MPa in No. 1, 2 and 3, and 1MPa only in No. 4. The vertical compressive stress of 1 MPa is the lowest value that can be safely tested with this loading facility.

For the experimental results, the equivalent stiffness, equivalent damping ratio, and energy absorption were calculated from the hysteresis loop at the 5th cycle, and the change rate was evaluated based on + 23 °C.

2.3 Specimens

The specimens were HDReX and HDR-S, two high damping rubber bearings manufactured by Sumitomo Riko Co., Ltd. The nominal shear modulus was 1.2 MPa. HDR-S has already been put to practical use for the purpose of prolonging the period and reducing the response due to the absorption of seismic energy by using a natural polymer and compounding additives that provide damping performance. HDReX uses a polymer with a lower glass transition point than the natural polymer. It is currently being developed for the purpose of reducing temperature dependency, hardening, and improving damping performance compared to HDR-S. The size and rubber thickness of the specimen are to be selected from two types according to the experimental conditions in consideration of the capacity of the loading facility. In No. 2, the size of the specimen is adjusted to that in No. 3. For that reason, the specimens using No. 1 and 4 have a plane size of 170 mm × 170 mm and rubber thickness of 7 mm × 3 layers, and No. 2 and 3 have a plane size of 120 mm ×

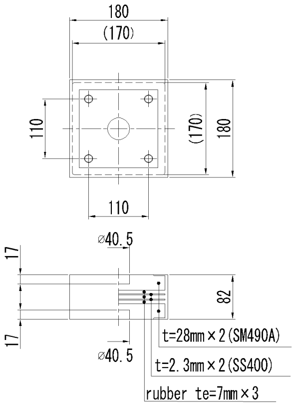
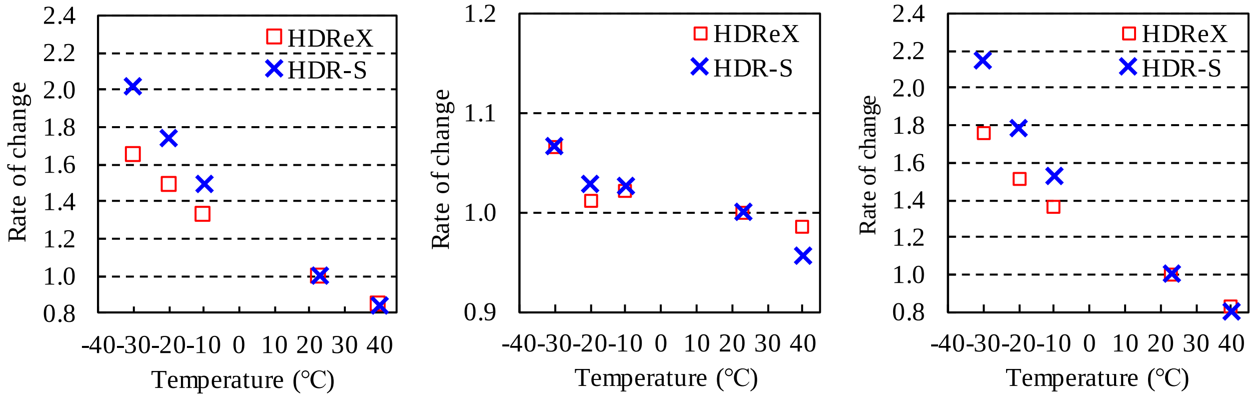


Fig. 3 - Specimen used No. 1 and 4

Table 2 - Number of the experiments

No.	Number of rubber types	Number of temperature conditions	Number of experiments
1	2	5	10
2	2	4	8
3	2	4	8
4	1	4	4
		Total	30



