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Research on the ultraviolet aging performance of polyurethane elastomers

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Abstract

Purpose – This study aims to carry out optimization and improvement work on the artificial climate aging and ultraviolet aging tests of elastic expansion joints in railway concrete bridges.

Design/methodology/approach – Three polyurethane elastomer specimens with different chemical compositions were adopted. According to relevant standard regulations, the aging test process was analyzed and evaluated in detail, and reasonable improvement suggestions were put forward. The effectiveness was verified through actual tests.

Findings – The final test results indicate that the combination of artificial climate aging tests and ultraviolet aging tests is technically feasible and has significant advantages in practical applications.

Originality/value – This study optimizes the conditions of artificial climate aging and ultraviolet aging tests, compares the advantages and disadvantages of different aging test methods, and proposes a combined test scheme of artificial climate aging and ultraviolet aging and verifies its effectiveness. The results provide valuable reference for simulating the actual aging behavior of polyurethane elastomers, material performance evaluation, and application in railway bridge engineering. It is conducive to promoting the reasonable application of this material in engineering, improving engineering quality, reducing costs, and has economic and social benefits.

Keywords Engineering materials, UV aging, Experimental study, Polyurethane elastomers, Tensile strength

Paper type Research article

1. Introduction

Polyurethane elastomers (PU) are widely used in construction, transportation, machinery and many other fields due to their excellent wear resistance, oil resistance, tear resistance and good bonding performance. In the field of construction, PU elastomers are often used in building sealing and waterproofing projects. Its excellent elasticity and weather resistance can effectively prevent water seepage, ensuring the structural safety and service life of the building. In the transportation industry, polyurethane elastomers can be used as lining materials for automotive tires to enhance their wear resistance and tear resistance and improve driving safety. In mechanical manufacturing, it can be used to make various mechanical seals and shock-absorbing components, effectively improving the operational stability and reliability of mechanical equipment. However, polyurethane elastomers will inevitably face the problem of aging during long-term use. Especially in the outdoor environment, it is affected by a combination of factors such as ultraviolet rays (Wang, 2003), temperature and humidity (Zhang, 2017), resulting in a significant decline in material performance. For example, in some outdoor polyurethane elastomer sealing materials, after prolonged exposure to sunlight, their tensile strength and elasticity will significantly decrease, resulting in cracking, deformation and other phenomena, thus affecting the sealing effect and failing to meet the actual usage requirements. Therefore, in-depth research on the aging performance of

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polyurethane elastomers is of great practical significance for prolonging their service life, improving the reliability of use and their application in the railway field.

In recent years, more research has been conducted on the aging properties of polyurethane elastomers. Literature Xie, Zhu, and Zhang (2003) has studied the changes in the mechanical properties of polyurethane elastomers under different environmental conditions and found that ultraviolet radiation is one of the main factors leading to the deterioration of material properties. The effect of ultraviolet absorbers on the photostability of polyurethane elastomers was experimentally verified (Zhang, Li, & Wang, 2013). However, most of the existing studies have focused on the effects of a single aging factor, and there are relatively few studies on performance changes under combined aging conditions. In addition, existing aging test methods have deficiencies in simulating actual usage environments and need to be further optimized and improved.

The purpose of this study is to deeply optimize and improve the artificial climate aging and ultraviolet aging test conditions stipulated in “TJ/GW 120-2013 Temporary Technical Conditions for Elastic Expansion Joints of Railway Concrete Bridges” (China Railway Publishing House, 2014). By comparing the advantages and disadvantages of different aging test methods, a composite test scheme combining artificial climate aging and ultraviolet aging was proposed, and its effectiveness was verified. The research results are of great significance for more accurately simulating the aging behavior of polyurethane elastomers in actual usage environments, and can provide reliable references for the performance evaluation of materials and their applications in railway bridge engineering. Meanwhile, this research is also conducive to promoting the rational application of polyurethane elastomer materials in practical engineering, improving project quality, reducing project costs, and having significant economic and social benefits.

