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Creep and Recovery Behaviors and Deformation Mechanism of Silicone Rubber Foams with Different Systems

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Abstract. Creep and recovery behaviors of polymer composites are fundamental manifestations of their viscoelastic nature and directly determine the material's reliability in complex environments. In-depth investigation of the creep and recovery behaviors of materials plays an indispensable role in illustrating their deformation and failure mechanisms. In this study, we employed DMA to investigate the creep and recovery behaviors of SHF and PVF under different temperatures and stresses. The Burgers model and Weibull distribution function were also used to fit the results. It was found that SHF exhibits predominantly elastic deformation with only 3.72% unrecovered deformation at 45 kPa and 205 °C, whereas PVF is dominated by viscous plastic deformation with 51.15% unrecovered deformation under the same condition. Fitting results reveal that the Burgers model accurately describes the viscoelastic creep processes of both materials and that the Weibull distribution function effectively quantifies their residual deformation characteristics. This performance disparity can be attributed to their different crosslinked networks. Thermally induced post-curing of residual Si–H groups in SHF increases crosslink density and enhances elasticity. However, high temperatures and stresses induce softening of PVF matrix, leading to irreversible chain dynamics.

Keywords: creep and recovery, silicone rubber foam, models, mechanisms

1. Introduction

Silicone rubber foam is a porous elastic polymer material which is composed of a Si-O-Si bond main chain and organic group-modified side chains [1]. It combines the excellent electrical insulation, chemical stability and other tunable properties of silicone rubber with the unique properties of foam materials, such as light weight, thermal insulation and compressibility. Therefore, it has been widely applied in many fields, including the electronics industry, healthcare, and aerospace engineering [2-4].

However, during practical service conditions, since silicone rubber foam is subjected to constant stress and temperature fluctuations over extended periods, the internal molecular chains and pore structure will gradually undergo slippage and yielding, ultimately resulting in permanent deformation [1]. This deformation impairs the material's elastic recovery properties, rendering it incapable of meeting the core requirements of precision component positioning and vibration damping in practical applications, thereby affecting the equipment's operational stability and service life [3].

Creep strain of polymeric materials typically comprises instantaneous elastic deformation, delayed high-elastic deformation, and irreversible viscous flow. If a material lacks sufficient creep recovery capability, repeated stress application can lead to the accumulation of creep strain, which ultimately results in material failure and affects its service life [5]. Therefore, a systematic comparative study of the creep and recovery behavior of silicone rubber foams with different formulations under varying temperatures and stress levels is of great significance for practical applications. This study utilized Dynamic Mechanical Analyzer (DMA) to conduct detailed tests of creep-recovery properties under varying temperatures and stress levels. Furthermore, the Burgers viscoelastic constitutive model and the Weibull distribution function were used to fit the creep and recovery curves, thereby enabling quantitative analysis of the material's creep strain. This study clarifies the differences in the creep behavior of the two silicone rubber foams under different temperatures and loading conditions, providing reliable experimental data and a theoretical basis for optimizing material election and assessing service life in engineering applications.

2. Experimental

2.1. Chemicals and samples

For this research, silicon-hydrogen rubber foam (SHF) and peroxide-vulcanized silicone rubber foam (PVF) were supplied by a third-party company and were used directly without any further purification or activation. Both materials had a density of 0.35 g/cm^3. Prior to the test, all materials underwent a 2-hour high-temperature vulcanization (210 °C) treatment to eliminate residual stresses generated during processing. Then samples were cooled naturally to room temperature before testing.

2.2. Methods

In order to investigate the effects of temperature and stress on the creep-recovery behavior of silicone rubber foam systematically, this study adopted the single-variable method and designed two sets of experiments: The first set examined the temperature effect via measuring the creep-recovery behavior of the materials at four temperatures (25, 70, 115 and 160 °C) respectively under a constant compressive stress of 15kPa; The second set measured the creep-recovery behavior of the materials at three stress levels (15, 30 and 45 kPa) under a constant temperature at 205 °C.