(a) Equivalent stiffness (b) Equivalent damping ratio (c) Energy absorption

Fig. 4 - The rate of change of mechanical characteristics in No. 1

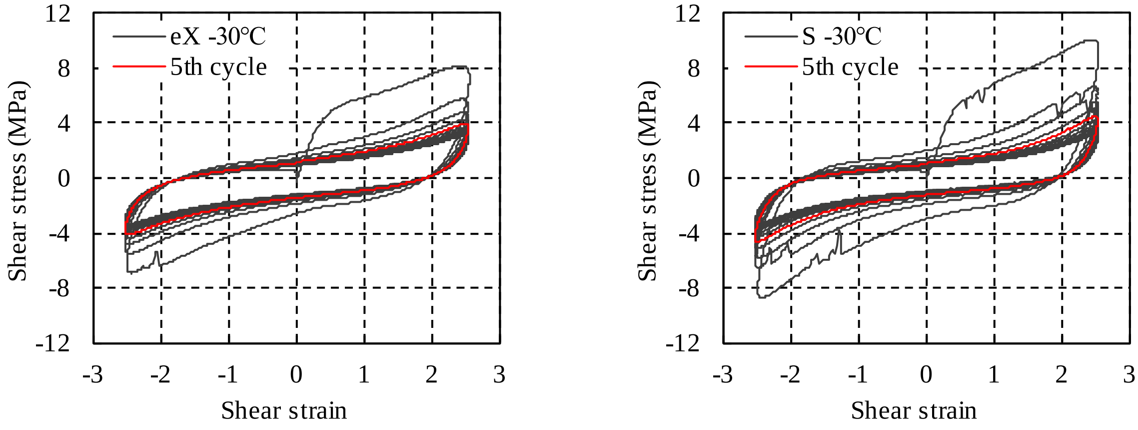
120 mm and rubber thickness of 5 mm × 3 layers. Fig. 3 shows a drawing of the specimen used in No. 1 and 4.

Prepare different specimens for all experiments. In addition, because the number of each experiment is one, there is a concern that the results may vary due to individual differences of the specimens. However, individual differences are reduced by making each specimen collectively at the time of manufacture. The number of experiments is 30 in total, as shown in Table 2, depending on the type of specimen and temperature conditions. A total of 34 specimens, including 4 for internal temperature control, are prepared.

3. Experimental results and discussion

3.1 The basic temperature dependence

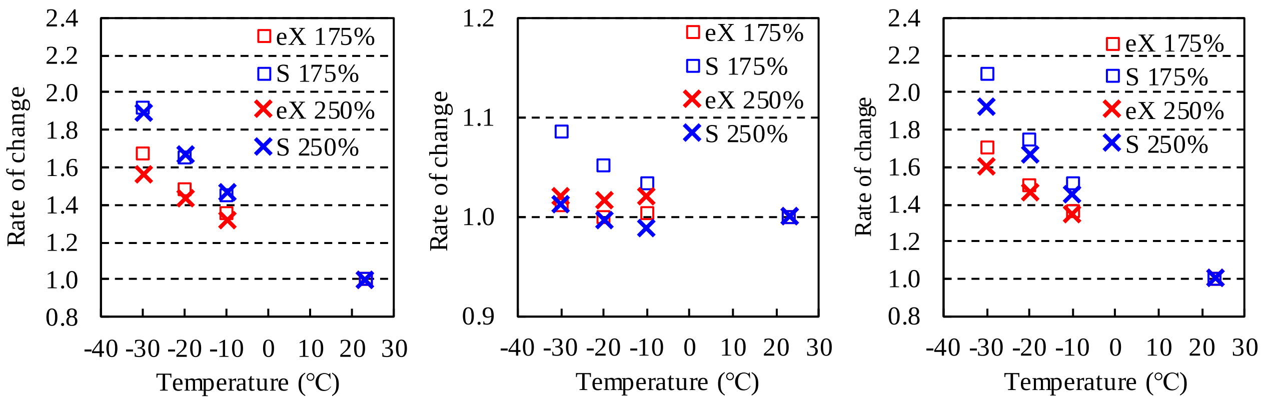
First, Fig. 4 shows the rate of change of the equivalent stiffness, equivalent damping ratio, and energy absorption in No. 1. For both rubber types, the rate of change in equivalent stiffness increased with decreasing temperature. In comparison by rubber type, HDR-S has a larger rate of change. This is because HDR-S uses a natural polymer, but HDReX uses a material with a lower glass transition point than the natural polymer, making it difficult to crystallize at low temperatures. At +40°C, there was no difference between rubber types.



