Effect of aging of foam rubber on properties and constitutive models

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Abstract: This article reviews the effects of aging on properties and constitutive models of foam rubber materials. Firstly, the change of aging indicators such as compression set and stress relaxation with time and temperature, and the influence of relative density, hardness of materials, the size and shape of the cell on the aging indicators are introduced in this article. Secondly, this article also introduces the strengths and application of commonly used hyper-elastic material constitutive models such as Arruda-Boyce model, Van der Waals model, Neo-Hookean model, Mooney-Rivlin model, Yeoh model, and Ogden model, and introduced the influence of aging on model parameters. Finally, the influence of aging on the model parameters is introduced.

1. Introduction

Foam rubber is a hyper-elastic material obtained from a rubber matrix through a foaming method. It has good shock absorption, heat insulation, sound insulation, and sealing properties. It is often used for positioning, shock absorption, anti-rotation, and other working conditions between important parts[1]. Foam rubber is subjected to tensile or compressive stress for a long time during use, and it may be exposed to temperature and humidity, which can lead to chemical and structural changes[2]-[3]. These changes will lead to the degradation of the macro properties of foam rubber and affect the safety of the equipment.

The performance of foam rubber under compression and tension is very different. This article pays more attention to the change in performance of foam rubber during the aging process under the condition of long-term compression load. Indexes such as compression set and stress relaxation are commonly used to measure the degree of performance of compressed foam rubber. In the aging process of foam rubber, the compression set and stress relaxation are related to the change of the stress-strain curve[4]. Therefore, choosing a constitutive model that can accurately describe the stress-strain response of the material, and studying the changes of model parameters during the aging are also important means to study the aging of foam rubber.

This article aims to overview the changes regularities of compression set and stress relaxation of compressed foam rubber during the aging, and study the reasons and influencing factors of these changes. In order to find a suitable constitutive model for foam rubber, the common constitutive models and their application of Hyper-elastic Materials are introduced. Finally, the changes of model parameters during aging are introduced.
2. The changes regularities of aging index

Accelerated aging tests are often used to study changes in foam rubber properties. Zhang\(^5\) and Yan\(^6\) used the accelerated aging method to study the performance changes of silicon foam and found that the compression set of silicon foam gradually increased with aging time, and the higher the temperature, the faster the compression change. Zhang\(^5\) also found that the displacement-load curve of silicon foam gradually shifts to the left and becomes steeper with the aging time. Zhang analyzed that the reason for these changes is that the rubber matrix undergoes oxidative degradation during the aging process, and the internal cells will undergo permanent deformation, which will cause the material to become hard and brittle, resulting in changes in the macroscopic properties of the silicon foam. Although the research of Zhang revealed the changing trend and change mechanism of foam rubber properties, it failed to give a specific function description.

Huang’s research\(^7\) found that the stress relaxation of silicon foam has a linear relationship with the natural logarithm of time. Liu\(^8\) found that the relationship between the change rate of load and temperature can be described using the Arrhenius model for polyurethane foam. Their research results show that the aging process of foam rubber conforms to the principle of time-temperature equivalence.

The research results of Huang\(^7\) and Ma\(^9\) show that the stress relaxation of Silicon foam reduces at first and increases then with the increase of the initial compression amount. This means that the relationship between the rate of stress relaxation degradation and compression is not monotonous, which is contrary to common sense, this paper holds that the main reason for this phenomenon is that the stress relaxation data obtained in the literature are not for the same compression. Although the research results in the literature have strong engineering guiding significance, in order to show the effect of different compression on the stress relaxation clearly, the initial load value before aging should be tested at the specified compression (such as 20%), and then measure the load at this compression (20%) after aging to determine the stress relaxation level, rather test the initial load value under varies compression (such as 20%, 30%, 40%), and then test the value under varies compression (such as 20%, 30%, 40%) after aging.