All tests were conducted using a Dynamic Mechanical Analyzer (DMA Q800) under its creep mode. Prior to tests, the specimens were cut into standard 1 × 1 × 1 cm^3 cubes, and a new specimen was used for each test. During the test, a 0.05 N preload force was applied to samples first; then the compressive stress was increased to the set value and held constant.. After that, the foam was heated to the target temperature and held for 5 minutes. Subsequently, the compressive stress was applied and maintained for 45 minutes, then the pressure was immediately removed and the deformation recovery process was recorded for a further 45 minutes.

3. Results and discussions

To better understand the creep-recovery behavior of both samples, we analyzed the fundamental time-strain relationship alongside the established mechanical models.

As shown in Figure 1a, both types of foam undergo the three characteristic stages of creep deformation under different temperatures, but they exhibit completely opposite temperature-dependent creep behaviors. The creep deformation of SHF decreased with increasing temperature and the highest strain was 42.63% at 25°C. After unloading, the material undergoes rapid instantaneous elastic recovery followed by gradual delayed viscoelastic recovery, and the unrecovered deformation at all tested temperatures is no more than 4%. However, the creep strain of PVF consistently increased as the temperature increased gradually. For example, the maximum creep strain of the sample was 21.99% at 25 °C and rose to 29.8% at 160 °C. Furthermore, the unrecovered deformation of the foam showed a considerable upward trend with increasing temperature, reaching 13.4% at 160 °C, which is far higher than the 0.49% observed at 25 ℃. Compared to SHF, the creep strain of PVF was significantly lower than that of SHF under all temperature conditions, indicating that the crosslink network formed by PVF possesses higher initial stiffness, allowing the material to have greater resistance to initial deformation [6].

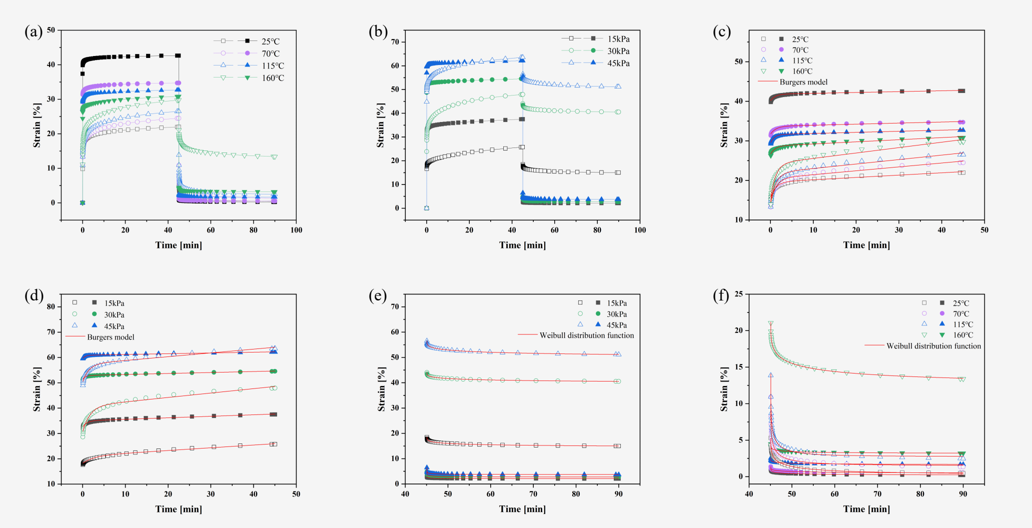

Figure 1. (a) The creep and recovery strain of SHF (solid symbols) and PVF (hollow symbols) at different temperatures under a constant stress of 15 kPa, and (b) at different stresses under a constant temperature of 205 °C. Corresponding Modeling results for the Burgers mode (creep) : (c) constant stress 15 kPa at different temperatures and (d) constant temperature 205℃ at different stresses, and the Weibull distribution function (recovery) : (e) constant stress 15kPa at different temperatures and (f) constant temperature 205℃ at different stresses

Tests were also performed to compare the creep and recovery response of two types of materials at different stress levels of 15, 30 and 45 kPa (205 °C). Clearly, the creep responses of them show obvious differences by the change of stresses (Fig. 1b), and the high stress level can bring large creep strain and accelerate the deformation of polymer materials.

