Research Article

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Study on the aging of three typical rubber materials under high- and low-temperature cyclic environment

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Abstract: As the key components of sealing applications, rubber seals are subject to complicated environmental conditions during the service lifetime. In this study, the aging of three typical rubber materials, ethylene–propylene–diene monomer rubber, liquid silicone rubber, and fluorine rubber, was tested under different high- and low-temperature cycle aging environments. The experimental results confirm that the reciprocating temperature cycle causes a type of fatigue failure, which could result in an increase in the rubber compression set. In addition, a novel accelerated aging test method was proposed based on the dominant damage mechanism of rubber material caused by the temperature cycle treatments. Based on this method, the long-term aging test results of rubber samples under high- and low-temperature cycle conditions can be predicted. This method could significantly shorten the aging test time and reduce the test cost.

Keywords: high- and low-temperature cycle, sealing material, durability, lifetime prediction, aging

1 Introduction

Rubber, a sealing material with excellent mechanical properties, has been extensively applied in the sealing of energy power equipment in aviation, aerospace, transportation, electric power, etc. (1–3). The durability and reliability of rubber seals are critical for the lifetime (4–6). During long-term operation, the sealing materials age and degrade under the action of oxygen, high temperature, water, acid, temperature cycles, etc.

Chang et al. (7) investigated the aging of silicone rubbers with different types of hardness subjected to dry and humidified air at different temperatures. With increasing temperature, the aging of silicone rubbers became more severe, as indicated by the variations in the permanent compression set value, mechanical properties, and surface morphology. Li et al. (8) studied the aging mechanism of silicone rubbers in simulated proton exchange membrane fuel cells (PEMFCs) in humid, acidic, and high-temperature environments. The results indicate that the aging mechanism is mainly due to decomposition in the backbone and hydrolysis of the crosslinking. Wang et al. (9) investigated the chemical and mechanical degradation of a type of silicone rubber. The weight loss test results indicate that the exposure time and the compression load had great influences on the weight loss of the silicone rubber specimens. The specimens degraded more severely in strong acid solutions and when greater compression loads were applied. The degradation mechanism could have been chain scissoring in silicone rubber and the hydrolysis of the crosslinking positions. Wu et al. (10) studied the degradation of silicone rubber as a PEMFC sealing material during different cold-start processes. The results indicate that rubber under temperature cycle has an aging trend similar to that of thermo-oxygen aging. With an increasing number of temperature cycles, the hardness of silicone rubber increased, and its weight tended to decrease. In addition, some studies on the aging of reactor sealing materials, including accelerated aging experiments
of rubber materials at different compression rates, voltages, and vibrations, investigated the changes in material properties and seal failure forms (11–14).

The lifetime prediction of rubbers, which are influenced by many factors, is a complex problem. It is of great significance to study the aging mechanism and the interaction among these factors for the prediction of the actual service life of rubbers. Existing research on PMFEC sealing rubber material aging has primarily focused on the roles of high temperature, acidity, and some other significant factors in the rubber aging process, whereas some potential aging factors have been ignored, such as the temperature cycle (15). For example, the rubber seals of PEMFCs are used in vehicles; when the vehicles do not work, the temperature of the rubber seals remains consistent with the environmental temperature. The temperature of the fuel cell stack can be as low as −40°C in winter in some cold regions (16,17), and it can reach up to 90°C after the vehicle starts (18,19). During the whole life cycle, the temperature of PEMFC rubber seals tends to change periodically over a wide temperature range. Such temperature cycles often occur up to several thousand times, thus negatively affecting the sealing performance and service life of rubber materials (20). Although existing research has investigated the aging of silicone rubber under temperature cycle conditions and analyzed the corresponding aging mechanism, the effects on the temperature cycles and thermal aging were not distinguished. First, controlled trials under a cycle temperature aging environment were designed in this study to solve the above problem. The effect of temperature cycles on the aging of rubber samples was analyzed after the effect on thermal aging was ruled out. The compression set measurement results suggest that the greater the number of temperature cycles, the larger the compression permanent deformation of the rubber samples. The attenuated total reflection-Fourier transformed infrared (ATR-FTIR) test results show that temperature cycles will cause molecular chain degradation in rubber. Rubber samples undergo recurrent thermal stress when subjected to repeated cycles of high- and low-temperature fluctuations. In general, the effect of the temperature cycle on the rubber is a type of thermal fatigue failure. Second, the impact of thermal aging and thermal fatigue on rubber’s compression set was investigated. Finally, a test method was provided in this work to estimate the effect of thermal fatigue on the compression set of rubber by employing an equivalent strain cycle test instead of a temperature cycle aging test. In this study, the aging process of rubbers under high- and low-temperature cycling environments was explained, and a prediction technique of rubber compression set under the influence of thermal cycling and thermal fatigue was put forward. This method can serve as a reference for the actual life prediction of rubber static sealing, such as sealing gaskets in PEMFCs, lithium batteries, and many other sealing applications.

