where

$$\left.\begin{aligned}\tan\psi''&=x\sqrt{\frac{a+b}{a-b}}=\sqrt{\frac{a+b}{a-b}}\tan\frac{\varphi_a}{2}\\ \sin^2\alpha&=1-\frac{a-b}{a+b}=\frac{2b}{a+b}\end{aligned}\right\}\cdots\cdots\text{(App. 4')}$$

therefore

$$\mathbf{Y}=\frac{2\sqrt{a+b}}{b}\{K(\alpha)-E(\alpha)-F(\alpha,\psi')+E(\alpha,\psi')\}-\frac{2}{\sqrt{a+b}}F(\alpha,\psi'')\quad\cdots\cdots\text{(App. 5)}$$

when $\varphi_a=\pi$ then $\tan\psi'=0$, $\tan\psi''=\infty$

$$(\mathbf{Y})_{\varphi_a=\pi}=\frac{2\sqrt{a+b}}{b}\{K(\alpha)-E(\alpha)\}-\frac{2}{\sqrt{a+b}}K(\alpha)=\frac{2a}{b\sqrt{a+b}}K(\alpha)-\frac{2\sqrt{a+b}}{b}E(\alpha)\quad\cdots\cdots\text{(App. 6)}$$

OIL-RESISTANT RUBBER PACKING

By

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I. FOREWORD

Packing is used everywhere not only in electrial machines or chemical apparatus but also in articles of daily use. We know "packing" is so familiar when we remember in our home that bottle for medicine or cosmetics has packing made of rubber or vinylresin inside its cover preventing inner substance to leak. We find its important service when we take a cup of beer and imagine if a cork packing within the lid of container becomes useless, how untasteful the drink would be.

In the same manner, packings are indispensable in the electrical machine, and it is difficult to find any machine without packing. In spite of its importance, the research about the functionality and material of packing had been apt to be forgotten for the reason of its non-attractive work. But to-day higher grade characters are required about electrical machines, and the research has been making a progress to know how to use and what kind of material should be used for packing, and recently we can find some reports about packing in bulletins of many countries.

In this article I will explain about characters of the oil-resistant rubber packing, utilized for transformer or other oil-immersed type electrical machines, quoting our experiments about its elastic behavior.

II. CHARACTERS NECESSARY FOR THE OIL-RESISTANT RUBBER PACKING

Oil-resistant rubber packing employed in electrical machine should have many characters, although some of these are not always necessary for one machine or one characteristic is especially important for other machine.

Necessary characters are as follows:

1. Low permanent compression set

Permanent compression set is defined as plastic deformation of packing which occurs when packing is used for a long time. The stress, necessary for initial strain, decreases as time elapses. The worst happens when the stress becomes zero owing to perfect plastic deformation and functionality of packing is completely lost. The contrast to this case is that when the compressive stress keeps its initial value. This is when packing is perfectly elastic. Actual packing cannot be perfectly elastic, and so we are obliged to say that the more elastic, the better. For this reason low permanent compression set is desirable not only for the oil-resistant type but also for the others in general.

2. Low swelling when immersed in insulating oil

Large swelling of rubber packing results in the loss of functionality of packing owing to slip out of the packing, and in an extreme case, destruction of machine occurs by swelling pressure. In physicochemical sense the oil resistance of rubber is that rubber does not swell and lose its mechanical strength, owing to the diffusion or permeation of oil molecules in rubber. Accordingly, low swelling is indispensable as rubber packing. But as the measurement of swelling is rather difficult, weight increase by immersion in oil is measured for convenience as an estimation of the oil resistance, and low weight change is desirable for oil-resistant rubber packing.

3. Low soluble ingredient and none injurious soluble matter

Rubber itself and many ingredients may be soluble in insulating oil except carbon black, but about rubber I will mention in the following chapter. Some of the ingredients react with rubber molecules, and none reactive matters such as plastisizers and lubricants come in question. These are necessary for synthetic and natural rubber compounding, and so we should pay attention not to use soluble plastisizers or lubricants. Even if, these are partly soluble, solute is not harmful to insulating oil and other materials.

