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New rubber in seismic and vibration systems for insulating building structures against natural and technogeneous dynamic impact

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Abstract. In the article, the important aspects of improving the rubber, developed previously by M.S. Poliakov Institute of Geotechnical Mechanics, by using new chemical ingredients are considered. Of our rubber, rubber-metal elements were made and used under static and dynamic loads for over fifty years. Owing to the obtained experimental information, new optimal variant was chosen for the rubber formulation, which provides sufficient stability of the rubber and its resistance to aging. This composition of the rubber was patented in Ukraine. Further, the results of long-term tests of rubber elements in the radiation field of hard γ-radiation are presented in the paper. It is for the first time, when an important regularity is stated: aging-resistant rubber is also resistant to the action of γ-radiation, which indicates the similarity of the mechanisms of structural changes in the material.

1. Introduction

For protecting building structures against dynamic interactions of natural and man-made nature, special vibroseismic protection (VSP) systems were designed; their detailed description is given in [1, 2]. Over the past about fifty years, among the numerous designs of such systems, the most widespread system was the VSP, elastic elements of which were made of rubber. It is enough just to become familiar with different international projects on seismic and vibration isolation of structures in order to get convinced of the dominant role of the rubber VSBs (vibroseismic blocks). For example, in Japan [3-6], from 1981 to 2018, more than 6,000 buildings and structures were built with the laminated rubber-metal VSBs; the similar VSBs are used in Australia, Russia and other countries. The authors of this work have 17-year experience in using VSBs in the construction of residential buildings in Ukraine. Up to date, 16 buildings (from 10 to 27 floors) have been built and commissioned. Industrial studies of the building structures have shown high efficiency of the vibroseismic protection system with the rubber elements.

Rubber turned out to be the most suitable structural material primarily due to its ability to stand large reversible deformations and significant dissipation. Rubber parts are precisely those elements in which part of mechanical energy of external influence is converted into thermal energy and energy, which is spent for changing structure of the material. In this case, the presence of energy dissipation is a prerequisite for the rubber element to perform protective functions; the element, by dissipating the energy, changes its own structure and, therefore, increases durability of buildings and structures. In addition, dissipation underlies the protective functions as it the slows the rubber aging rate [7]. At the same time, rubber as a structural material is not without some drawbacks.

One of the significant drawbacks of rubber is instability of its physical and mechanical parameters over time, the so-called aging effects. A lot of researches are devoted to this problem; some of them is given below. A review of works on rubber aging up to 1976 is presented in [8] and up to 2012 – in [7]. The peak of scientific researches on rubber aging was in the second half of the last century. Among the well-known are the works of G. M. Bartenev, Yu. S. Zuev, A. S. Kuzminsky and others, and of such foreign authors as A. Pine, L. Mullins, E. Andrews, etc.; the aging of rubber during its storage or it is in a stressed state is the subject of modern works [9-14]. At the same time, there are practically no works on the aging of rubber vibroseismic blocks: there is only fragmentary information about the durability of layered VSBs. Thus, in the reports at the conference “Technologies of earthquake-resistant construction”, (Bishkek, February 8-9, 2021) it was noted that after 40 years of operation in a residential building, rubber-metal VSBs remained in a normal state; however, there is no data on the aging of these VSBs. The authors of this work carried out experimental studies of a residential building after seven years of operation; in all octaves, the seismic and vibration protection system did not exceed norms set by the sanitary standards.

As one can see, despite the importance of the problem, research works in the field of rubber aging are absolutely insufficient. First and foremost, this is due to the multifactorial nature of the problem, complexity and duration of experimental studies, rather complex structure of the material with a large energy dissipation, as well as the dependence of aging on such external factors as stress, heat, radiation, action of oils or acids, etc. The lack of scientific literature is also associated with the fact that the leading firms developing new rubber brands report only the final results necessary for advertising their product, while results of the studies specifically on the effects of aging are carefully hidden, which is quite justified by the tough competition in the service market.

It should be emphasized that according to the requirements of Eurocode 8 [15], physical and mechanical parameters of the VSBs should be stable throughout the whole period of building and structure operation, i.e. for about 75-100 years. And deviation of the parameters from the designed ones should not exceed the permissible norms; otherwise it is necessary to envisage a possibility for replacing of VSB in the building structures. Experimental studies of VSB are regulated by the standards [16, 17] including the standards of the European Union [18, 19].

Despite the existing method for accelerated testing of rubbers for thermal aging [16, 18], results obtained for the standard specimens (thin double-sided blades) not always can be applied to the massive VSB with such a long term of operation. Therefore, it is quite appropriate to compare the results obtained with the results of industrial tests of massive rubber or rubber-metal products operating for a long time under cyclic and static loads.