(a) HDReX

(b) HDR-S

Fig. 5 - Hysteresis loops at -30°C



(a) Equivalent stiffness

(b) Equivalent damping ratio

(c) Energy absorption

Fig. 6 - The temperature dependence for differences in strain level

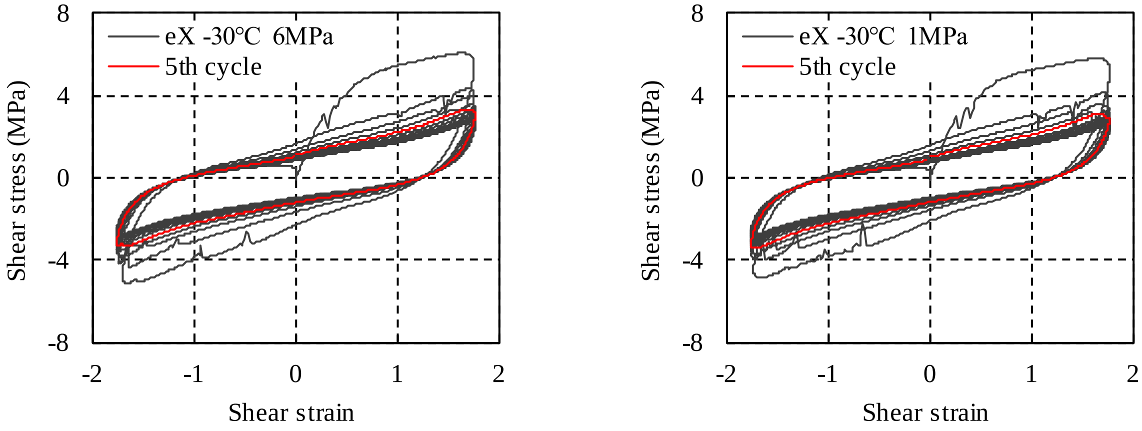
The rate of change of the equivalent damping ratio for both rubber types was below 1.1 even at -30°C, hence no clear temperature dependence was observed.

As in the case of equivalent stiffness, the rate of change in energy absorption increased with decreasing temperature, and the rate of change in energy absorption was slightly greater than that of equivalent stiffness.

3.2 The temperature dependence for differences in strain level

Fig. 5 shows the hysteresis loops at -30°C and 250% shear strain, and Fig. 6 shows the rate of change based on the difference in strain level. Marks are distinguished by rubber type and strain, and are shown in the legend. As for the equivalent stiffness, the rate of change was slightly lower in HDReX at 250%. In HDR-S, there was no difference in the change rate due to the strain level in Fig. 6 (a). However, as shown in Fig. 4 (a), the rate of change is larger than that of No. 1 in the result of No. 2, so that the rate of change may be smaller at 250% as in HDReX.

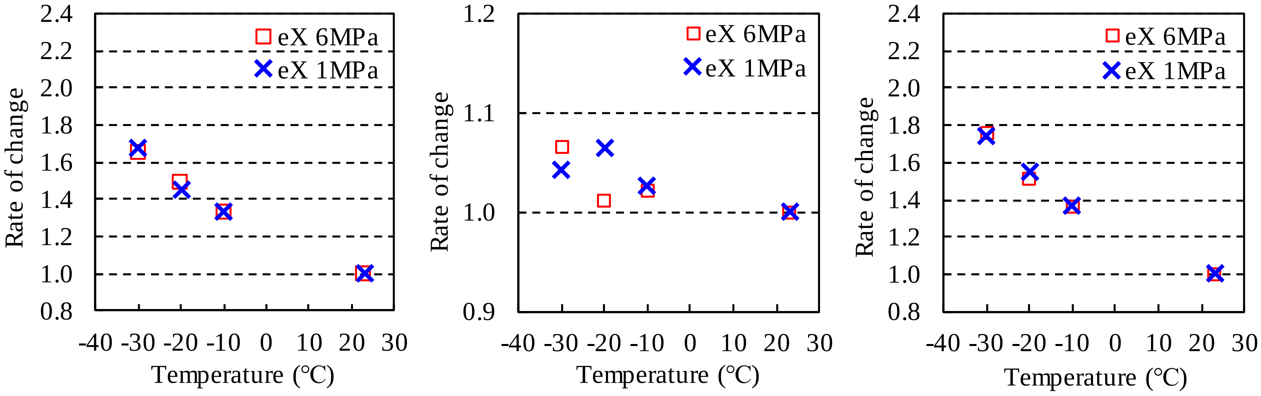
For the equivalent damping ratio, the rate of change was almost 1.0 at 250%. Although the change rate tends to increase slightly at 175% of HDR-S, the change rate was as small as 1.1 or less, so it was unlikely that there was a clear difference due to the difference in strain.