At the same stress levels, SHF exhibits superior creep resistance and elastic recovery performance compared to PVF. As shown in Figure 1b, the creep curves of the SHF all reached the strain plateau rapidly at the early stage of loading. A significantly lower creep strain rate for SHF is also observed under these three stress levels. This stable and controllable deformation behavior suggests that instantaneous elastic deformation dominates the strain process in SHF, which is attributed to its stable crosslinked chemical network in the structure. By contrast, PVF shows substantial viscous deformation during creep process, which indicates that C-C crosslinks formed during the synthesis are unstable and the material has abundant structural defects [7].

Moreover, Fig. 1b demonstrates that SHF produces better creep resistance and lower unrecovered deformation in comparison with PVF, which correspond to the parameters from models that will be discussed in detail later. The unrecovered deformation of SHF is only 3.72%, while that of PVF is as high as approximately 51.14% under 45 kPa stress. Even at the lower stress level (15 kPa), the unrecovered deformation of the PVF reaches about 15.01%, far exceeding the 2.12% observed in the SHF. These results further validate the findings from creep behavior: because SHF undergoes elastic deformation, it recovers rapidly upon unloading, and the applied stress has negligible effect on its recovery behavior. In contrast, PVF has significant loss in recovery due to the presence of a higher percentage of viscous deformation. Therefore, these results demonstrate that SHF exhibits more reliable mechanical stability and recovery performance than PVF across different stress levels.

To further quantify the creep and recovery behavior of silicone rubber foam, we employ the Burgers model to fit the experimental data, which is a well-known model that combines the Maxwell and Kelvin-Voigt elements to evaluate the mechanical properties of polymers. The Maxwell element consists of an elastic spring and a viscous damper connected in series, and is primarily used to describe instantaneous elastic deformation and viscous flow characteristics of the material. On the other hand, the Kelvin-Voigt element consists of an elastic spring and a viscous damper connected in parallel, and it is used to characterize the material's viscoelastic hysteretic deformation and elastic recovery capacity. Therefore, the Burgers model formed by the series connection of these two elements can comprehensively characterize the creep response of silicone rubber foam under long-term loading, and it can be described by the following formula:

$$\varepsilon(t)=\frac{\sigma_0}{E_M}+\frac{\sigma_0}{E_K}\left[1\text{-}\exp\left(\text{-}\frac{tE_K}{\eta_K}\right)\right]+\frac{\sigma_0}{\eta_M}t \tag{1}$$

where E_M and η_M are the spring modulus and dashpot viscosity of the Maxwell unit respectively; E_K and η_K are the spring modulus and dashpot viscosity of the Kelvin unit respectively; σ0 is the applied stress in the creep test.

Table 1. The fitted parameters of the Burgers model for SHF and PVF under different conditions

condition	E_M (kPa)	E_K (kPa)	η_K (kPa·min)	η_M (kPa·min)	E_M (kPa)	E_K (kPa)	η_K (kPa·min)	η_M (kPa·min)
25 ℃	0.374	8.614	9.055	696.572	0.964	3.728	4.661	256.067
70 ℃	0.474	7.358	9.041	559.076	1.062	2.365	2.963	152.687
115 ℃	0.510	6.858	5.759	546.594	1.043	2.000	2.574	132.742
160 ℃	0.564	7.140	7.537	280.274	0.992	1.655	1.974	109.724
15 kPa	0.461	6.105	5.933	251.652	0.827	5.105	13.240	138.669
30 kPa	0.584	19.582	13.263	774.267	0.986	2.914	4.958	172.302
45 kPa	0.755	36.113	24.119	1519.740	0.897	6.312	8.978	301.498

* The first four rows correspond to tests under a constant stress at 15 kPa; the last three rows correspond to tests under a constant temperature at 205 °C. The first four columns represent fitted parameters for SHF, and the last four columns represent fitted parameters for PVF.