4. Heat resistance

Packing for electrical machines should be heat-resistant for the reason that temperature rise of machine such as transformer is considerably high in its use. Of course chemical change of packing rubber may not occur except natural and some synthetics, but low compression set, low swelling and low solubility at high temperature, 100°C or so, are necessary for packing rubber. For many packings one side comes in contact with insulating oil, and the other side with hot air, and so we should pay attention to deterioration of rubber in comparatively high temperature air.

Above four characters are indispensable commonly to oil-resistant rubber packing. In addition to these followings are also necessary in general.

5. Low permeability of gases

Some electrical apparatus are enclosed with inert gases in these, and the packings for these should have low permeability of gases not to leak out the inner gas or not to diffuse in the outer air.

6. Resistance to oxidizing gases

Near electrical machine, oxidizing gases such as ozone and nitrogen oxide may exist to some extend, and so packing should be resistant to oxidizing gases.

7. Weathering proof

For outdoor use endurance to weathering is necessary for packing.

The characters enumerated above are required when packing are in use, but some others are important when machines are under construction. These are following ;

8. High mechanical strength or high deformation at rupture

In some cases considerably large deformation is required for packing in the construction, and for this reason high tensile, high compressive or high shear strength and also high deformation at rupture are necessay characters.

9. Proper elastic modulus or proper relations between compressive stress and strain

In relation to flange and stopper size proper elastic modulus or proper relations between compressive stress and strain are required by packing design.

10. High tear resistance

If tear strength of packing is weak, rupture may happen when machine is constructed, and so this character is essential.

11. Smooth surface

The surface of packing should be smooth, for if it is uneven, compressive stress at the surface cannot be uniform and excessive stress may be necessary to attain its aim. This is not only wrong, but occasionally packing is destroyed.

12. Easiness to adhere and high adhesive strength

Though not always required, easiness of adhesion is necessary sometimes. When adhesion of rubber packings to each other is necessary, each of them adhere better before vulcanization, but in some instance adhesive agent may be used, and so easiness to adhere and high adhesive strength are indispensable.

13. High accuracy of dimensions

Even though accuracy of dimensions cannot be expected so high as metal parts, considerably high accuracy is desirable especially about construction of accurate machines.

In addition to the above necessities, inflammability or resistance to chemicals of rubber packings is wanted in some case.

III. OIL-RESISTANT RUBBER

As everybody knows rubber packing is generally vulcanized after mastification and compounding raw rubber with carbon black, vulcanizer, accelerator and lubricant etc. The above mentioned characters necessary to oil-resistant rubber packing depends especially upon the kind of rubber and selection of ingredients.

1. Relation between the kind of raw rubber and oil-resistance

As packing for electrical machine, natural and synthetic rubbers are utilized in compliance with a purpose. Elastomers or materials of rubber elasticity can be classified chemically as follows :

1) Polyisoprene—natural and synthetic natural rubber
2) Polybutadiene—Buna etc.
3) Polybutadienestyrene—GR-S, Buna S etc.
4) Polybutadieneacrylnitrile—Hycar OR, Buna N etc.
5) Polyisobutyleneisoprene—Butyl rubber etc.
6) Polychloroprene—Neoprene WRT etc.
7) Polyacrylic rubber—Hycar PA etc.
8) Polyester-isocyanate—Moltprene etc.
9) Polysulphide rubber—Thiokol etc.
10) Silicon rubber
11) Fluoro carbon rubber