(a) 6MPa

(b) 1MPa

Fig .7 - Hysteresis loops at -30°C



(a) Equivalent stiffness

(b) Equivalent damping ratio

(c) Energy absorption

Fig. 8 - The temperature dependence for differences in vertical compressive stress

In the case of both rubber types, the rate of change in energy absorption was generally smaller for 250%.

Comparing the hysteresis loops in Fig. 5, at -30°C, HDR-S shows more pronounced hardening in the higher strain levels. The reason that the rigidity of the rubber bearing increases at low temperature is thought to be due to the decrease in flexibility due to the restricted mobility due to crystallization of molecules. Hardening occurs in the higher strain levels. For the two types of high damping rubber bearings used this study, HDR-S uses a natural polymer, but HDReX uses a non-natural polymer, and the difference in the polymer appears in the difference in the hardening.

3.3 The temperature dependence for differences in vertical compressive stress

Fig. 7 shows the hysteresis loops at a temperature of -30°C and Fig. 8 shows the rate of change for comparison based on the difference in vertical compressive stress. Marks are distinguished by vertical compressive stress and shown in the legend. There is no difference in the rate of change of the equivalent stiffness, equivalent damping ratio, and energy absorption due to the difference in vertical compressive stress.

4. Measurement of internal temperature

The high damping rubber bearing absorbs energy by deforming by shaking and converts it to heat. Therefore, since the internal temperature rises as the load is repeatedly applied, the internal temperature during the excitation is measured in a typical case among the above experiments. The internal temperature is measured by embedding a thermocouple (T type class 2) inside the specimen. The measurement point is one point at the center of the center layer of the rubber layer. The experiments where the internal temperature was measured were +23°C and -20°C in No. 1 and each experiment was performed once.

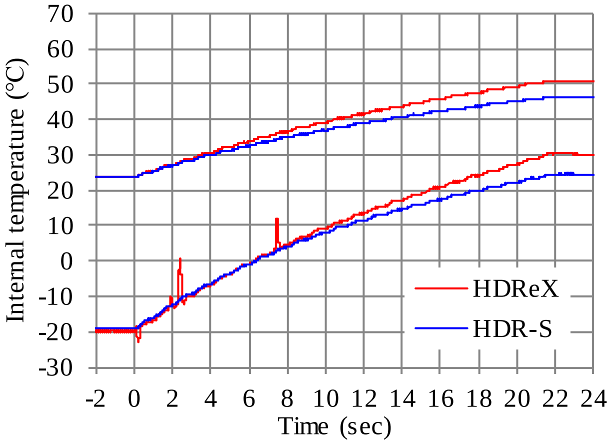


Fig. 9 - Internal temperatures in No. 1

Fig. 9 shows the time history of the internal temperatures in No. 1. The part where the temperature rises momentarily is considered to be a measurement failure. The internal temperature rose and kept alternately with the load of the excitation cycle of 2 seconds. in Fig. 9, the internal temperature of HDReX was higher at both +23°C and -20°C. Table 3 shows the specific heat of the rubber material used in this study. The specific heat differs slightly depending on the rubber type and also with the temperature. It is considered that the difference in the rise of the internal temperature is related to the specific heat of the rubber material and the energy absorption. However, a comparison of rubber types suggests that although HDReX has a slightly higher specific heat, it has a higher energy absorption, so that HDReX has a higher temperature. When the initial temperatures are +23°C and -20°C, the temperature rise is larger at -20°C. This is thought to be due to the lower specific heat and higher energy absorption at -20°C for both rubber types.

Table 3 - Specific heat of the rubber material (J / (g °C))

Temp.	HDReX (G12)	HDR-S (G12)
-20°C	1.123	1.093
+23°C	1.282	1.241

5. Ultimate limit experiments

Ultimate limit experiments were conducted on the mechanical characteristics for cyclic loading and up to failure in a low-temperature environment. Table 4 shows the specifications of the specimen.