Based on the modeling results (Table 1), the fitting curves (Fig.1c and Fig.1d) agree well with the experimental data, indicating that the Burgers model can accurately describe the viscoelastic creep behavior of both materials. The parameter E_M associated with the Maxwell spring represents the instantaneous elastic deformation generated by the material when stress is applied, which is fully recoverable upon stress removal. As temperature and stress increase, the E_M value of SHF continues to rise, indicating that high temperature and stress can significantly enhance the instantaneous elasticity of this material. In contrast, the E_M value of PVF increases and then decreases with rising temperature and stress, indicating that its crosslinked structure is thermally unstable under the influence of temperature and stress [7]. In terms of resistance to permanent deformation, the Maxwell viscosity η_M of both types of foam decreases with increasing temperature, reflecting a general deterioration in creep performance at high temperatures. However, the fitted values for SHF are more than twice those of PVF across the entire temperature range, which means that SHF still retains superior creep resistance even after degradation at high temperatures.

The parameter E_K represents delayed elasticity and reflects the rigidity of amorphous polymer segments, corresponding to the delayed elastic deformation that occurs slowly under stress and recovers gradually after the stress is removed. With regard to temperature, the E_K values of both systems show a downward trend as the temperature rises because high temperature severely weakens the material's delayed elastic recovery capability, causing more deformation to be converted into irreversible permanent deformation. Under varying stress, the E_K value of the SHF rises sharply with stress increasing, indicating that the material's delayed elastic recovery capability is greatly enhanced; whereas that of PVF displays irregular non-linear fluctuations with increasing stress, which reflects the structural heterogeneity and mechanical instability of the crosslinked network in PVF. The parameter η_K of the Kelvin-Voigt unit is related to viscosity and its changes directly reveal the kinetic characteristics of the material's reversible delayed deformation and the dynamic response behavior of the crosslinked network. As shown in the figure, the values for both systems decrease as temperature rises and PVF exhibits a more obvious decline. Combined with the drop in its E_K, high temperature accelerates its delayed deformation and weakens recoverable deformation, leading to obvious performance deterioration. Regarding stress dependence, the η_K value for SHF increases greatly with increasing stress. Together with the rise of E_K, its delayed deformation becomes stable and its delayed elasticity is improved under high stress. By contrast, PVF presents fluctuating and declining trends, revealing poor mechanical stability of its crosslinked network under high stress.

In order to further understand the recovery behavior of silicone rubber foam during the creep recovery process, this study employed the Weibull distribution function to fit the recovery data. This equation has been widely used to describe the time-strain relationship of viscoelastic materials by simultaneously quantifying both the time-independent instantaneous elastic recovery strain and the time-dependent viscoelastic recovery strain, thereby revealing key parameters such as shape factor and characteristic time. It can be described by the following formula:

$$\varepsilon_r(t)=\varepsilon_v\left[\exp\left(-\left(\frac{t-t_0}{\eta_r}\right)^{\beta_r}\right)\right]+\varepsilon_\infty \tag{2}$$

Where ε_v is the recoverable viscoelastic strain and ε_∞ is the permanent strain after the completion of recovery; η_r is the characteristic life, reflecting the rate of the recovery process; βr is the shape factor of the Weibull distribution, which determines the morphology of the recovery curve.

Table 2. The fitted parameters of the Weibull distribution function for SHF and PVF under different conditions

condition	ε_v (%)	ε_∞ (%)	η_r (min)	β_r	ε_v (%)	ε_∞ (%)	η_r (min)	β_r
25 °C	0.915	0.212	1.806	0.359	4.973	0.300	1.581	0.365
70 °C	0.968	0.425	2.399	0.288	9.538	1.501	0.338	0.342
115 °C	0.928	1.630	1.225	0.287	11.337	2.765	0.298	0.363
160 °C	1.326	3.166	1.124	0.310	8.691	12.488	4.258	0.331
15 kPa	1.040	2.115	0.471	0.316	4.05	14.459	5.794	0.335
30 kPa	2.144	2.741	0.222	0.277	4.655	39.445	12.958	0.308
45 kPa	2.738	3.718	0.067	0.241	6.951	49.611	12.539	0.321

* The first four rows correspond to tests under a constant stress at 15 kPa; the last three rows correspond to tests under a constant temperature at 205 °C. The first four columns represent fitted parameters for SHF, and the last four columns represent fitted parameters for PVF.

Fig.1e and Fig.1f show that the Weibull distribution function can accurately describe the creep recovery process of silicone rubber foams, and the obtained key parameters all have high accuracy and reliability and they are all listed in Table 2.

