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DEVELOPMENT OF HIGH DAMPING FERRITE RUBBER BEARING

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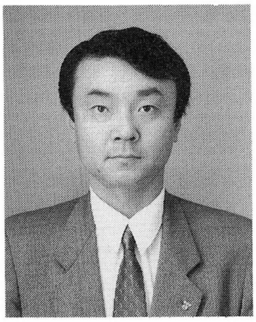
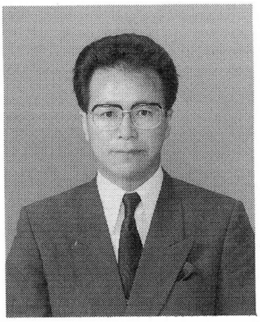
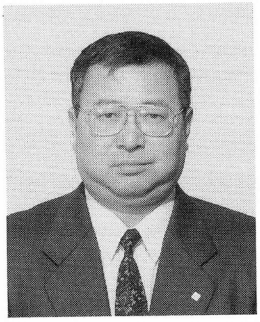
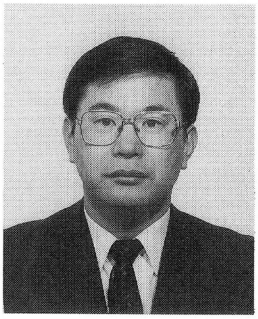

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SYNOPSIS

This paper describes the development of a high damping rubber bearing consisting of steel plates and thin ferrite rubber sheets which is obtained by mixing rubber with ferrite by-products. Dynamic tests were carried out, and the following conclusions were drawn. (1) The dynamic tests proved that the ferrite rubber bearing has a high damping effect. (2) The ferrite rubber bearing performs the functions of both isolator and damper. Equivalent damping factor obtained from cyclic loading tests , is about 11%. This damping factor is about three times as large as that of a natural rubber bearing. (3) The frequency and vertical load dependency of the hysteresis loop is disregarded in the actual seismic response range. (4) Endurance tests have confirmed that the ferrite rubber bearing can reasonably satisfy design requirements.

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1. INTRODUCTION

Recent years have seen vigorous efforts in research and development to improve "base isolation" design, along with conventional seismic design. In New Zealand, the United States and other countries, the base isolation system has been incorporated into many highway bridges1) and building structures2) in order to reduce the impacts of seismic force and retrofit existing structures. In Japan, too, the base isolation system has been introduced3)-5) mainly in the field of building, and is being accepted as an established practical technique.

Needs for the base isolation system are growing in other fields, too. The authors have been studying methods of designing base isolation systems for electric power facilities6) and trying to develop an effective base isolation system7) in an effort to enhance the seismic resistance of lifeline facilities and maintaining city functions even after the impacts of earthquakes. In the field of bridge structure, new highway bridges incorporating base isolation systems are under consideration, too.

Various types of base isolation system have already been developed for practical use. Basically, many of those systems consist of isolators often made of laminated rubber for carrying the load of the structure and extending vibration periods, and dampers designed to absorb vibrational energy. Gaining attention recently and now under development is a kind of base isolation system using high damping laminated rubber bearings combining the functions of the isolator and the damper. Since this integral isolator-damper has a better workability than an isolator-damper assembly, areas of use for this type of rubber bearing is expected to expand.

Taking note of ferrite byproducts as a promising new material, one of the authors has studied mix proportions for ferrite mixture composed of various binders.8),9) This study was aimed at using the vibration control effect of ferrite byproducts for seismic isolation and developing high damping laminated rubber bearings made of new material.10) On the basis of a study by the authors,6) the target value of damping factor has been set at 10% or above so that an adequate level of seismic isolation can be achieved. In the study, as a first step various mix proportions of ferrite rubber were tested to determine the mix proportions that meet the requirements of high damping rubber. Next, full-scale high damping rubber bearings were made by laminating rubber and steel plates. The performance of the bearings was then verified through mechanical property and endurance tests at various possible loads, deformation patterns and frequencies.

2. MIX PROPORTIONS and BASIC PHYSICAL PROPERTIES of FERRITE RUBBERS

Before making the laminated rubber bearings, the rubber material was put through a series of tests to determine the relations between mix proportions and damping characteristics/basic physical properties.

(1) Material

a) Ferrite Byproducts

Ferrite byproducts are magnetic oxides composed mainly of Fe_3O_4, which are produced as iron residues, titanium white byproducts or wastewater treatment residues. Table 1 shows results of the analysis of the ferrite byproducts. Hereafter these ferrite byproducts are referred to simply as "ferrite."

Generally, ferrite is a highly magnetic, black oxide that has a specific gravity of 5 or so and strength comparable to that of nickel. Ferrite has a high electrical resistance of 10^2 Ω cm and is in a chemically stable condition. Since ferrite is often produced in the form of sludge with a high moisture content, it usually has no binding power. Photo 1 shows an electron microscope photo of ferrite. Grain sizes of ferrite range from 1/100μm to several hundred μm, depending on places and times of generation. Grading was adjusted, as the grain size accumulation curve in Fig. 1 shows, for use in the study.