Of these elastomers, those which have oil affinitive molecular groups such as methyl or phenyl radical are apt to swell by insulating oil. Namely 1), 2), 3), 5) and 10) of the above Numbered are easy to swell. Contrast to these, oil exerts no influence upon those which have non oil affinitive molecular group or atom such as nitrile radical, ester or halogens. Accordingly, oil-resistant rubber should be selected from those except 1), 2), 3), 5) and 10). In those kinds there is Polychloroprene, which is of high mechanical strength and especially of good endurance, but swelling grade in insulating oil increases as temperature becomes high, so this rubber should be excluded from oil-resistant rubber for packing. Also 7) Polyacrylic rubber tends to have higher permanent set at high temperature, and about 8) Polysulphide rubber, sulphur in it may be corrosive to copper and insulating oil, and 11) Fluoro carbon rubber is yet too expensive to use in general. As the result 4) Polybutadieneacrylnitrile rubber (nitrile rubber) and 8) Polyester isocyanate rubber are the most desirable. The latter suits conveniently as sponge rubber, and so the former is used as general oil resistant packing. Copolymerization ratio of butadiene and acrylnitrile of nitrile rubber is different from one manufacturer to the other. If the content of acrylnitrile becomes higher, oil resistance is improved, though the compounding becomes less workable. The other character such as average molecular weight and the distribution of molecular weight etc. affect compounding characteristics, and so from the economical point of view, selection which type of nitrile rubber may be used should be done considering these situations.

2. Compounding and vulcanization

As mentioned before, carbon black, sulphur, sulphur compounds, zinc oxide, stearin and plastisizers are used as ingredients of compounding nitrile rubber. Selection of these ingredients is important to expect a high quality of packing. For instance carbon black such as EPC, HAF and SRF etc. are utilized, and as packing we should pay attention to reinforcing character of carbon black for comparatively high compressive deflection in its use.

For heat resistance, compounding ratio of sulphur and vulcanization accelerators, and also selection of these accelerators are important. Comparatively low sulphur compounding is desirable from this point, and at the same time attention not to debase mechanical strength should be taken care of.

Plastisizers are apt to dissolve in oil, and so low solubility and higher molecular weight of plastisizer are significant.

After determination what kinds of ingredient are used, and what ratio are the best, high manufacturing technique and quality control are indispensable, especially at vulcanization process of rubber packings.

3. Test of rubber packings

There are many kinds of form about rubber packing, and selection of rubber, compounding and also forming such as molding or extruding etc. are different from one to the other. For this reason test of rubber packings is inevitable and important. The ASTM methods of testing rubber products are

Table 1. An example of specification for oil-resistant rubber packing

Terms	Specification
External appearance	Smooth surface, uniform color and none foam at a section are necessary.
Hardness	Decided hardness is necessary.
Compressive deflection	Decided deflection is necessary at a standard compressive load.
Permanent compression set	Maximum allowable set value is decided.
Weight change immersed in oil and character of the oil after used	Maximum allowable weight change is decided. Acid value and color etc. is decided about oil.

Table 2. Standard tolerances

(unit: in)

Terms	Range of dimension	Tolerance
Direction perpendicular to parting line (Molding products)	up to ½	±0.010
	above ½ up to 1	±0.015
	above 1 up to 2	±0.031
	above 2 up to 3	±0.046
Directions except along the length (Extruding products)	up to ¼	±0.015
	above ¼ up to ½	±0.031
	above ½ up to 1	±0.046
	above 1 up to 2	±0.062

convenient and put in practice in the world. We have decided test methods and specifications in accordance with these, considering about characters already mentioned in the second chapter of this article. For reference we quote an example of specification for nitrile rubber packing in Table 1 and standard tolerances in Table 2.

IV. PERMANENT SET OF OIL-RESISTANT RUBBER PACKING

Of the characters necessary to oil-resistant packing, I will explain here experiments and consideration about permanent set character as one of the most important points. When rubber packing is used the stress caused by pressure in the rubber restrain an electrical machine from leak out of the inner oil, and if the stress becomes low, the probability of leak out of inner oil becomes great. For this reason we must pay attention upon stress relaxation character about rubber packing. I will explain a behavior of rubber as a result of experiment. Please look at the figure 1. In the upper parts of the figure variation of thickness and stress of packing rubber are indicated, and in the lower parts experimental process is explained. At first the thickness of the sample rubber is measured as *d*.—in this experiment plate form of rubber was used—, then the sample is immersed in insulating oil at 100°C. As time elapses the thickness of rubber increases owing to heat and oil to some extent. After immersion treatment in oil I pich up the sample from the oil and cool to room temperature and again measure the thickness. Some increase of the thickness is observed. This increase is indicated as α in the figure. Concretely this increase is up to 1% about good oil resistant rubber by treating rubber in oil at 100°C for 48 hours. Then the sample is compressed to about 70% of the initial thickness with metal stoppers not to overload the packing—this is also considered in real machine—. The deflection is indicated in the figure as ε. Inner stress σ_0 following outer compression originate in the sample. This value is