Table 5 shows the loading conditions of this experiment. First, experiments to confirm basic characteristics at a reference temperature of +23°C were performed. Next, in order to confirm the behavior against the cyclic load at +23°C, -20°C and -30°C, cyclic loading tests with the design allowable displacement (shear strain 250%) were performed. Then, in order to confirm that the safety against the loss of the function of the bearing is ensured, cyclic loading tests with a displacement (shear strain 300%) equivalent to 1.2 times the allowable displacement were performed. The excitation frequency was set to 0.2Hz depending on the performance of the loading facility. Finally, fracture tests with a monotonic load were performed. In each experiment, the interval of each experiment should be 24 hours or more to adjust the internal temperature of the specimen to the ambient temperature.

5.2 The result of ultimate limit experiment

In order to confirm the behavior against cyclic loading at each temperature during an earthquake, the rate of change of equivalent stiffness, equivalent damping ratio, and energy absorption are arranged by the number of cycles. The results at a shear strain of 250% are shown in Figs. 10-12. Since the hysteresis characteristics

Table 4 - Specifications of the specimen used the ultimate limit experiments

Rubber type	Nominal shear modulus	Size (mm)	Rubber layer		Number of Specimens
			te (mm)	n (layer)	
HDR-S	G12	□120	7	3	3
HDReX	G12	□120	7	3	3

Table 5 - Loading conditions of the ultimate limit experiments

Step	Temperature	vertical compressive stress	Excitation method	Speed	Shear strain	Number of cycle
1	23°C	6MPa	Sine wave	0.5Hz	±175%	11
2	23°C, -20°C, -30°C			0.2Hz	±250%	6
3	23°C, -20°C, -30°C				±300%	3
4	23°C, -20°C, -30°C		monotonic loading	8mm/s	About 470%	1

in the first cycle are significantly different from those in the second and subsequent cycles, the behaviors up to the sixth cycle are compared based on the hysteresis characteristics in the second cycle.

Equivalent stiffness and energy absorption tended to decrease as the number of cycles increases in all experiments. In addition, the equivalent damping ratio did not change much, but had no noticeable tendency, and differed depending on the rubber type and temperature. The rate of change of equivalent stiffness of HDR-S was -36% at -20°C and -38% at -30°C, whereas HDReX was -24% at -20°C and -28% at -30°C. Similarly, focusing on the rate of change of energy absorption, HDR-S is -37% at -20°C and -40% at -30°C, whereas that of HDReX was -30% at -20°C and -29% at -30°C.

Next, the results at a shear strain of 300% are shown in Figs. 13-15. The HDR-S shows a large rate of change in equivalent stiffness and energy absorption for each cycle, as in the case of approximately 250%.

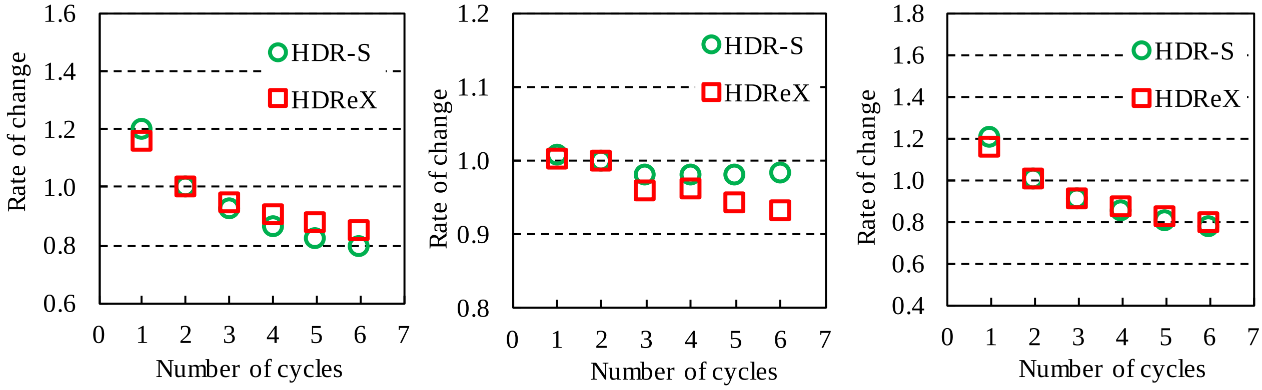
Finally, Fig. 16 and Table 6 show the results of the fracture test under monotonic loading. Table 6 shows the strain levels when the specimens broke. If the specimens did not break, Table 6 shows the strain levels when finished the experiments. For all rubber types, the breaking strain was over 300%, and it was confirmed that the safety factor was at least 1.2 times the design allowable displacement.