Table 1 Composition of By-product Ferrite

Component	Weight Percetage	Component	Weight Percentage
Fe	65.06	Mn	0.122
Cu	0.012	S	0.267
SiO_2	4.76	P	0.013
CaO	2.50	As	0.002
MgO	0.492	others	25.821
Al_2O_3	0.951		

(obtained from emission spectral analysis)

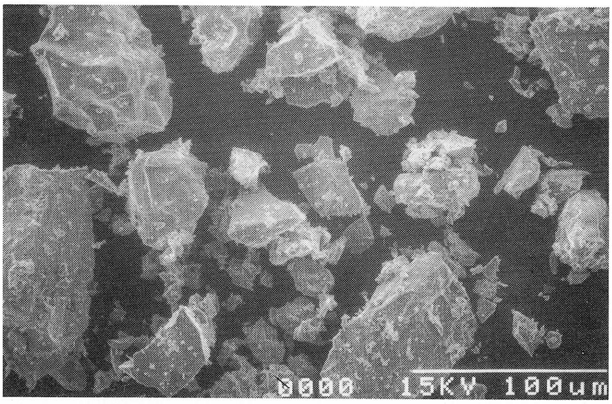


Photo 1 Electron Microscope Photo of By-product Ferrite

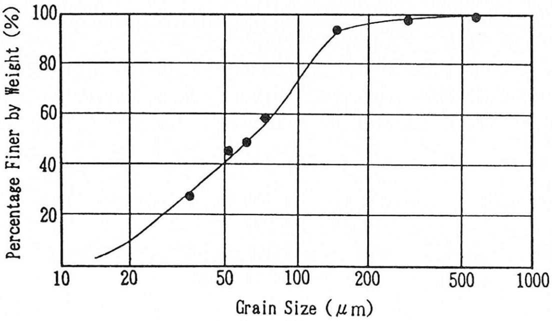


Fig. 1 Grain Size Accumulation Curve for Ferrite

b) Rubber

The rubber used in the study is composed mainly of natural rubber, which was mixed with high-endurance synthetic rubber in view of the environment for which the base isolation system is intended.

c) Coating Material

Ferrite grains were coated with asphalt. This is because asphalt coating is expected to improve vibration control effect of ferrite concrete (cases showing this have been reported), and because the possible influences of sharp-edged ferrite grains had to be avoided. Following the documented procedure,9) ferrite and asphalt were heated to a specified temperature and were mixed in an asphalt mixer for about two minutes. Two types of asphalt, straight asphalt and silicon asphalt, were used for coating. The silicon asphalt is a mixture of straight asphalt and 5% (weight) silicon oil.

In view of the result of a study on ferrite concrete,8) both asphalt-coated ferrite and uncoated ferrite were adopted.

d) Plasticizer

Plasticizer is usually used as lubricant to improve the workability of rubber and increase the flexibility of rubber products. In this study, naphthene-based process oil was used.

Other ingredients, such as vulcanizing agent, vulcanization accelerator and antioxidant, were added, too. Sulfur was used as vulcanizing agent.

(2) Rubber Mix

Standard mix proportions of rubber are shown in Table 2. The experimental design method was used in determining the rubber's mix proportions and analyzing test results. Factors and levels affecting the rubber's mix proportions are shown in Table 3. As factors, the content of ferrite (A), types of coating material (B), quantity of coating material (C) and the content of plasticizer (D) that were considered to affect damping effect greatly were adopted, and it was assumed that there is interaction between A and C. As for levels, quantities were divided into four levels so as to clearly differentiate mix proportions. Mix proportions were designed using the orthogonal table.11)-13)

The rubber used was composed of natural rubber and synthetic rubber, which were mixed in the proportion of 80% to 20% in terms of weight. Only one type of ferrite was used. The ferrite content was set at 100%, 200%, 300% and 400% of rubber in terms of weight. Three types of coating material were used to cover the surfaces of ferrite grains: "Asphalt 80/100," "Asphalt 200/250" and "Silicon asphalt." "80/100" and "200/250" mean that measured values obtained from penetration tests are within the ranges of 80-100 and 200-250, respectively. The quantity of coating material was set at 0%, 1%, 2% and 3% of rubber in terms of weight. "0%" means that coating material was not used.

The number of rubber's mix proportions as determined by the experimental design method based on the orthogonal table totaled 32. For purposes of comparison, a type of natural rubber usually mixed into conventional laminated rubber that did not contain ferrite was added, bringing the total to 33.

Table 2 Basic Mix Proportion of Laminated Rubber Bearing

proportion		Weight Percentage %
Rubber	Natural Rubber	80
	Synthetic Rubber	20
Ferrite		100~400
Coating Material		0~2.5
Carbon-black, Reinforcing Agent		———
Plasticizer		32~48
Vulcanizing Agent		1.9
Antioxident		7.5

Table 3 Factors and Levels of Rubber Mix Proportion

(Weight percentage %)

Factor	Level			
Content of Ferrite A	A_1(100)	A_2(200)	A_3(300)	A_4(400)
Type of Coating Material B	B_1 (AS 80/100	B_2 (AS 200/250)	B_3 (SILICONE-AS)	——
Content of Coating Material C	C_1(0.0)	C_2(1.0)	C_3(2.0)	C_4(3.0)
Plasticizer D	D_1(32)	D_2(48)	———	——

※AS 80/100 : Abbr. for "straight asphalt 80/100" ; 80/100 indicates a penetration of 80/100.
AS 200/250 : Abbr. for "straight asphalt 200/250" ; 200/250 indicates a penetration of 200/250.
SILICONE-AS : A mixture of straight asphalt 80/100 and silicone at the ratio of 95:5.