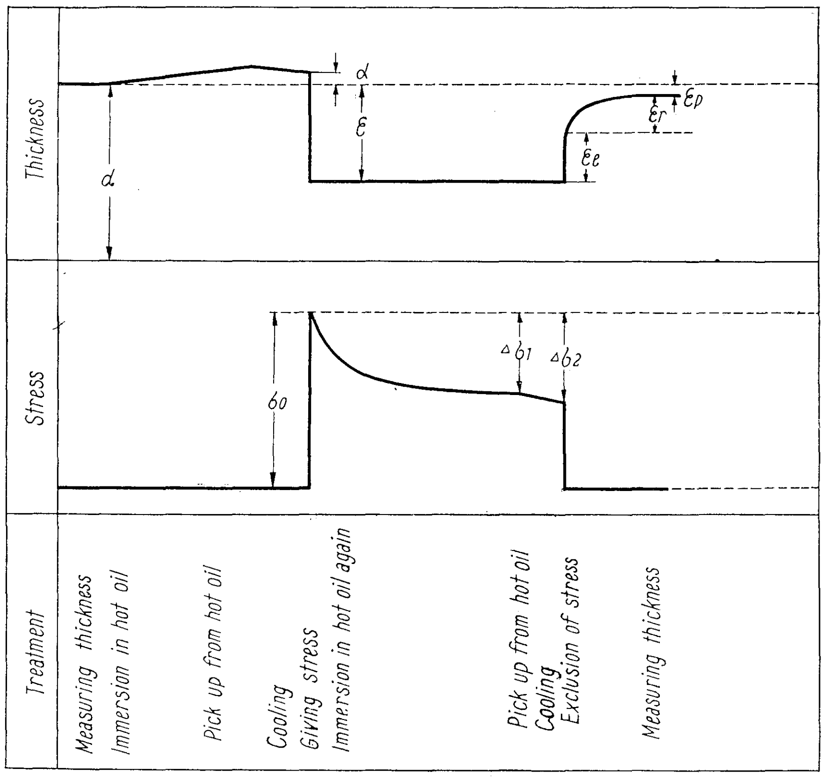


Fig. 1. Variation of thickness and stress during the test of compression set

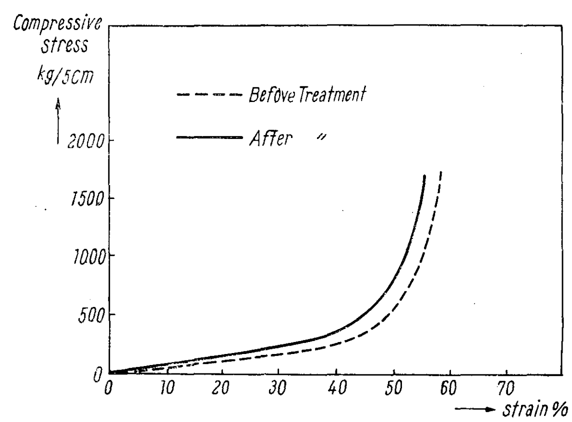


Fig. 2. Compressive stress-strain relation

different from packing to packing according to the kind of rubber, compounding and form etc., and I will show an example of compressive stress strain character of O-ring type packing in the figure 2. In this you can see the grade of stress according to strain. In the figure two curves are shown ; one is before oil immersion and other after immersion. This results indicate the stress necessary to attain a required deflection. Return to the first experiment in the figure 1. The deflection ε is kept constant value by metal stoppers, but the stress becomes lower as time elapses. This phenomena is the stress relaxation. This relaxation has a spectra about each rubber, but we can show it approximately as next formula :