These results indicate that HDReX has a smaller rate of change due to the cycle than HDR-S, and is especially stable against cyclic loading at low temperature environment.

6. Conclusion

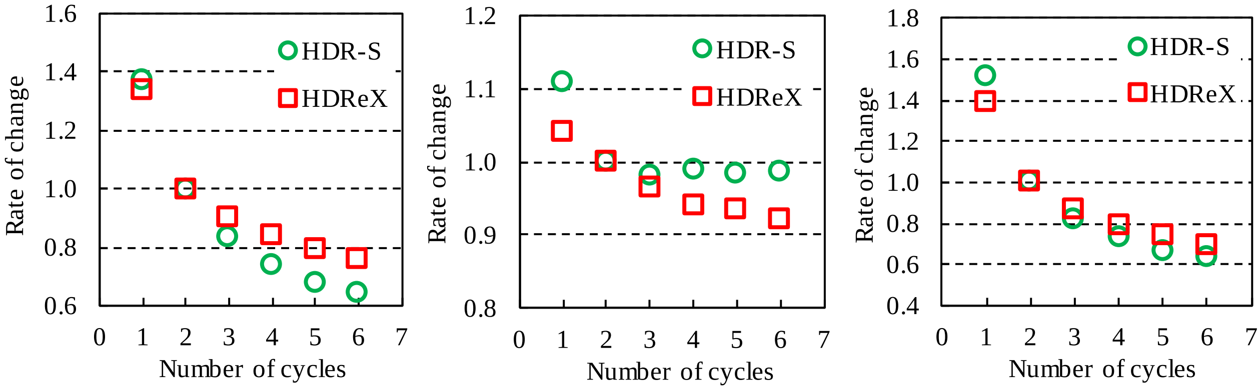
In this study, the mechanical properties of high damping rubber bearings were examined by loading tests in low temperature environments. After confirming the basic temperature dependence, we focus on temperature dependences for differences in strain level and vertical compressive stress. As a result, the rate of change in equivalent stiffness and energy absorption increased with decreasing temperature. No temperature dependence was found in the equivalent damping ratio.

The larger the strain, the lower the rate of change in equivalent stiffness and energy absorption. There was no clear difference in the tendency due to the difference in vertical compressive stress.



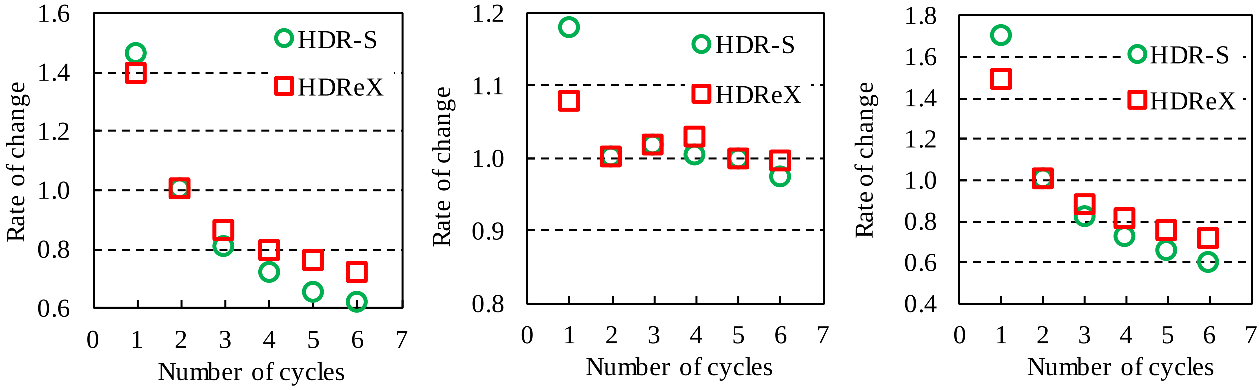
(a) Equivalent stiffness (b) Equivalent damping ratio (c) Energy absorption

Fig. 10 - Rate of change per cycle (+23°C, 250%)