(3) Test Method

Table 4 lists check items of the rubber material test.

a) Damping Characteristics Test

In this test, a dynamic viscoelasticity measuring and testing machine[14) specifically developed for the measurement of the dynamic behavior of high polymer materials was used. Fig. 2 illustrates the setup of a specimen in a jig. A beam-shaped sample is clamped at its ends, and sinusoidal vibration is given to the center of the sample through a motorized clamp. Thus, by measuring strain, the dynamic modulus of elasticity and the damping factor can be calculated. The sample used measured 50mm x 4mm x 2mm(thickness). The temperature of the specimen was 20 , and the vibration frequencies used were 0.3Hz and 1.0Hz. The sample was clamped at both ends and was measured in the bending mode.

b) Basic Physical Properties

Basic physical properties of the rubber were measured in accordance with JIS K 6301, Physical Testing Methods for Vulcanized Rubber. The tests conducted are (1) hardness test, (2) tensile test and (3) low elongation stress test.

Table 4 Test Items in Rubber Material Test

Test Item	Measured Value	Specimen	Test Method
Damping Characteristics Test	Damping Factor Dynamic Modulus of Elasticity	50mm×4mm×2mm (thickness)	As described separately
Hardness Test	Hardness	Thickness:12mm	JIS K6301(3)
Tensile Test	Tensile Strength Elongation	Dumbell Type 3	JIS K6301(1)
Impact Resilience Test	Stress of 25% Elongation	Strip Type 1	JIS K6301(11)

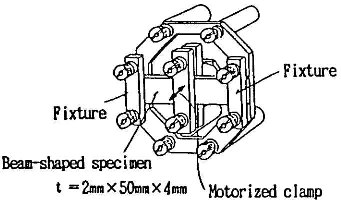


Fig. 2 Outline of Specimen and Jig

(4) Test Results

The variance of test results for the items listed in Table 3 was analyzed. The analysis revealed significant differences between different levels of A (quantity of ferrite), but factors B, C and D and their interaction did not show any significant difference. For the quantity of ferrite that showed significant differences, optimum level was estimated. Fig. 3(a)-(c) illustrate the relations between the damping factor, elongation and stress required for 25% elongation, and the quantity of ferrite. These figures show the range of 95% reliability of the indicated effect at each level.

a) Relationship between Ferrite Content and Damping Factor

Natural rubber has a damping factor of around 3%. This figure shows this damping factor jumps to about 10% if adequate amount of ferrite is added. The damping factor peaks when the ferrite content is between 100% and 200%. It is thought, therefore, that the damping factor does not necessarily become greater even if more ferrite is added.

b) Relationship between Ferrite Content and Elongation

Elongation peaks when the ferrite content is between 100% and 200%, and it tends to become smaller as the amount of ferrite increases. Regardless of ferrite content, however, ferrite-mixed rubber shows extendibility similar that of natural rubber, indicating that the rubber has extendibility adequate for use as material for laminated rubber bearings.

c) Relationship between Ferrite Content and 25% Elongation Stress

Addition of ferrite increases the stiffness of the rubber. Although there occurs no major change at the ferrite contents of 100%-300%, the stiffness increases further when the ferrite content reaches 400%.

Factors B, C and D caused no significant difference among levels. For purposes of comparison, however, the relations between selected damping factors and different levels of these factors are shown in Table 5 and Fig. 3(d) and (c). Here the influence at each level is represented by a point estimation value (simple mean value).

d) Relationship between Types of Coating Material and Damping Factor

Comparison of asphalt 80/100, asphalt 200/250 and silicon asphalt indicated that these coating materials bring similar damping factors.