The authors have almost fifty-five years of experience in laboratory and industrial testing of such heavy vibration machines as conveyors of the KV2T type (two-pipe vibrating conveyors). Various tests are carried out on it, as evidenced by numerous publications, for example [20-22]. Massive rubber-metal blocks (RMBs) function in the conveyors as the main elastic links and are subjected to cyclic loads. The same blocks were used as vibration isolators, which experienced quasi-static compression deformations.

The authors obtained experimental data of how the main deformation parameters of rubbers with basic composition identical to the rubbers in VSB were changed under the long-term loading.

In engineering practice (in Ukraine, Japan, Russia, Australia, etc.), VSB are usually made in the form of simple geometric shapes; most often these are single-layer or multi-layer rubber or rubber-metal elements of a cylindrical shape, sometimes with a lead core [19]. As a rule, they are manufactured by molding of rubbers, which are based on natural caoutchouc (NC) or synthetic isoprene caoutchouc (SKI-3). More strong requirements are stipulated for such rubbers: they should be low- or medium-filled, feature high energy dissipation and be resistant to aging. According to the calculations, for example, the conditionally equilibrium shear modulus should not increase by more than 22-25% during the operation of a building structure for 75-10 years. This work is devoted to the consideration of this problem.

The objective of this work was to create a new low-modulus rubber resistant to aging under prolonged static and dynamic loads; and to confirm stability of rubber parameters in the course of time by the accelerated aging method and independent experimental studies.

2. Methods

The previously described nonlinear synergistic model of rubber aging [7] confirms complexity of the processes occurred in the material structure with time. Perhaps, that is the reason why there are no mathematical models which take into account all the variety of physical and chemical transformations during the rubber parts storage or their operation under static and dynamic loads. Therefore, according to existing standards [16, 18], today the most suitable method for the integral assessment of the effects of aging is method of the accelerated heat aging. In this case, the problem is reduced to establishing a correlation between the aging data at different temperatures. It is also important to choose an indicator responsible for changing of the material structure. In context of this work, the conditionally equilibrium shear modulus G_∞ is taken as a responsible indicator: it takes into consideration purpose of rubber functions in the SVBs (seismovibroblocks); it is sensitive to the effects of aging; it changes monotonically with time; and it is the main parameter for the quasi-static calculations.

The essence of the developed method consists in determining a dependence of G_∞ on time at several (at least four) elevated temperatures, calculating on the basis of the obtained data a coefficient characterizing a dependence of the rate of the indicator change on the aging temperature and extrapolating the obtained data to the given temperature, which is equivalent to the corresponding climatic conditions.

According to [16], the following conditions should be fulfilled: choosing of model samples, choosing of the executive equipment, and choosing of the temperature range and test duration. Typically, standard specimens in the form of thin double-sided blades are used for such tests. Disadvantage of these specimens is that in thin strip under action of tensile deformation and in natural SVB under compression and shear deformations stress fields are completely different. Therefore, rubber-metal blocks of the RMB102 type (rubber dimensions: 50 mm × 100 mm × 200 mm) made of low-modulus rubber of type A were chosen as model specimens. Besides, such specimens successfully work as elastic links in the KV2T-type vibrating conveyor, and they are well studied [7].

The tests were conducted in special heat chambers with a maximum permissible error of ±1 °C and forced ventilation. For determining the main indicator G_∞, dynamic shear modulus G_{dyn} and energy absorption coefficient ψ, special equipment was used including the universal testing stand “INSTRON 1126” with an error of 1-2% for determining deformations and 2% for determining load.

According to the standard, thermal aging is carried out at temperatures $T_1 < T_2 < T_3 < \ldots < T_n$ where $n \geq 4$; interval between the temperatures should not be less than 10 °C; minimum test temperature T_1 should be equal to or higher than the absolute maximum operating temperature; maximum test temperature $T_{\max}$ should be 10 °C lower than the temperature at which phase, structural or chemical transformations begin in the specimen material. For the investigated SVB, maximum temperature is summer temperature when it reaches about 55 °C, therefore $T_1 = 55$ °C; maximum temperature at which phase transformations are possible is in the range of 100-110 °C, therefore, $T_{\max} = 100$ °C. Thus, the chosen temperature range is 55 °C, 70 °C, 85 °C, 100 °C.

Duration of the tests was chosen as follows: due to the indicator G_∞ slow changing with time, the experiment at a temperature of $T_1 = 55$ °C was lasted for a little more than three years; at a temperature of $T_2 = 70$ °C – for one year; at a temperature of $T_3 = 80$ °C – for 200 days; at a temperature of $T_4 = 100$ °C – for 150 days.