2 Materials and methods

2.1 Experimental materials

To get some broad conclusions, three rubber compounds that are frequently utilized in seals were used. Figure 1 presents the rubber samples employed in this study. Liquid silicone rubber (LSR), ethylene propylene diene
monomer rubber (EPDM), and fluorine rubber (FPM), as shown in Figure 1, were employed for the rubber test in this research (the hardness of the three rubber materials is 70HA, provided by Zhongding Sealing Parts Co., Ltd., Joint Research Center, Ningguo, Anhui, China). Referring to GB/T 7759.1-2015, type A rubber compression was selected as samples (21), and the samples were molded into cylinders 29.0 ± 0.5 mm in diameter and 12.5 ± 0.5 mm in height.

2.2 Experimental testing

2.2.1 Compression set test

The compression set is a crucial metric for assessing the rubbers’ service life in static sealing. In accordance with GB/T 20028-2005 and GB/T 27800-2021 standards, in the field of lifespan prediction, the relationship between compression set and aging time is typically established through aging experiments, and aging time is then calculated using the critical value of compression set for rubbers, where the critical value of compression set is associated with service circumstances. In this study, compression set was utilized to demonstrate how rubber lifetime is affected by aging (22,23).

According to GB/T 7759.1-2015, samples were compressed by 25% (the compression strain of samples was 25%). Up to the designed aging time, samples were taken out of the aging box and cooled for 2 h at room temperature. Then, the fixtures were released and the samples were kept at room temperature for 30 min. In order to obtain reliable results, three samples were used at each test point. The thickness of the samples was measured, and the compression set can be determined by the following equation:

\[ C_s = \frac{H_0 - H_1}{H_0 - H_s} \times 100\% \]  

where \( H_0 \) is the initial height of the rubber samples, \( H_1 \) is the free recovery height of the rubber samples at room temperature after the compression set test, and \( H_s \) is the height of the limit block.

2.2.2 ATR-FTIR test

ATR-FTIR was used to analyze the changes in the molecular structure and functional groups on the surface of rubber samples. Attenuated total reflection technology can be used to identify specific molecules and groups located on the surface layer and analyze the chemical degradation mechanism of rubber during the aging process. ATR-FTIR measurements were performed using a Nicolet 50 FTIR spectrometer (Thermo Fisher Scientific, Waltham, MA, USA). Samples were scanned from 400 to 4,000 cm\(^{-1}\) at a resolution of 0.5 cm\(^{-1}\).