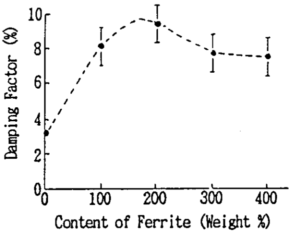


Fig. 3(a) Relationship between Content of Ferrite and Damping Factor

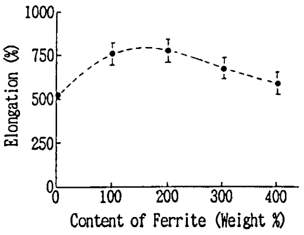


Fig. 3(b) Relationship between Content of Ferrite and Elongation

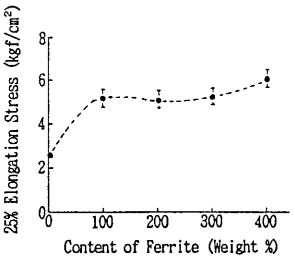


Fig. 3(c) Relationship between Content of Ferrite and 25% Elongation Stress

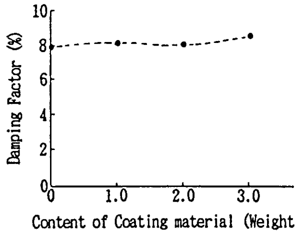


Fig. 3(d) Relationship between Content of Coating Material and Damping Factor

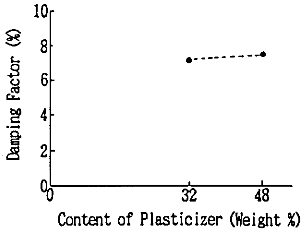


Fig. 3(e) Relationship between Content of Plasticizer and Damping Factor

Table 5 Relationship between Types of Coating Material and Damping Factor

Type of Coating Material	AS 80/100	AS 200/250	SILICONE-AS	Non-Coating
Damping Factor(%)	8.3	8.3	8.2	8.0

e) Relationship between Coating Material Content and Damping Factor

Four coating materials contents of 0%, 1%, 2% and 3% brought similar damping factors. This indicates that the quantity, or even the existence, of ferrite does not significantly affect the damping factor.

f) Relationship between Plasticizer Content and Damping Factor

The quantity of plasticizer did not significantly affect the damping factor.

3. MECHANICAL PROPERTIES of FERRITE RUBBER BEARING

On the basis of the results of analysis of mix proportions for the ferrite rubber, full-scale laminated rubber bearings were made. The performance of the bearings was verified through dynamic tests with an actuator.

(1) Specimens

Prepared for the testing are laminated rubber composed mainly of natural rubber (hereafter referred to as "Natural Laminated Rubber") and laminated rubber containing ferrite (hereafter referred to as "Ferrite Laminated Rubber"). Natural rubber was assumed in the design of laminated rubber, and the design vertical load was set at 30tf. The horizontal spring constant was set at 0.3tf/cm so that the natural period became two seconds or so. In the design, the target values of horizontal deformation capacity and vertical spring constant were set at 15cm or more and 150tf/cm (500 times as high as horizontal spring constant) or more, respectively.

The configuration of the laminated rubber bearing thus designed is shown illustrated in Fig. 4. The laminated rubber (both natural rubber and ferrite rubber) is an alternate lamination of rubber sheet (twenty-four x 5mm thick layers) and steel plate (twenty-three x 2.3mm thick layers), and was pressurized, vulcanized and formed in a mold.

(2) Mix Proportions of Laminated Rubber

The mix proportions of the laminated natural rubber bearing and the laminated ferrite rubber bearing prepared as specimens are shown in Table 6. The mix proportions of the natural rubber bearing are the ones already proven in actual base isolation systems. Five types of laminated ferrite rubber bearings were prepared on the basis of the results of the rubber material test. Shown in the table are the mix proportions of F1 and F2, which are considered to be

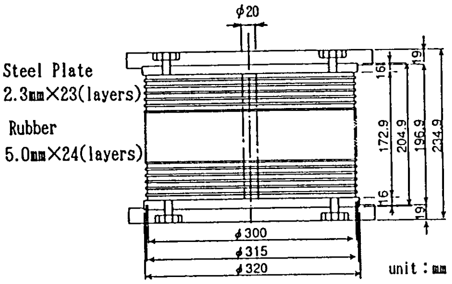


Fig. 4 Device Using Laminated Ferrite Rubber for Tests

Table 6 Mix Proportion for Laminated Rubber Bearing

(Weight Percentage %)

Type / proportion		Natural Rubber	Ferrite Rubber	
		NR	F1	F2
Rubber	Natural Rubber	100	80	80
	Synthetic Rubber	—	20	20
Ferrite		—	200	100
Coating Material		—	1.5	—
Carbon-black, Reinforcing Agent		33	27	27
Plasticizer, Antioxident		44	9.7	41
Vulcanizing Agent		5.0	2.9	4.3

representative. Since F1 is designed for reinforcing effect, it does not contain carbon black. F1 contains only a minimum amount of plasticizer because asphalt coating of ferrite offers adequate flexibility.

Uncoated ferrite was used in F2 because in the rubber material test, the damping factor and elongation were hardly affected by coating. Since F2 was prepared by adding ferrite to the natural rubber mix, it does not differ substantially from the natural rubber mix.

(3) Test Method

In the test, the loading system used is showned in Fig.5. The loading system is designed to impose dynamic horizontal shear deformation with an actuator, while maintaining vertical load. In the test, horizontal vibration (0±300mm, 0-4Hz, 0-60tf) was produced under vertical load (0-150tf). A laminated rubber bearing subjected to a large shear deformation is shown in Photo 2.