$$\sigma_t = \sigma_0 \ e^{-\int \frac{t}{\tau} d\tau} \qquad \cdots\cdots(1)$$

In the formula

σ_t = the stress at time t

$$\tau = \eta / G \qquad \cdots\cdots(2)$$

η = Viscosity

G = Modulus

From this relation after treatment of oil immersion for t hours, decrease of the stress $\Delta\sigma_1$, noted in the figure 1, is shown as follows :

$$\Delta\sigma_1 = \sigma_0 \ (1 - e^{-\int \frac{t}{\tau} d\tau}) \qquad \cdots\cdots(3)$$

This value becomes $\Delta\sigma_2$ when the sample cools. When I exclude compressive load, inner stress becomes zero and the thickness recovers instantly to some extent. This recovery may be complete by ideal elastic materials, but in real packing rubber this recovery is not complete and its grade ε_e is not equal to initial deflection ε. Continuously when we observe the behavior of rubber after the first recovery ε_e, we will find that recovery increases as time passes. This is an retarded elastic recovery, and if we mark it as ε_r, ε_r may be shown as a function of time ; $\varepsilon_r\ (t)$*. The formula (4) is defined as permanent compressive set.

$$\varepsilon - [\varepsilon_e + \varepsilon_r \ (\infty)] \qquad \cdots\cdots(4)$$

But in practice instant elastic recovery ε_e is important and also considering experimental difficulty, we adopt the next expression as the set.

$$\varepsilon - [\varepsilon_e + \varepsilon_r \ (t \approx 0)] \qquad \cdots\cdots(5)$$

In experiment and test one minutes or so may be selected as time t (≈ 0)*.

I will show an experiment of the situation of these behavior in the figure 3 after an oil-resistant rubber of hardness 60 is immersed in hot oil at 100°C

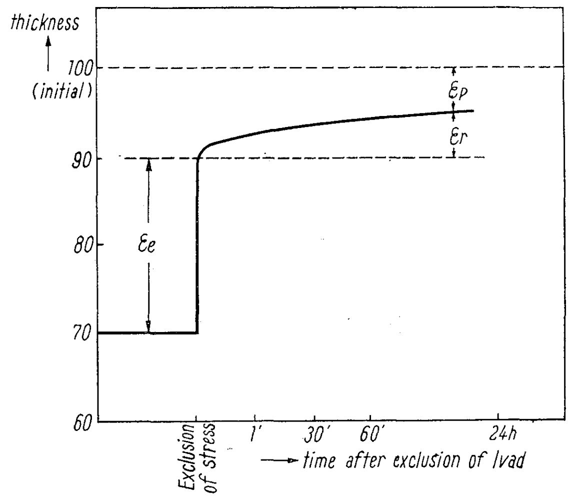


Fig. 3. Recovery of compressive strain

for 336 hours and the load is excluded. In this I show a recovery of thickness as time goes.

Also we must pay attention to $\Delta\sigma_1$, because the inner stress is $\sigma_0 - \Delta\sigma_1$ at time t, and by this stress leakage of oil can be stopped. The less the stress decrease $\Delta\sigma_1$, the better the functionality of packing. The stress decrease $\Delta\sigma_1$ is most important, but to measure it or $\sigma_0 - \Delta\sigma_1$ is difficult, and so measuring the set $[\varepsilon - \{\varepsilon_e + \varepsilon_r \ (t \to 0)\}]$ corresponding to the stress $\sigma_0 - \Delta\sigma_1$ becomes indispensable for the purpose to estimate the quality of rubber packing.

The above mentioned behavior of rubber can be considered conveniently using the four element model of viscoelastic material indicated in the figure 4.