2.3 Experimental procedure

2.3.1 Temperature cycle control aging experiment-A

A temperature cycle control aging test was designed, as shown in Figure 2, to investigate the changes of rubber caused by temperature in an onboard environment. The

![Figure 2: Temperature cycle control aging experiment-A.](image)
The highest temperature was set up to 90°C, and the lowest temperature was \(-40°C\). It took 40 h for the Group 1 samples to experience one temperature cycle time and 1 h for those of Group 2 samples. The total aging time was 240 h. During the specific aging time, the two groups of rubber samples experienced the same degree of high-temperature aging. Based on the differences between the two experiments, the effect on thermal aging in the high- and low-temperature cycles was excluded. The compression set and ATR-FTIR test data of the control samples of the two groups were examined, and then, the effect of the temperature cycles on the rubber was studied.

### 2.3.2 Temperature cycle control aging experiment-B

High-temperature aging and temperature cycle aging tests were conducted based on the compression set measurement results to conduct an in-depth study on the coupling relationship between thermal aging and thermal cycle factors with regard to the permanent compression deformation of rubber during the aging process. The Group 3 samples were aged at a constant temperature of 90°C, and the Group 4 samples were aged in a high- and low-temperature cycle aging environment with highest and lowest temperatures of 90°C and \(-40°C\), respectively, as shown in Figure 3. Since the growth rate of the permanent compression set of rubber under a high-temperature environment is much higher than that under a low-temperature environment, the high-temperature holding time served as the aging time in the aging test (24,25). The total aging time was 288 h in high-temperature condition.

### 2.3.3 Equivalent strain cycle experiment

Fatigue could result in the damage of some network structures in rubber that are damaged. With an increasing number of cycles, the fatigue damage of rubber gradually accumulates and ultimately affects the performance of rubber material (26,27). There are significant differences in the thermal expansion coefficients of the rubber material and metal fixture in the temperature cycle environment, so the thermal expansion of rubber is constrained, and the thermal stress cycle occurs in the process. In accordance with the analysis and verification results of the main failure mechanism of rubber material caused by the temperature cycle, a novel test method was developed by replacing the temperature cycle aging test with an equivalent strain cycle fatigue test to predict the compression set of rubber samples caused by reciprocating temperature change.

Since the thermal expansion coefficient of the rubber material is significantly higher than that of the metal fixture, the deformation of the metal fixture during the temperature-changing process can be ignored. The stress amplitude \(\Delta\sigma\) of rubber in the reciprocating temperature-changing process can be obtained as follows (15):

\[
\Delta\sigma = E\alpha \Delta T, \tag{2}
\]

where \(\alpha\) is the thermal expansion coefficient of the rubber material, \(\Delta T\) is the ambient temperature difference, and \(E\) is the modulus of the rubber.

The same stress cycle process can be achieved by loading the repeated strain cycle load on the rubber sample. The equal effect change amplitude required for loading is expressed as follows:

![Figure 3: Temperature cycle control aging experiment-B.](image-url)
\[ \Delta \varepsilon = a \Delta T. \] (3)

For the aging experimental environment in this study, the highest ambient temperature was set to 90°C, and the lowest temperature was set to −40°C. Table 1 lists the thermal expansion coefficient of the three materials and the strain amplitude of the strain cycle experimental loading.

The equivalent strain cycle experiment of rubber was performed using a universal testing machine. The initial compression state of the rubbers should be the same as which in the aging test. The surface of the metal head was coated with a thin layer of silicone oil lubricant; then, the rubber was compressed to a 25% strain state. This compression state was maintained for 24 h to avoid the effect of the stress relaxation on the experimental results. After the compressed stress stabilized, the state at this moment was taken as the initial condition for the strain cycle experiment. First, the pressure head of the testing machine compressed the strain amplitude of \( \Delta \varepsilon \) at a constant rate of 0.5 mm-min\(^{-1}\). Meanwhile, the pressure head was unloaded back to the original position at the same rate to complete a cycle. Subsequently, the compression stress of rubber at this time was recorded in the strain cycle experiment. In order to obtain reliable results, three samples were used at each test point. After \( N \) strain cycles, the compressive stress decreased by \( \Delta \sigma_N \), which is due to the irreversible strain caused by fatigue. The strain in this part was denoted as the accumulated residual strain. Afterward, the accumulated residual strain \( \varepsilon_N \) of the rubber material after \( N \) cycles can be obtained as follows:

\[ \varepsilon_N = \frac{\Delta \sigma_N}{E_0}, \] (4)

where \( E_0 \) is the tangent modulus at the current compression ratio and \( N \) is the number of cycles.