Test items are as follows:
a) Damping characteristics
b) Influence of horizontal amplitude on restoring force characteristics
c) Influence of frequency on restoring force characteristics
d) Influence of vertical load on restoring force characteristics
e) Vertical deformation characteristics
f) Horizontal deformation characteristics

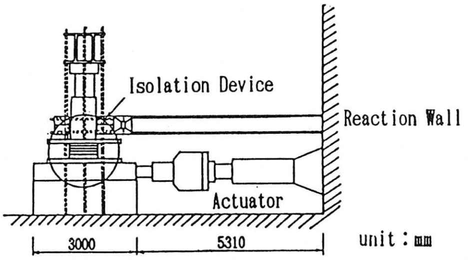


Fig. 5 Testing Equipment
for Dynamic Characterisitics

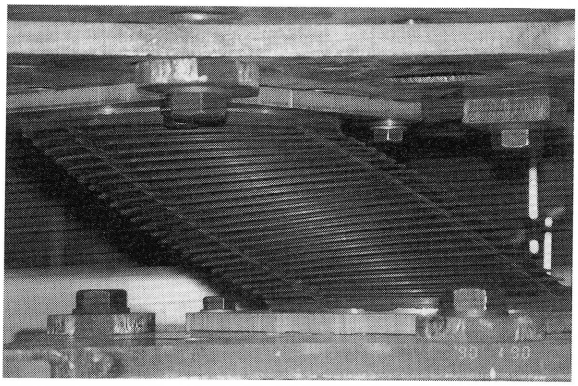


Photo 2 Dynamic Loading Test
for Laminated Rubber Bearing

(4) Test Results

a) Damping Characteristics

Horizontal vibration (horizontal amplitude 150mm, frequency 0.5Hz, vertical load 30tf) was given to each rubber bearing. Equivalent damping factors determined from the observed hysteresis loop for each rubber bearing are shown in Table 7. Equivalent stiffness is defined as the gradient of a straight line connecting the maximum deformation point and the origin. Equivalent damping factor was determined from the inner area of hysteresis loop.

The damping factor for the natural rubber was around 3%, while that of the ferrite rubber was two or three times higher. Above all, F2 showed the highest damping factor of about 11%.

The damping factor of F1 and F2 do not differ substantially. Therefore, the restoring force characteristics of F2, which were regarded as representative of the restoring force characteristics of the ferrite rubber, were used for comparison with the natural rubber. Characteristics of the ferrite rubber as compared with those of the natural rubber are described below.

Table 7 Relationship between Types of Rubber and Damping Factor

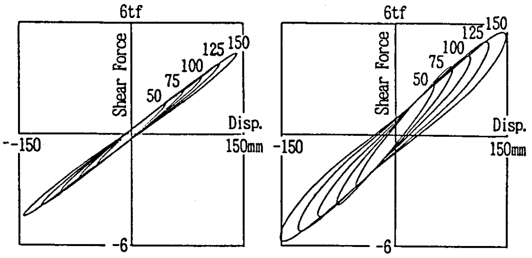
Rubber	Natural Rubber	Ferrite Rubber	
	NR	F1	F2
Damping Factor(%)	3.0	10.1	10.9

※ Conditions : horizontal amplitude 150mm frequency 0.5Hz
vertical load 30tf

b) Influence of Horizontal Amplitude on Restoring Force Characteristics

Fig. 6 shows the relationship between horizontal load and horizontal displacement of natural rubber (NR) and ferrite rubber (F2) under increasing cyclic horizontal amplitude. Maintaining frequency and vertical load at 0.5Hz and 30tf respectively, the horizontal amplitude was changed within the range of ±50-±150mm so that the shear strains in rubber of about 40-125% were simulated.

The stiffness and hysteresis loop of the natural rubber hardly changed even when displacement became greater. By contrast, the stiffness of the ferrite rubber decreased as horizontal displacement increased, and both equivalent stiffness and equivalent damping factor showed dependence on displacement. The hysteresis loop of the ferrite rubber showed smooth curves, indicating that it has a greater energy absorption capacity than NR even at low levels of displacement.



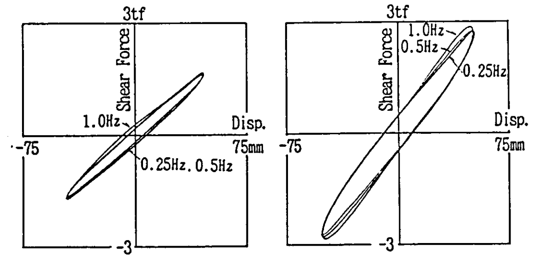
(a) Natural Rubber(NR) (b) Ferrite Rubber(F2)

Fig. 6 Influence of Horizontal Amplitudes on Restoring Force Characteristics

c) Influence of Frequency on Restoring Force Characteristics

Fig. 7 shows the relationship between horizontal load and horizontal displacement under different excitation frequencies. Maintaining horizontal amplitude and vertical load at ±50mm and 30tf respectively, frequency was set at 0.25Hz, 0.5Hz and 1.0Hz.

The stiffness of the natural rubber and the ferrite rubber hardly changed even at higher frequencies, but the inner area of hysteresis loop somewhat increased as frequency rose. Conversion to equivalent damping factor indicates that the inner area at 1.0Hz is 10% larger than at 0.25Hz.