In the process of thermal aging, periodically, at least 7 times, the quasi-static shear rigidity is measured, which is determined on the linear section of the force-displacement deformation curve. Period of rest before each measurement is 24 hours at room temperature.

Analytical processing of the experimental results obtained during five years has shown that in all cases indicator G_∞ changes exponentially up to a certain limiting value G_∞^{00} that does not depend on the test temperature. Within the experimental error, the exponential law can be applied for describing the functional dependences $G_\infty \sim t$

$$\frac{dG_\infty}{dt} = -k_i\left(G_\infty^{00} - G_\infty^{0}\right), \text{ or } G_\infty(t) = G_\infty^{00} - \left(G_\infty^{00} - G_\infty^{0}\right)\exp\left(-k_i t\right), \tag{1}$$

where the values of the modules are measured in MPa, t – in days; initial and limiting values of the modulus for all evolution curves are equal to $G_\infty^{0} = 55$ MPa and $G_\infty^{00} = 0.879$ MPa, respectively. Constants of the aging process rate take the following values depending on the test temperature (table 1):

Table 1. Constants of the aging process.

T, °C	55	70	85	100
k, (days)$^{-1}$	0.00078	0.00236	0.0074	0.022

Further, we determine the equivalent temperature T_e = 25 °C by the nomogram in accordance with the method [23] and build the graph ln$k$ ~ 1/T (figure 1).

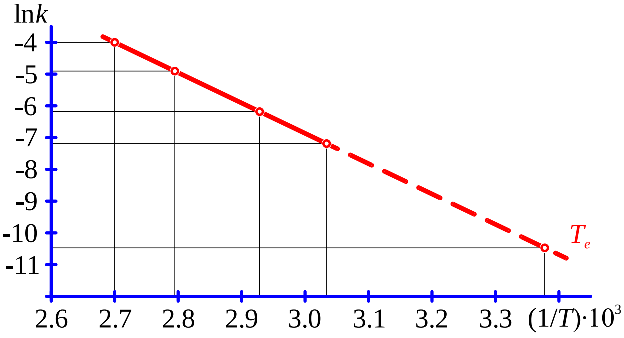

Figure 1. Dependence of ln k on T^{-1}.

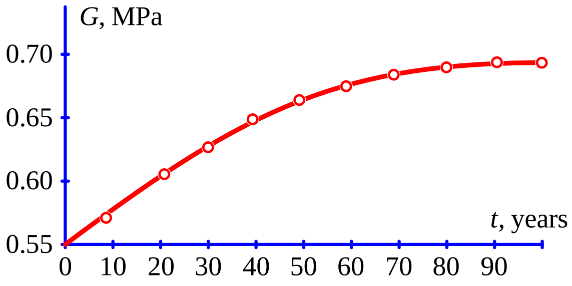

Figure 2. The predicted curve of the change with time of the conditionally equilibrium shear modulus G_∞.

By applying the graph of dependence ln$k$ ~ 1/T to the equivalent temperature T_e, we determine a constant of the process rate at T_e (figure 1): $k_e = 2.75\cdot 10^{-5}$; $\ln k_e = -10.5$. By putting the obtained values of k_e and G_∞^{00} into equation (1), we calculate the value of the equilibrium modulus G_∞ depending on the given values of t_i.

Then, the forecast curve $G_\infty \sim t$ is plotted for the accepted value of T_e (figure 2), which corresponds to the equation:

$$G_\infty(t_i) = 0.879 - 0{,}329\exp\left(-2.75\cdot 10^{-5} t\right) \tag{2}$$

The prediction curve can be used for determining value of the main indicator G_∞ at the given duration of operation.

In particular, from the plotted forecast curve, it follows that after 50 years of operation of rubber-metal blocks at a temperature of 25 °C, their stiffness will change by no more than 11%.

The theoretical prediction (2) is confirmed by the long-term operation of rubber-metal blocks of the RMB101 type in the vibrating two-pipe conveyors KV2T. After 55 years of operation in extreme conditions (cyclic shear deformations were up to 30% at a load frequency of 10.2 Hz), their static rigidity increased by no more than 25%.

3. Results and discussion

The long-term experimental studies of the static and dynamic characteristics of the rubbers under study show that in the course of time, elastic and dissipative characteristics of the rubbers will change significantly: rigidity increases monotonically, and dissipation decreases; that is the evidence that predominantly structuring reaction occurs in the material.