The aging characteristics of silicon foam are also related to the properties of the material. Shi\(^1\) found that the stress relaxation of silicon foam increases with density, and the relationship between the two is approximately linear. The cell types and sizes also have an impact on the aging performance of silicon foam. Foams with high open cell content, uniform cell size, and circular cell, helps reduce the stress relaxation of foamed silicon\(^10\), and the cell diameter has a smaller effect on the stress relaxation rate\(^12\). The hardness of silicon foam also affects the aging characteristics of the material. Zhang\(^13\) found that the hardness and stress relaxation are inversely proportional. The increase of hardness is helpful to maintain stress during aging.

3. The constitutive model of common hyper-elastic materials and the change of model parameters with aging time

3.1. Common constitutive models of hyper-elastic materials

The constitutive models of hyper-elastic materials are divided into two categories: one is the continuum constitutive model based on phenomenological theory, and the other is the constitutive model based on thermodynamic statistical methods\(^14\).

The thermodynamic constitutive model has the advantages of few parameters and clear physical meaning. Commonly used constitutive models based on thermodynamic statistical methods include the Arruda-Boyce model\(^15\) and Van der Waals model\(^16\) are commonly used constitutive models for this method. The Arruda-Boyce model has two parameters, which parameters can only change the stress-strain ratio but cannot change the curve shape, so the data fitting effect is not well when as a foam rubber constitutive model. The Van der Waals model has 4 parameters, compared with the Arruda-Boyce model, the Van der Waals model can change the shape of the curve and has better data fitting capabilities.

The constitutive models based on phenomenological theory include Neo-Hookean\(^17\), Mooney-Rivlin\(^18\), Yeoh\(^19\) and Odgen\(^20\). The Mooney-Rivlin, Neo-Hookean, and Yeoh model mainly uses strain
invariants to describe the constitutive relationship of materials. These three models are all deformed based on formula (1).

\[ W = \sum_{i,j=1}^{N} C_{ij} (I_1 - 3)(I_2 - 3) \]  

(1)

Where \( I_1 \) represents the first strain invariant, \( I_2 \) represents the second strain invariant, \( C_{ij} \) represents the model coefficient.

When formula (1) keeps only the first term, the Neo-Hookean model is obtained

\[ W = C_{10}(I_1 - 3) \]  

(2)

When formula (2) keeps the first two terms, the Mooney-Rivlin model is obtained

\[ W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \]  

(3)

The Neo-Hookean model and Mooney-Rivlin model are simple and convenient to apply. However, because there are not enough expansion items and the shear modulus does not change with strain, the two models have a better fitting effect for the small deformation stage, but there will be deviations in the large deformation stage[14, 21].

As shown in equation (4), the Yeoh model discards the second strain invariant and retains the higher-order terms of the first strain invariant. The Yeoh model is simple in form, but because it has a higher-order term of strain invariant, it can better reflect the behavior of foam rubber in the large deformation stage. However, because the model discards the second strain the model appears "softer" when predicting the biaxial tensile strain behavior[22].

\[ W = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3 \]  

(4)

The Ogden model mainly uses three main elongation rates \( \lambda_1, \lambda_2, \lambda_3 \) to describe the material constitutive relationship. Compared with formula (1), the Ogden model considered that the three principal elongations are asymmetric[23], so the Ogden model is more flexible, adapted to a wide range of deformation, and is widely used. The deformed Hyper-foam model of the Ogden model is also often used as a constitutive model of foam rubber materials. The Hyper-foam model expression is shown in formula (5)

\[ U(\lambda_1, \lambda_2, \lambda_3) = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i} \left( \mu_i + \nu_i + \frac{\lambda_i^{\alpha_i} + \lambda_i^{\beta_i} + \lambda_i^{\gamma_i} - 3}{\varphi_i} \right) \]  

(5)

Where, the \( \lambda_1, \lambda_2, \lambda_3 \) are the main deformation, \( \mu_i \) and, \( \alpha_i \) and \( \beta_i \) are the material parameters.