The changing relationship between the accumulated residual strain and cycle number \( N \) refers to the form of the S–N fatigue curve formula, and the fitting expression is written as follows:

\[ \varepsilon_N = K (2N)^d, \] (5)

where \( K \) and \( d \) are experimental constants.

Next, combined with Eqs. 4 and 5, the compression set of rubber samples caused by circulation is written as follows:

\[ C_{CN} = \frac{H_0 \cdot \varepsilon_N}{H_0 - H_s} = \frac{H_0 \cdot K (2N)^d}{H_0 - H_s}. \] (6)

To verify the feasibility of the proposed method, the predicted results calculated by Eq. 6 were compared and analyzed with the experimental data of the temperature cycle control aging experiment.

3 Results and discussion

3.1 Temperature cycle control aging experiment-A test results

The experimental samples were placed into two aging environments, Group 1 and Group 2 (Figure 3), for aging experiments to indicate the effect of reciprocating temperature changes on the rubber. The effect of the number of cycles on the permanent compression deformation test and chemical degradation of rubber was examined by comparing the two groups of experimental samples.

3.1.1 Compression set test results

Figures 4a, 5a and 6a illustrate the test results of the permanent compression deformation of three types of rubber samples in Group 1 and Group 2 under environmental aging. Under the same aging time, the permanent compression set of rubber samples in the Group 2 aging condition was larger, whereas the Group 2 samples experienced more cycles. These results suggest that the rubber materials that experience more temperature cycles in the experiment were subjected to a greater permanent compression set caused by reciprocating changes in temperature. The experimental data were processed to determine the relationship between the cycle number \( N \) and the permanent compression deformation of rubber caused by circulation, where the permanent compression deformation caused by circulation is expressed as \( C_{CN} \). As depicted in Figures 4b, 5b and 6b, the increase in cycle number \( N \) will result in a greater permanent compression deformation \( C_{CN} \) of rubber samples. Under the experimental conditions
of $N$ cycles, the cumulative residual strain satisfied the following relationship: LSR > FPM > EPDM.

The performance deterioration of rubber materials is a complex process of chemical and physical changes. Physical and chemical changes will unavoidably take place when rubbers are compressed. As a result of these changes, rubbers begin to aging, and one macroscopic sign of this aging is an increase in compression permanent deformation. If the compression force disappears, these changes will prevent rubbers from returning to its original state; thus, compression permanent deformation is generated. The temperature, time of the compression state, and aging environment all affect the value of permanent compression deformation. High temperatures cause physical and chemical changes in rubbers that permanently alter their original network. On a macro-level, this is manifested as compression permanent deformation. Under the temperature cycling environment, due to the significant differences in the thermal expansion coefficients of the rubber material and the metal fixture in the temperature cycle environment, the rubber will experience periodic reciprocating thermal stress during the aging process, while the periodic stress load can also cause the damage effect on the rubber network even if the stress loads are much lower.

![Figure 4](image1.png)

**Figure 4:** Compression set test results of LSR under (a) different environmental aging and (b) different cycle number $N$ conditions.

![Figure 5](image2.png)

**Figure 5:** Compression set test results of EPDM under (a) different environmental aging and (b) different cycle number $N$ conditions.
With an increasing number of cycles, the fatigue damage of the material will be more serious, which further leads to the deterioration of the performance of the rubber material. This process explains the greater compression set of rubber samples under reciprocating temperature changes.