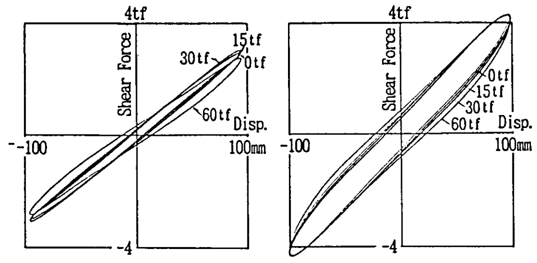
(a) Natural Rubber(NR)　　(b) Ferrite Rubber(F2)

Fig. 7 Influence of Frequency on Restoring Force Characteristics

d) Influence of Vertical Load on Restoring Force Characteristics

Fig. 8 shows the relationship between horizontal load and horizontal displacement of both natural rubber and ferrite rubber under changing vertical load. Maintaining horizontal amplitude and frequency at ±100mm and 0.5Hz respectively, vertical load was set at 0tf, 15tf, 30tf and 60tf.

Stiffness decreased slightly as vertical load increased. This is considered to be because of a not-so-high secondary shape factor (diameter/total rubber thickness) of 2.5. Both natural rubber and ferrite rubber showed this tendency.



(a) Natural Rubber(NR)　　(b) Ferrite Rubber(F2)

Fig. 8 Influence of Vertical Load on Restoring Force Characteristics

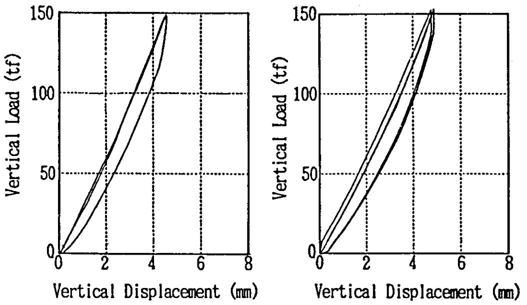
e) Vertical Deformation Characteristics

Fig. 9 shows the relationship between vertical load and vertical displacement of both natural rubber and ferrite rubber under vertical load. Three loading cycles were repeated while vertical load was changed from 0 to 150tf (vertical stress=212kgf/cm^2).

The load-displacement curves are close to straight lines at the loads of 0-150tf, and the gradient can be regarded as almost linear. Although vertical load of up to five times as high as the design load was applied, residual displacement in both natural rubber and ferrite rubber after unloading was very small. Vertical spring constants for the natural rubber and the ferrite rubber were about 300tf/cm (about 1,000 times higher than in horizontal direction) and about 320tf/cm (about 700 times higher than in horizontal direction) respectively, indicating their extremely high vertical stiffnesses.

f) Horizontal Deformation Characteristics

Fig. 10 shows the relationship between horizontal load and horizontal displacement of both natural rubber and ferrite rubber observed in the horizontal strength test. Maintaining vertical load at 30tf, horizontal displacement was changed from 0 to 250mm statically. The stiffness of the ferrite rubber fell slightly as the displacement exceeded 50mm, but the increase was almost linear and, as in the case of the natural rubber, hardening was not observed in this range. At the maximum displacement of 250mm, shear strain was about 210% and local shear strain including strain under vertical load reached about 400%; however, rubber deformation and rubber-metal bonding surfaces showed no signs of abnormality, indicating stable deformation capacity. The effective area of overlapping surfaces was about 8% of the area of laminated rubber surface, which was enough to carry the vertical load of 30tf.



(a) Natural Rubber(NR)

(b) Ferrite Rubber(F2)

Fig. 9 Relationship between Vertical Load and Vertical Displacement

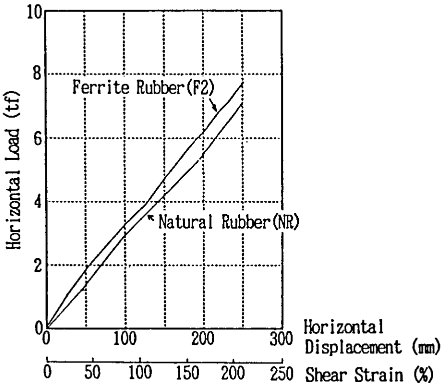


Fig. 10 Results of Horizontal Deformation Capacity

4. LAMINATED FERRITE RUBBER ENDURANCE TEST

To examine the endurance of laminated rubber, a compression creep test and a cyclic horizontal loading test were performed.

(1) Test Method

a) Creep Test

The creep test was performed using the laminated natural rubber and the laminated ferrite rubber used in the mechanical property test. As illustrated in Fig. 11, the testing apparatus used consisted of steel bars for prestressed concrete, couplers, a oil pressure jack and a load cell. Each set of testing apparatus was placed in a room kept at 20℃. A constant compressive load of 30tf ($P=42kgf/cm^2$ in terms of compressive stress), which equals to the design load, was applied after the temperature of the laminated rubber and the jig reached a predetermined level. This measurement was carried out continually for the period of one month. Each specimen was equipped with three displacement gauges, which were installed between flanges of laminated rubber, and displacements measured by those gauges were averaged.

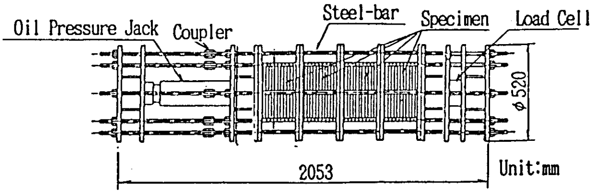


Fig. 11 Apparatus for Creep Test

b) Cyclic Horizontal Loading Test

The cyclic horizontal loading test was performed using the above-mentioned compression/shear tester. Five-hundred cycles of excitation was applied continually at horizontal amplitudes of ±100mm (shear strain in rubber: about 83%), frequency of 0.5Hz and the vertical load of 30tf. Internal temperature of the laminated rubber bearing during excitation was measured with thermometers embedded in the rubber.