### 3.2. The constitutive model parameters of foam rubber change with aging time

During the aging process, the stress-strain curve of the foam rubber will change. The slope of the curve increases with the aging time[24], the parameters of the constitutive model also change accordingly. Xie[25] used the Ogden model as a constitutive model of a filled rubber and found that the parameter \( \mu \) changes significantly with aging, and the change \( \alpha \) is not obvious. By assuming \( \alpha \) constant, Xie found that the parameter \( \mu \) and the aging temperature meet the Arrhenius model. Jin[26] used the Hyper-foam model as the constitutive model of silicon foam, by using the Prony series expansion to fit the model parameters, Jin started from the perspective of uncertainty quantification in the fitting process[27] considers that there is a correlation between the parameters \( \mu \) and \( \alpha \). Maiti[4] used the Ogden Hyper-foam + Two-network Tobolsky model as the constitutive model of a certain silicon foam cushion, by considering that \( \alpha \) is unchanged, the parameter \( \mu \) during the aging process is fitted. Maiti used the constitutive model to predict the compression set and load retention of the silicon foam cushion and found that the prediction results were consistent with the experimental structure. It can be analyzed from the literature that at present, numerical fitting methods are mainly used to study the parameter changes of the constitutive model, to converge the calculation results, the above methods all limit the model parameters.
4. Conclusions
This article reviews the effects of foam rubber on material properties and constitutive models during the aging process. In the aging process, the oxidative degradation of the rubber matrix and the damage of the cell microstructure will cause irreversible changes in the permanent of the foam rubber materials. The higher the temperature, the longer the aging time, the more obvious the material performance degradation. The performance degradation of foam rubber is also affected by the characteristics of the material itself. The higher the open-cell content of the material, the more uniform the cell distribution, the greater the hardness, the less stress relaxation during the aging process. As the relative density of the material increases, the stress relaxation will increases. The size of the cell has no obvious effect on the stress relaxation of the material.

This article also introduces common constitutive models of hyper-elastic materials and the influence of aging on model parameters. Constitutive models can be divided into thermodynamic statistical constitutive models and phenomenological constitutive models. Commonly used thermodynamic statistical constitutive models include Arruda-Boyce model and Van der Waals model. Commonly used phenomenological constitutive models include Neo-Hookean model, Mooney-Rivlin model, Yeoh model, and Odgen model. Because the situation is flexible and can be applied to large deformation strains, the Odgen Hyper-foam model is often used as a constitutive model of foam rubber materials. At present, numerical fitting methods are mainly used to study the changes of constitutive model parameters with aging time. The research on the parameter changes of the foam rubber constitutive model needs to be further in-depth.

Acknowledgments
Key academies and key disciplines and major construction projects in the military (430169, 430183), Naval academies and major disciplines major construction projects (430618)

References
[1] Shi Y, Zhang C, Zhao Q, Ding G, Luo S. (2007) Study on the effects on compression stress relaxation of HTV silicone rubber-foams. J. New Chemical Materials. 21-22.
[2] Patel, M., Morrel, P. R., Murphy, J. (2005) Continuous and intermittent stress relaxation studies on foamed polysiloxane rubber. J. Polym. Degrad. Stab. 87, 201–206.
[3] Coons, J. E., McKay, M. D., Hamada, M. S. (2006) A Bayesian analysis of the compression set and stress–strain behavior in a thermally aged silicone foam. J. Polym. Degrad. Stab. 91, 1824–1836.
[4] Maiti, A., Small, W., Lewicki, J. P., Chinn, S. C., Saab, A. P.. (2019). Age-aware constitutive materials model for a 3d printed polymeric foam. J. Scientific Reports. 9(1): 15923.
[5] ZHANG K, FAN J, WU J, MA Y. (2007 ) Study on Thermal oxidative Ageing Mechanisms of Silicone Rubber Foam Materials. J. Synthetic Materials Aging and Application. (03):18-21.
[6] Yan X, Zhou Y, Wen M, Li J, Zhou X, Wang P. (2009) Study on the effects of multi-factor accelerating ageing on the mechanical properties of the silicone rubber foam materials. J. New Chemical Materials. 37(05): 66-68.
[7] Huang Y, Zhang F, Hu W. (2009) The research of the stress relaxation of cellular silicone materials. J. New Chemical Materials. 37(08): 85-87.
[8] Liu Y, Wu L, He C, Deng J, Zhang T, Yi K, Sun S. (2005) Research on Prediction of Storage Life of Rigid Polyurethane Foam. J. China Plastics. (05):87-90.
[9] Ma Y, Wang F. (2019) Study on the compressive stress relaxation properties of foamed silicone rubber. J. Organic Silicone Material. 33(04): 296-301.
[10] Ding G, He C, Shi Y, Luo S. (2008) Study on the pertinences between the compress stress relaxation characteristics and the pore structure of the silicone rubber foam. J. New Chemical Materials. (06): 47-49.
[11] Fan Z, Chen C, Hu W, Wan Q. (2015) EFFECTS OF MICROSTRUCTURE ON THE LARGE COMPRESSION BEHAVIOR OF RUBBER FOAMS. J. Mechanical Strength. 37(05): 892-
[12] Sha Y, Zhang C, Li J, Luo S. (2013) The influence of cell structure on the properties of silicone rubber foam materials. J. Materials for Mechanical Engineering. 37(02):25-28.