### 3.1.2 ATR-FTIR test results

The ATR-FTIR spectra of LSR samples subjected to different aging conditions are shown in Figure 7. The peaks at 3,378 cm\(^{-1}\) are assigned to the –OH bond stretching vibration. The peaks at 2,960 cm\(^{-1}\) are assigned to the C–H bond stretching vibration from methyl groups. The peaks at 1,262 cm\(^{-1}\) are assigned to Si–CH\(_3\) bond stretching vibrations. The peaks at 1,080 and 1,010 cm\(^{-1}\) are assigned to Si–O–Si bond stretching vibrations. The peaks at 790 cm\(^{-1}\) are assigned to Si–(CH\(_3\))\(_2\) bond stretching vibrations (13,28,29). A comparison of the spectra of the original and aged samples indicates that the peak at 3,378 cm\(^{-1}\) assigned to the –OH bond increased for the aged sample, which was due to the oxidation reaction during the aging process. A comparison of the spectra of the Group 1 and Group 2 aged samples indicates that the peaks at 1,080 and 1,010 cm\(^{-1}\) assigned to the Si–O–Si bond were lower for the Group 2 samples, which means that some rubber

![Figure 6: Compression set test results of FPM under (a) different environmental aging and (b) different cycle number \(N\) conditions.](image-url)

![Figure 7: ATR-FTIR spectra of the LSR samples.](image-url)
molecular chains were damaged due to the influence of the thermal stress cycle.

The ATR-FTIR spectra of EPDM samples subjected to different aging conditions are shown in Figure 8. The peaks at 3,378 cm\(^{-1}\) are assigned to the –OH bond stretching vibration. The peaks at 2,960 and 2,815 cm\(^{-1}\) are assigned to methylene stretching vibrations. The peaks at 1,535 cm\(^{-1}\) are assigned to zinc stearate. The peaks at 1,032 cm\(^{-1}\) are assigned to the C–O bond stretching vibration from aliphatic esters (30–33). A comparison of the spectra of the original and aged samples indicates that the peak at 3,378 cm\(^{-1}\) assigned to the –OH bond and the peak at 1,032 cm\(^{-1}\) assigned to the C–O bond increased for the aged samples, which was due to the formation of new oxygen-containing groups from the oxidation reaction during the aging process. A comparison of the spectra of the Group 1 and Group 2 aged samples indicates that the peak at 1,032 cm\(^{-1}\) assigned to the C–O bond was slightly higher for the Group 2 samples, which may be because some rubber molecular chains were damaged due to the effects on the thermal stress cycle, and the free radicals at the fracture combined with oxygen could generate additional C–O bonds.

The ATR-FTIR spectra of FPM samples subjected to different aging conditions are shown in Figure 9. The peaks at 2,920 and 2,815 cm\(^{-1}\) are assigned to methylene stretching vibrations. The peak at 1,720 cm\(^{-1}\) is assigned to the C=O bond stretching vibration. The peaks at 1,560 cm\(^{-1}\) are assigned to the C=C bond stretching vibration. The peak at 1,410 cm\(^{-1}\) is assigned to the CF bond stretching vibration. The peaks at 1,194 and 1,136 cm\(^{-1}\) are assigned to CF\(_2\) bond stretching vibrations. The peak at 890 cm\(^{-1}\) is assigned to the CF\(_3\) bond stretching vibration (34–36). A comparison of the spectra of the original and aged samples indicates that the peaks assigned to CF and

Figure 8: ATR-FTIR spectra of the EPDM samples.

Figure 9: ATR-FTIR spectra of the FPM samples.
CF₂ bonds decreased for the aged samples, which was due to the degradation of FPM during the aging process. In addition, the peak at 1,720 cm⁻¹ assigned to the C=O bond increased for the aged samples, which was due to some of the C=C bonds in the rubber molecular chain being oxidized to form C=O bonds. A comparison of the spectra of the Group 1 and Group 2 aged samples indicates that the peak at 1,560 cm⁻¹ assigned to the C=C bond was lower for the Group 2 samples because some rubber molecular chains were damaged due to the effects on the thermal stress cycle.