The unrecovered deformation of both types of foam shows an upward trend with increasing temperatures and stresses, which indicates that external loading and thermal effects exacerbate irreversible structural changes within the material, though the magnitude of these changes differs significantly between the two materials. Specifically, the increase in unrecovered deformation for SHF is gradual and limited, enabling the material to retain good stability across a broad range of operating conditions, whereas PVF experiences a sharp rise in unrecovered deformation with increasing temperature and stress. Its crosslinked network is prone to irreversible damage, leading to a markedly weaker resistance to permanent deformation.

In terms of recoverable viscoelastic strain, both types of foam rises continuously with increasing temperature and stress, suggesting that external forces can activate more chain segments to participate in reversible viscoelastic deformation, thereby enhancing the material's elastic recovery potential. Notably, the recoverable viscoelastic strain of SHF increases steadily as operating conditions become more severe, maintaining stable recovery capacity even at high temperatures. In contrast, the recoverable viscoelastic strain of PVF increases substantially at low and medium temperatures and under low stress, but declines under high-temperature conditions, indicating that high temperatures damage its crosslinked network, converting part of the reversible deformation into permanent damage.

When it comes to the temporal characteristics of creep recovery, the two types of foam exhibit completely opposite trends. For SHF, the characteristic recovery time shortens and the recovery rate accelerates as the temperatures and stresses increase. The driving force for chain segment recovery dominates at high temperature and stress levels, leading to a faster relaxation process. In contrast, the characteristic recovery time of PVF is prolonged under severe temperature and stress conditions.

Based on the above findings, we propose the deformation mechanism for two different rubbers under various temperatures and stresses. The reduction in creep deformation with increasing temperature in the open-cell silicon–hydrogen rubber foam can be attributed to a temperature-induced shift in the balance between instantaneous and time-dependent deformation. Specifically, the maximum creep strain decreases and the strain plateau is reached more rapidly with increased temperatures. Physically, this behavior results from thermally induced post-curing of residual Si–H groups left in the raw materials during synthesis, which increases crosslink density at higher temperatures. This increased crosslink density limits chain mobility and promotes solid-like behavior within the polymer network, leading to lower creep deformation. In the open-cell structure, where deformation is governed by the solid skeleton rather than gas pressure, these effects suppress creep deformation and promote rapid instantaneous and elastic recovery. As a result, the material exhibits a transition toward a more elastic-dominant mechanical response at higher temperatures, which is consistent with the creep and recovery test results and other characterizations [8, 9].

In contrast, the pronounced temperature-dependent creep behavior of PVF can be attributed to the combined effects of matrix softening and irreversible chain dynamics. Elevated temperatures weaken the intermolecular forces between polymer chains, reduce segmental stiffness, and significantly enhance chain mobility, thereby triggering temperature-activated softening of the polymer matrix. With the softened matrix, time-dependent viscous creep deformation dominates the total deformation under constant loading, leading to higher creep strain at elevated temperatures. Under prolonged loading, the mobilized polymer chains undergo irreversible relative slippage, dislocation, and viscous flow. These permanent configurational changes cannot automatically revert upon unloading, resulting in irreversible plastic deformation that ultimately manifests as significant residual strain. Consequently, the material evolves into a deformation state governed by viscous flow and structural irreversibility as temperature increases, fully consistent with the creep and recovery behaviors documented in the experimental data.

4. Conculsion

Creep and recovery behaviors of SHF and PVF are systematically investigated by DMA under varying temperatures and stresses, and the experimental data are quantitatively fitted using the Burgers model and the Weibull distribution function. The results reveal that fundamental differences in their crosslinked network structures lead to distinct mechanical properties between the two materials. SHF demonstrates excellent creep resistance and rapid elastic recovery under all test conditions, with outstanding structural stability. In contrast, although PVF has higher initial stiffness, it still shows a significant decline in creep resistance under long-term loading accompanied by prominent irreversible viscous deformation, and its uncovered deformation increases significantly as conditions become more severe. These performance differences provide guidance for their targeted application in different service scenarios and future performance optimization. Based on these findings, SHF is more suitable for high-temperature and high-load fields such as aerospace and precision electronics, where long-term stability is critical, while PVF can be used in low-temperature and low-load conditions such as general cushioning packaging, building seals and normal industrial thermal insulation.

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