The rubber was created in laboratory and industrial conditions for about fifty years. In laboratory conditions, standard double-sided blades were used to determine strength indicators, and real rubber-metal elements RMB102 were used to determine the initial rheological parameters. Fatigue changes in rubbers were determined by placing RMB102 elements as the main elastic elements, subjected to shear and compression, of KV2T industrial conveyors, which are set at mining enterprises for transporting bulk materials in the mode: amplitude – 10.5 mm at a frequency of 11 Hz.

The process of creating rubber that is dynamically durable, with reduced heat generation and acceptably stable indicators during long-term operation is described in more detail in [20]. Here we note that the resulting rubber (table 2) successfully passed industrial tests for 4 years (35,000 hours) without noticeable signs of destruction. During this time, the rigidity characteristics increased by only 17-25% compared to the original version with an operating time of 15,000 hours, the rigidity characteristics of which increased by 80% during this time.

The compound of the new rubber (table 2) was obtained by selecting the main ingredients and their content, as well as by adding new ones that significantly increased their fatigue and anti-aging properties. For this purpose, elastopar was added to the rubber content in the amount of 0.5 mass parts per 100 mass parts of rubber. This made it possible to more than double increase the durability of the rubber and significantly enhance the resistance to aging.

Table 2. Composition of new rubber.

Ingredients	Content, parts mass per 100 mass parts of caoutchouc
Caoutchouc SKI-3	100
Sulfur	1.5-2.0
CBS (N-cyclohexyl-2-benzothiazole sulfenamide)	0.8-1.0
Carbon black N220	5-15
Stearic acid	1.0
Zinc oxide (ZnO)	5.0
Neozone D (phenyl-2-naphthylamine)	2.0
4010Na;	2.0
Elastopar (N-methyl-N'-4-dinitrosoaniline)	0.5

The low-modulus rubber created is widely used in practice in various industries in different vibration equipment. It shows excellent results in long-term operation under intensive cyclic loads, under conditions of exposure to aggressive environments, temperature, and hard γ-radiation. At the same time, its rigidity characteristics remain acceptable throughout its entire lifetime without visible signs of destruction (table 3 [20]).

The RMB102 made of new rubber and used in KV2T conveyors as vibration isolators were also tested; it is noted that with a relative compression ratio of 10-12%, the quasi-equilibrium rigidity monotonically increased by 20-24% during about 50 years.

Independent experimental studies of RMB102 blocks made of new rubber were carried out under the action of ionizing radiation as well: a set of blocks received a dose of hard γ-radiation of 30 Mrad. It was found that hard γ-radiation has a negative effect on the rubber: radiation damage increases rigidity and reduces energy dissipation; in addition, metal reinforcement is oxidized and ozone cracks appear on the free surface of the rubber-metal blocks. It is further noted that the new rubber up to certain doses (in our case, up to 30 Mrad) is resistant to the action of ionizing radiation; durability of the RMB102 was up to 25,000 hours, which is quite acceptable for machines used for transportation and processing of radioactive materials.

Table 3. Characteristics of new rubber and BRM102 based on it.

Indicators	Value
Tear resistance, MPa	29.0
Relative elongation, %	780
Residual elongation, %	14
Hardness by Shore A	38
Dynamic modulus at impact tension, MPa	2.17
Internal friction modulus at impact tension, MPa	0.21
Heat generation, °C	38÷40
Dynamic shear modulus RMB102, MPa	0.76
Energy dissipation coefficient RMB102	0.35
Steady-state temperature inside RMB102, °C	50÷55
Durability RMB102, h	more than 35000
Product characteristics	No visible signs of destruction

An important pattern is noted for the rubbers under study – their resistance to both aging under static and dynamic loads, and resistance to the action of ionizing radiation. This indicates the similarity of the mechanisms of structural changes in the material.

Therefore, the new rubber is recommended for manufacturing of vibroseismic blocks to be installed in the vibroseismic protection systems of buildings and structures during their long-term operation (for 75-100 years).

Other rubbers less resistant to aging and fatigue failure, obtained during the research, have also found application in industry on less loaded vibration equipment (a = 6-8 mm, f = 10-12 Hz). Factors influencing the choice of a specific type of rubber are its rigidity parameters, cost, etc.

A Ukrainian patent was received for slightly modernized rubber (carbon black P803 was replaced with carbon black N220) [24].

4. Conclusions

1. A new low-modulus rubber resistant to aging under long-term static and dynamic loads was created.
2. Stability of the new rubber parameters was confirmed by the method of accelerated aging and by independent long-term industrial testing of the massive model rubber-metal parts.
3. Studies of natural and technogenic seismicity [25, 26] make it possible to use low-modulus rubbers particularly effectively in seismic insulation systems for buildings constructed for highly seismic regions of the Republic of Kazakhstan [27], Ukraine and other countries.

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