The comprehensive analysis result of the infrared spectra of the above three rubber materials (LSR, EPDM, and FPM) suggests that high temperature primarily affects the thermal oxygen aging reaction of rubber. During the reciprocating temperature change, the thermal stress cycle caused by the difference in thermal expansion performance between the rubber and the metal fixture causes the fatigue damage of the rubber material and the fracturing of molecular chains with the stress concentration in rubber.

### 3.2 Temperature cycle control aging experiment-B test results

Figures 10a, 11a and 12a present the permanent compression deformation test results of the experimental rubber
samples in the aging environments of Group 3 and Group 4. Under the same high-temperature aging time, the rubber samples in the aging environment of Group 3 were only affected by thermal aging, while the rubber samples in the Group 4 aging environment were simultaneously affected by thermal aging and thermal cycling. Based on the findings of Group 3, it can be stated that the compression set rise rate of FPM is less than that of EPDM and LSR per unit aging time. This is due to the superior thermal aging resistance of FPM. Under the same high-temperature aging time, the rubber samples in the aging environment of Group 4 had more serious permanent compression deformation, consistent with the rule obtained in the above temperature cycle control aging experiment. In a high- and low-temperature cycle aging environment, the thermal aging of rubber at high temperatures was the major factor leading to the increase in its permanent compression deformation, and the temperature circulation further facilitated the increase in the permanent compression deformation of rubber.

In the experiment, the compression set of rubber samples in the environment of Group 3 (continuous constant high-temperature environment) is expressed as $C_{ST}$. The compression set of rubber samples in the environment of Group 4 (high- and low-temperature cycle environment) is expressed as $C_{SR}$. The compression set of rubber caused by thermal cycling over the aging time is expressed as $C_{SN}$, which can be obtained according to the experimental data in Figures 4b, 5b and 6b.

Once $C_{ST} + C_{SN}$ is calculated, the result is compared with $C_{SR}$, as depicted in Figures 10b, 11b and 12b. The above result reveals that the two sets of data overlap within the allowable range of error, so the corresponding relation can be written as follows:

$$C_{ST} + C_{SN} = C_{SR} \quad (7)$$

Since $C_{ST} + C_{SN}$ is approximately equal to $C_{SR}$, the effects of thermal aging and thermal cycling on the permanent compression deformation of rubber are considered to be independent of each other within the allowable range of error.

In a temperature cycle aging environment, the thermal stress cycle caused fatigue damage to rubber. Due to the small frequency of the cycle, it had a low amplitude and small number of total cycle times, so it pertains to the scope of mild fatigue, and the molecular chain inside the rubber may have ruptured (network damage), whereas no macro-fracturing occurred (generation of new free surface area). Under these conditions, the fatigue damage is insufficient to affect the thermal aging of rubber, or its effect on thermal aging can be ignored.

### 3.3 Equivalent strain cycle test results

Figures 13a, 14a and 15a illustrate the test results of the equivalent strain cycle experiments of the three rubber samples, suggesting that the cumulative residual strain of the rubber samples will increase with an increasing number of cycles. Eq. 4 is modified to fit the experimental data, and the results of the fitting parameters are listed in Table 2.
The fitting parameters are substituted into Eq. 5 to obtain the compression set caused by the circulation, and the predicted results are compared with the experimental test results, as presented in Figures 4b, 5b and 6b. As depicted in Figures 10b, 11b and 12b, the predicted results are consistent with the test results of the compression set in the above experiment. This indicates that temperature cycling promotes the growth of the rubber compression set due to the reciprocating thermal stress during aging. In addition, the compression set of rubber samples caused by circulation can be examined through an equivalent strain cycle test instead of a temperature cycle test in the allowable error range.

![Figure 13](image1.png) **Figure 13:** Accumulated residual strain (a) and cycle-induced compression set prediction (b) of LSR samples.