(a) Equivalent stiffness (b) Equivalent damping ratio (c) Energy absorption

Fig. 11 - Rate of change per cycle (-20°C, 250%)

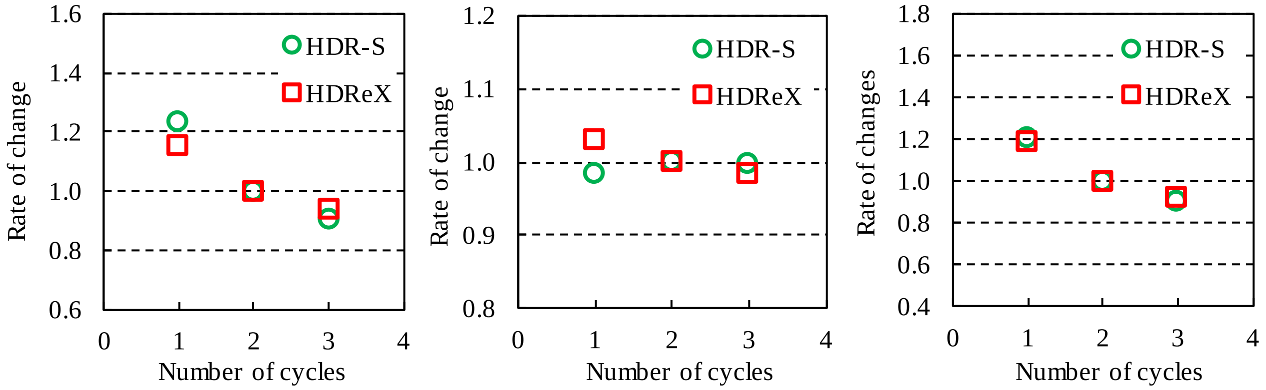


(a) Equivalent stiffness (b) Equivalent damping ratio (c) Energy absorption

Fig. 12 - Rate of change per cycle (-30°C, 250%)

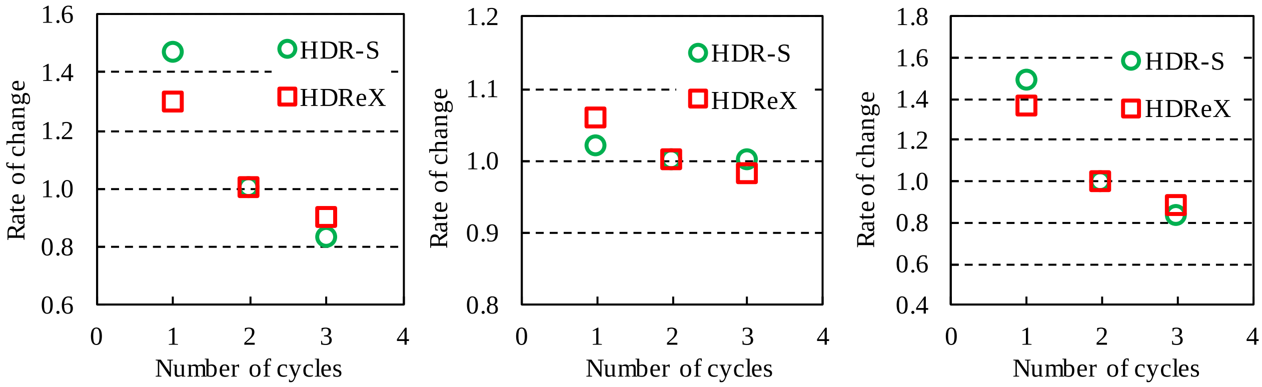
The internal temperature rose and kept alternately with the load of the excitation cycle

In cyclic loading tests under allowable design displacement (250%), the rate of change of the equivalent stiffness and energy loss of HDR-S significantly increased specially in -30 degrees in Celsius. Finally, all specimens did not break under cyclic loading test of 120% allowable design displacement under any temperature cases.