[13] Zhang C, Luo S, Shi Y, Lu A, Ding G. (2008) Study on the connection between rigidity and compression properties of silicone rubber foam. J. New Chemical Materials. (08):77-78.

[14] Xu L, Wu G. (1999) Some forms of rubber strain energy function in finite element analysis. J. China Rubber Industry. (12): 707-711

[15] Ellen, M, Arruda, et al. (1993) A three-dimensional constitutive model for the large stretch behavior of rubber elastic materials. J. Journal of the Mechanics & Physics of Solids.

[16] GUO Z, SLUYS L J. (2008) Constitutive Modelling of Hyperelastic Rubber-like Materials. J. Delft University of Technology. 55( 3) : 109-132.

[17] Treloar L R G. (1943) The elasticity of a network of long-chain molecules I. J. Transactions of the Faraday Society. 39: 36-41.

[18] DONG L, LAKES R S. (2011) Frequency Dependence of Poisson’s Ratio of Viscoelastic lastomer Foam. J. Cellular Poly- mers. 30(6) : 277-286.

[19] Yeoh O H. (1993) Some forms of the strain energy function for rubber. J. Rubber Chemistry nd Technology. 65(5): 754—771.

[20] Ogden R W. (1972) Large deformation isotropic elasticity-On the correlation of theory and experiment for incompressible rubberlike solids. J. Proceedings of the Royal Society of London. A326: 565—584.

[21] Wei Y, Fang Q, Jin Z, Feng X. (2014) Research progress on the constitutive model of filled rubber. J. Chin Polym Bull. (05): 15-21.

[22] Li X, Wei Y. (2016) AN IMPROVED YEOH CONSTITUTIVE MODEL FOR HYPERELASTIC MATERIAL. J. Engineering Mechanics. 33(12): 38-43.

[23] GREGORY M J. (1975) The Stress-strain Behavior of Filled Rubbers at Moderate Strains. J. Plastics and Rubbers Materials and Applications. 4( 4) : 184-188.

[24] ANHTH, VU-KHANHT. (2005) Effects of thermal aging on fracture performance of polychloroprene. J. Mater Sci., 40 (19) :5243 -5248.

[25] Xie Z, Wang Y, Wan Z, Gu Q. (2008) Thermal aging of filled rubber constitutive relationship. J. Journal of Harbin Institute of Technology. (09): 1404-1407.

[26] Jin F, Xiao S, He Q, Jia D, Fang Y. (2018) Uncertainty characterization of super-elastic compression and stress relaxation of silicon foam. J. Chin J Appl Mech. (06): 1200-1206 +1414.

[27] ZHANG Y, NIU W, LIU X. (2013) Selection of static constitutive models for polyurethane based on Bayesian posterior probability. J. Chinese journal of solid mechanics. 33(S): 242-246.