![Figure 14](image2.png) **Figure 14:** Accumulated residual strain (a) and cycle-induced compression set prediction (b) of EPDM samples.

<table>
<thead>
<tr>
<th>Material</th>
<th>$K$</th>
<th>$D$</th>
<th>$R^2$</th>
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<tbody>
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<td>LSR</td>
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<td>0.48</td>
<td>0.99</td>
</tr>
<tr>
<td>EPDM</td>
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<td>0.94</td>
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<tr>
<td>FPM</td>
<td>$2.38 \times 10^{-4}$</td>
<td>0.43</td>
<td>0.99</td>
</tr>
</tbody>
</table>

**Table 2:** Rubber material parameters
In the high-temperature acceleration aging compression test, the compressed permanent deformation can be regarded as a function of temperature and time. The variable rate of compressing set between different temperatures meets the Arrhenius relationship, and its expression can be written as follows (37):

\[ k = A \exp \left( \frac{-E_a}{RT} \right) \] (8)

where \( A \) is the characteristic factor, \( E_a \) is the apparent activation energy, \( R \) is the gas constant, and \( T \) is the absolute temperature.

The relationship between the aging estimate index representing the aging characteristics and the aging time can be described as the following expression (38, 39):

\[ C_{iT} = 1 - B \exp(-k \cdot t^\beta) \] (9)

where \( B \) is the test constant, and \( \beta \) is the experimental constant, which need to be determined by high-temperature accelerated aging experiments.

Combined with Eqs. 6, 7, and 9, the prediction model of the compression set of rubber samples in a high- and low-temperature environment can be written as follows:

\[ C_t = C_{iT} + C_{iN} = 1 - B \exp(-k \cdot t^\beta) + \frac{H_0 \cdot K(2N)^d}{H_0 - H_b} \] (10)

where \( t \) is the high-temperature aging time experienced by the rubber and \( N(t) \) is the number of temperature cycles experienced by the rubber during the high-temperature aging time.

Therefore, for the compression set prediction of rubber samples in a high- and low-temperature cycle environment, the high-temperature accelerated and equivalent strain cycle experiments can be conducted separately to test the two aging factors (thermal aging and thermal fatigue) in the temperature cycle process, respectively, and then, the test results are imported into the prediction model to obtain the long-term compression set test results of rubber samples under high- and low-temperature cycle conditions. In this test, a high-temperature accelerated aging environment is required, whereas a temperature cycling environment, particularly a low-temperature environment, is not necessary. As a result, the time required to conduct an aging test is greatly shortened, and the cost of the test is decreased.

**4 Conclusions**

Through the temperature cycle aging test and strain cycle test, the effects of thermal cycling on the aging process of three typical rubber materials (LSR, EPDM, and FPM) were investigated. The following conclusions can be made.

1. Thermal cycling raises the compression set of rubber in an aging environment, which is due to thermal fatigue caused by the substantial differential in thermal expansion characteristics between the rubber sample and the metal fixture under the situation of temperature cycling aging condition.
2. The ATR-FTIR test results reveal that a section of the molecular chain was broken during the temperature cycle operation.

3. When subjected to a temperature cycle aging condition between −40°C and 90°C, the coupling effects of thermal aging and thermal cycling on the compression set of rubber are roughly independent of one another.

4. The suggested accelerated aging test technique for rubber is performed using high-temperature accelerated aging and equivalent strain cycle tests, and the test results are imported into the proposed model to forecast the long-term aging compression set test results under temperature cycling conditions.

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**Author contributions:** Sen Li: writing – original draft, methodology, experimental data acquisition; Yuchao Ke: resources, technical or material support; Lingyun Xie: resources, technical or material support; Zhenzhen Zhao: resources, technical or material support; Xiaoyu Huang: experimental design, experimental data processing; Yichun Wang: resources, instructional support; Zixi Wang: writing – review and editing, instructional support, resources.

**Conflict of interest:** The authors state no conflict of interest.

**Data availability statement:** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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