(2) Test Results

a) Creep Test

Results of the creep test are shown in Fig. 12. As shown, the rates of progress of creep in both natural rubber and ferrite rubber changed in the logarithmic diagram one day or so after the test began. It is indicated that creep progressed rapidly at first, but the rate of progress fell about one day after the test began. It is also indicated that the relationship between the amount of creep and elapsed time as plotted on the log-log scale shows a close resemblance to a straight line. The amounts of creep 60 years later estimated by extrapolation were about 0.3mm for the laminated natural rubber and about 0.4mm for the laminated ferrite rubber. Since the total thickness of rubber is 24 layers x 5mm = 120mm, the amount of creep is 0.3-0.4% of the rubber thickness. Values of measured creep were rather small probably because the test was conducted at room temperature under relatively low bearing stress. It is thought, however, that laminated ferrite rubber develops a little more creep than laminated natural rubber, but will still be small enough to permit long-time use.

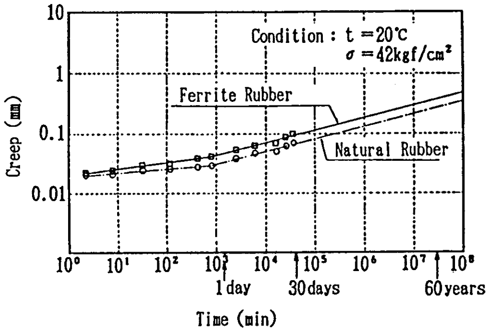


Fig. 12 Results of Creep Test

b) Cyclic Horizontal Loading Test

Relations between the number of cycles and rises in internal temperature are shown in Fig. 13. Excitation caused rises in internal temperature of both the natural and ferrite rubbers: about 15℃ for the natural rubber and about 20℃ for the ferrite rubber after 500 cycles of excitation. Since the rubber material in the laminated ferrite rubber has a damping effect, internal temperature rise in the ferrite rubber is greater than in the natural rubber. As the number of major vibration cycles in an actual earthquake is considered to be 10 or so at most, temperature rise should be 3℃ or less.

Changes in equivalent stiffness and equivalent damping factor of laminated ferrite rubber under cyclic load are shown in Fig. 14. The figure indicates that the stiffness and the damping factor are hardly affected by the number of loading cycles, indicating the stability of rubber material. Taking this into consideration with the above-mentioned temperature rise in the rubber, it can be considered that rubber is not affected by temperature.

To confirm this, relations between the equivalent damping factor and temperature of rubber material in specimen F2 was examined using the damping characteristic tester mentioned in Section 2 for the rubber material shown in Fig. 2. Results are shown in Fig. 15. Three excitation frequencies of 0.3Hz, 1.0Hz and 10Hz were used, and temperature was changed within the range between -80℃ and +80℃ . Test results indicates that the damping factor peaked at around -30℃ . The modulus of elasticity increases monotonously as temperature decreases. Considering the range of operating temperature, it can be said that both equivalent damping factor and elastic modulus remain almost constant under normal operating conditions.

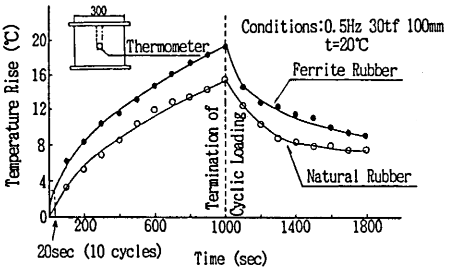


Fig. 13 Internal Temperature Rise under Cyclic Loading Test

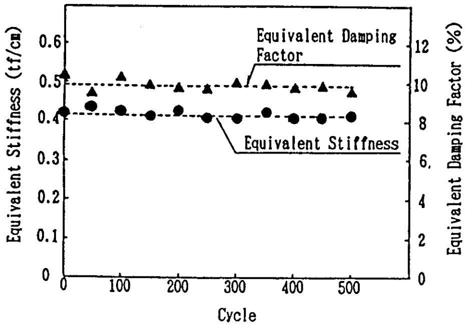


Fig. 14 Results of Cyclic Loading Test (Laminated Ferrite Rubber)

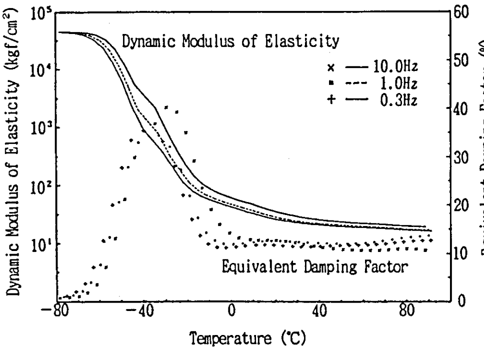


Fig. 15 Temperature Characteristics of Ferrite Rubber (Modulus of Elasticity and Equivalent Damping Factors)

5. CONCLUSION

Physical tests for rubber mixed with ferrite were performed so as to determine the mix proportions that satisfy the requirements of high damping rubber. Full-scale high damping rubber bearing models were prepared, and physical tests were conducted under conditions under which an actual base isolation system is expected to operate. Findings from these tests can be summarized as follows:

(1) High damping rubber could be obtained by mixing rubber with ferrite.