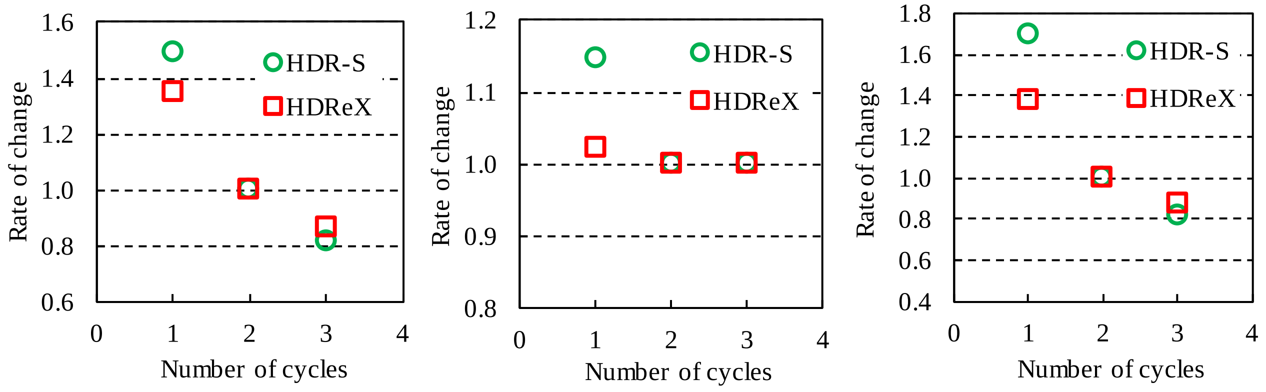
(a) Equivalent stiffness (b) Equivalent damping ratio (c) Energy absorption

Fig. 13 - Rate of change per cycle (+23°C, 300%)



(a) Equivalent stiffness (b) Equivalent damping ratio (c) Energy absorption

Fig. 14 - Rate of change per cycle (-20°C, 300%)

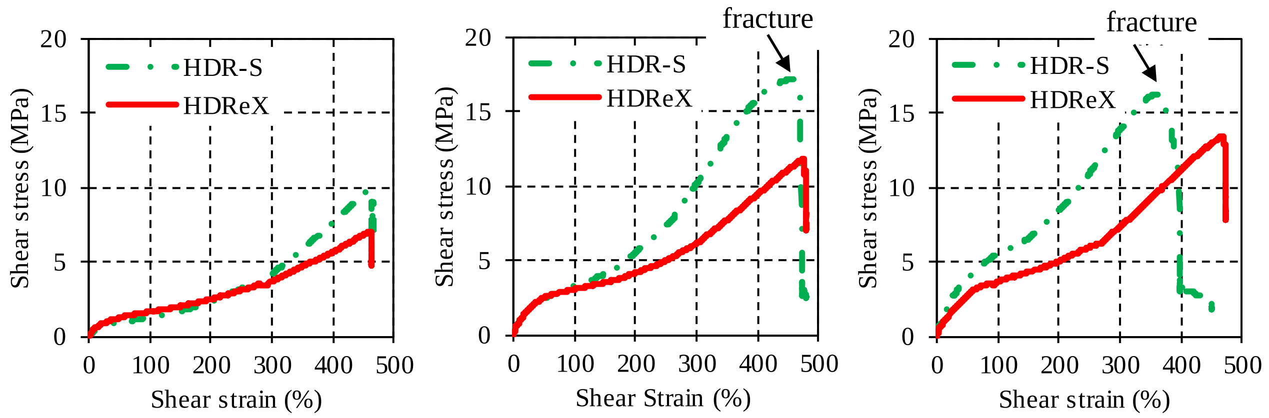


(a) Equivalent stiffness (b) Equivalent damping ratio (c) Energy absorption

Fig. 15 - Rate of change per cycle (-30°C, 300%)

7. Acknowledgements

We acknowledge the work of past and present members of our laboratory.



(a) +23°C (b) -20°C (c) -30°C

Fig. 16 - Stress-strain relationship from the fracture tests

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Table 6 - Results of the fracture test

Rubber type	Shear stress (MPa)		Strain at fracture (%)
23°C			
	250%	300%	
HDR-S	3.3	4.2	464% (Did not break)
HDReX	3.1	3.7	464% (Did not break)
-20°C			
Rubber type	Shear stress (MPa)		Strain at fracture (%)
	250%	300%	
HDR-S	7.3	10.1	455%
HDReX	5.0	6.2	478% (Did not break)
-30°C			
Rubber type	Shear stress (MPa)		Strain at fracture (%)
	250%	300%	
HDR-S	11.0	14.0	359%
HDReX	6.0	7.4	468% (Did not break)