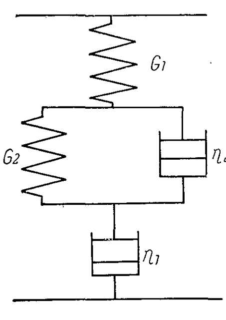


Fig. 4. The four element model of Viscoelastic material

The model consists of a spring (modulus G_1), parallel component of another spring (modulus G_2) and a dashpot (viscosity η_2), and another dashpot (viscosity η_1). These three correspond each other to instant elastic recovery, retarded elastic recovery, and permanent set or plastic deformation. To minimize permanent set no last dashpot is desirable, that is to say viscous quality η_1 is none about real packing rubber.

In the test of packing rubber we express the following formula as a measure of compressive permanent set in per cent for convenience.

* In these expression time t is measured from the time of exclusion of compressive load, and it is different from t in the formula (1) or (3).

$$\frac{\varepsilon - [\varepsilon_e + \varepsilon_r\ (t=\text{one minute})]}{\varepsilon} \times 100$$
$$= \frac{\varepsilon_p}{\varepsilon} \times 100 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Also I show another experiment. In this three rubber packing plate were used, one of which was of the worst quality, and the other two comparatively good. The samples were compressed to 70% of initial thickness, and immersed in hot oil at 100°C continuing for a few weeks. After each week, permanent sets expressed by the formula (6) were measured. The results are indicated in the figure 5.

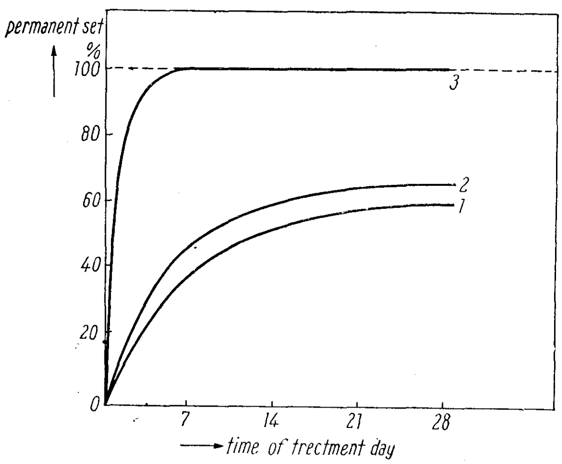


Fig. 5. Relation between time of treatment and compression set

In the figure (3) is the worst, and the other good samples keep about one third of initial elasticity. This means approximately that initial stress σ_0 of following formula (7) may satisfy the rubber packing design.

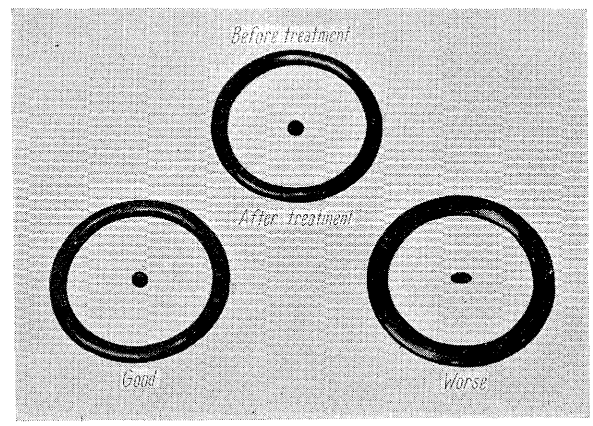
$$\sigma_0 = 3\theta\ (P_i \sim P_0) \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

In this formula

σ_0 = initial pressure in unit area
P_i = inner pressure in unit area
P_0 = outer pressure in unit area
θ = safety coefficient

Safety coefficient may be elected as about 10, considering maximum pressure difference $(P_i \sim P_0)$.

In the figure 6 I show a photograph of O-ring



rubber packing; one is good, the other is worse, and at the center of ring packings section of each packing is shown. You can see how the section of a worse one at the right becomes deformed greatly.

V. CONCLUSION

We mentioned briefly about necessary characters, manufacturing process and elastic behavior of oil-resistant rubber packings. At the other opportunity I will introduce other detail experiments.

I acknowledge Mr. T. Koshiishi and Mr. H. Tsuchiya for their efforts in the above mentioned experiments at the Material Research Laboratory.