(2) A factor that greatly affects damping performance is the content of ferrite, and the damping factor is maximized at a ferrite content (by weight against rubber) of around 200%. As the ferrite content increases, stiffness increases and elongation decreases. Therefore, if rubber is to be used in the form of laminated rubber bearings, the ferrite content should be 100-200%.

(3) Within the normal range of horizontal displacement, the stiffness of the laminated ferrite rubber tended to decrease as the horizontal displacement increased, indicating influences of shear strain. The damping factor of the ferrite rubber during major deformation was about 11%, which was three or four times as high as that of the natural rubber. Thus, stable and smooth restoring force characteristics for very small to large amplitudes were confirmed.

(4) Influence of vertical load and frequency on the restoring force characteristics of the laminated ferrite rubber is similar to that of the laminated natural rubber.

(5) A shear test under constant vertical load using a full-scale laminated rubber bearing model confirmed the followings:
  (i) Vertical load carrying capacity (5 times as large as design load)
  (ii) Capacity for major deformation (shear strain γ=200%)
  (iii) Stability under cyclic load (n=500 cycles)
  (iv) High damping performance (h=10% or above)

From above, it has been confirmed that the laminated ferrite rubber can serve as high damping rubber combining the performances of isolator and damper.

(6) Creep resistance of the laminated ferrite rubber is 1.2-1.4 times as high as that of the laminated natural rubber. This indicates that the ferrite rubber can sufficiently endure sustained load with minimum creep.

6. CLOSING REMARKS

A large number of studies on high damping laminated rubber are now under way, and some ideas are already being put into practice. The newly developed laminated ferrite rubber, which has been prepared by adding ferrite to a proven base mix of natural rubber, shows stable behavior similar to one of natural rubber. The ferrite rubber can be produced just as natural rubber is produced, and the fact that there is an ample supply of ferrite byproducts is one of the favorable aspects. The authors sincerely hope that this study will help to improve techniques for using ferrite byproducts[15] and promote the practical use of base isolation technology.

The authors would like to take this opportunity to express hearty thanks to Professor Emeritus Keizaburo Kubo of University of Tokyo, for his invaluable advice on this development, and to the staff of Nichireki Chemical Industry Co., Ltd. for the kind assistance in the manufacture and testing of rubber used in the study. Special thanks also go to the staffs of The Tokyo Electric Power Company, Inc. and Okumura Corporation.

REFERENCES

1) Technology Research Center for National Land Development , Survey Report on Base Isolation Systems for Bridges in New Zealand, Study Mission of the Research Committee on the Seismic Design of Highway Bridges Equipped with Base Isolation Systems, 1987.
2) Technology Transfer Institute, Survey Report on Seismically Isolated Structures in the Western Countries, 1986.
3) Takeuchi, M., Utilization of Base Isolation Systems, JSCE, Vol. 71, No. 4, pp. 56-57, 1986.
4) Horiguchi, J., Kaizu, N., and Mashiba, J., Development of Base Isolation System for Transforming Equipment, 7th Japan Earthquake Engineering Symposium, pp 1645-1650, 1986.
5) Takeuchi, M., Harada, O., et al., Base Isolation System and Its Verification Experiment, The Thermal and Nuclear Power Generation, Vol. 38, No. 5, pp. 37-47, 1987.
6) Suzuki, H., Takeuchi, M., et al., Fundamental Studies on Optimum Design for Base Isolation Devices, Journal of Structural Engineering , Vol. 35A, pp. 621-627, 1989,JSCE.
7) Suzuki, H., Takeuchi, M., et al., Experimental Study on Base Isolation Systems for Electric Power Facilities, Proc. 20th JSCE Earthquake Engineering Symposium, pp. 493-496, 1989.
8) Mayama, M., Vibration Characteristics of Coated Ferrite Concrete, Proceedings of JSCE, No. 384/V-7, pp. 93-101, 1987.
9) Mayama, M., Vibration Characteristics and Mechanical Properties of Ferrite-Epoxy Mixtures, Proceedings of JSCE, No. 385/VI-7, pp. 59-68, 1987.
10) Suzuki, H., Kubo, K., Takeuchi, M., and Mayama, M., Vibration Energy Absorption Material and Equipment, Patent Gazette (A), 1990-190633, 1990.
11) Taguchi, G., Experimental Design Method (New Ed.) Part I and II, Maruzen, 1962.
12) Taguchi, G., Orthogonal Table and Line-Dot Diagram, Maruzen, 1962.
13) Washio, Y., Introduction to Experimental Design Method, Japanese Standards Association, 1988.
14) Nichigo Shoji, PL-DMTA Technical Data.
15) Mayama, M., and Yamauchi, F., Application of Ferrite Byproducts in Civil Engineering, JSCE, Vol. 72, No. 5, pp. 35-40, 1987.