2. The structure and properties of polyurethane elastomers

The physical properties of polyurethane elastomers mainly include tensile strength, elongation at break (Xie *et al.*, 2003), hardness, abrasion resistance and tear resistance, which are closely related to the molecular structure. Studies have shown that the length and composition of the soft segments have a significant impact on the performance of polyurethane elastomers. When the length of the soft segments is longer, both the flexibility of the molecular chains and the elasticity and elongation at break of the material are improved. At the same time, longer soft segments can increase the sliding ability between the molecular chains, thereby enhancing the material’s wear resistance and tear resistance. For example, in some polyurethane elastomer materials, appropriately increasing the length of the soft segments allows the molecular chains to stretch and deform better when subjected to external force, thereby increasing the elongation at break of the material. The composition of the soft segments also affects the performance of the material, such as the significant difference in performance between polyester-polyurethane elastomers and polyether-polyurethane elastomers. The content and chemical structure of the hard segments also affect the performance of the material. As the content of hard segments increases, the tensile strength of the material improves significantly. This is because the chemical bonds in the hard segments increase the interaction between the molecular chains, making the material less likely to deform or break under force. However, the increase in the content of hard segments also leads to a decrease in the material’s elongation at break, because the increase in hard segments enhances the material’s rigidity and reduces the flexibility of the molecular chains. In addition, the chemical structure of the hard segments can also affect the material’s performance. For example, polyurethane elastomers synthesized from aromatic isocyanates are different from those synthesized from aliphatic isocyanates in terms of light stability and mechanical strength. Reference Xu and Zhang (2011) examined the tensile properties of polyurethane elastomers with different formulations and found that the tensile strength of the material increased significantly with the increase of hard segment content, but the elongation at break decreased. Specifically, when the hard segment content gradually increased from a lower level, the tensile strength showed a significant upward trend, while the elongation at break gradually decreased. This result further confirms the significant effect of hard segment content on the tensile properties of polyurethane elastomers. In addition, the study shows that the wear resistance and tear resistance of polyurethane elastomers are closely related to their molecular structure. Polyurethane elastomers with longer soft segments have better wear resistance and tear resistance because longer soft segments provide better flexibility and molecular chain slip ability, allowing the material to better disperse stress when subjected to friction and tear forces, thereby improving the wear resistance and tear resistance of the material (Aglan, Calhoun, & Allie, 2008).

3. The aging mechanism of polyurethane elastomers

Polyurethane elastomers, as a high-performance polymer material, are widely used in various fields. However, during long-term use, its performance can be affected by a variety of factors, leading to a gradual decline in material performance and ultimately affecting its service life and application effect. Among them, ultraviolet radiation is one of the important factors that cause rapid aging of polyurethane elastomers. Ultraviolet radiation has a high radiation energy that can penetrate into the chemical structure of the material and break its chemical bonds, thereby accelerating the aging and failure process of the material.

Microscopically, the ultraviolet radiation band is mostly between 180 nm and 400 nm, and within this wavelength range, there is a high radiant energy of 314 to 419 kJ/mol (Jiang, Liu, Tong, Feng, & Li, 2005), but the conventional covalent bonds of elastomer materials, except for O-H, C-H, and C-F bonds, are mostly between 167 and 418 kJ/mol. Most of them are below 400 kJ/mol. It can be seen that ultraviolet radiation can basically break most of the chemical bonds in polyurethane elastomers, causing ultraviolet aging damage to polyurethane elastomer materials, reducing material performance indicators and, in practical applications, affecting the service life of the product. If the material is exposed to high density and high energy ultraviolet radiation, more chemical reactions will occur under the influence of outdoor conditions, and it will be a series of reactions because the polyurethane elastomer material is also affected by conditions such as temperature, humidity and oxygen. When the energy absorbed by the long chains of chemical polymers is higher than their dissociation energy, the long chains of polymers break, and then a series of chemical reactions are triggered by photoexcited states, mainly including the following types: when old chemical bonds break, new bonds gradually form, and this process involves cross-linking reactions; The polymer long main chains of elastomer materials break, and aging degradation occurs in the process; There are oxidation reactions and various gas reactions; In addition to these reactions, there may also be chemical reactions such as disproportionation, isomerization, and recombination.

There are two mechanisms for the photodegradation of polyurethane: one is photoinduced Fries rearrangement by direct absorption of ultraviolet radiation, and the other is photoinduced free radical oxidation rearrangement products. Under the action of ultraviolet light, the dicarboxylic acid bridge structure of the aromatic ring is oxidized to quinone-imine bonds or azo compounds. This leads to yellowing of the polyurethane elastomer components and a decline in the mechanical properties of the material. Therefore, the light stability of polyurethane must be achieved from two aspects: one is the addition of ultraviolet absorbers to reduce direct absorption of light radiation, and the other is the addition of phenolic antioxidants or steric hindrance ammonia to suppress free radical oxidation reactions. Polyurethane elastomers synthesized with aromatic isocyanates have poor light stability. Due to the inclusion of benzene rings, the concentration of benzene rings decreases, and the higher the light stability, the worse. The more carbon atoms between the polyester polyol esters, the longer the soft segment, the fewer benzene rings in the polyurethane elastomer will be relatively and the light aging reaction will be weakened, thereby enhancing the resistance to UV aging. Another method is to add UV absorbers and antioxidants, which can significantly improve UV resistance, or to add color pastes, especially yellow and red ones, which can greatly enhance UV resistance of polyurethane elastomers. This is mainly because chrome yellow, iron red, titanium dioxide and carbon black themselves are good UV stabilizers that can prevent UV damage to the elastomer segments (Ministry of Railways of the People's Republic of China, 2005).

Most polyurethane elastomers contain aromatic diisocyanates, which will change color under ultraviolet light, especially prone to discoloration and yellowing (Aglan, Calhoun, & Allie, 2008). Aromatic diisocyanates and their initial reaction products are highly prone to oxidative discoloration when exposed to light with wavelengths ranging from 300 to 400 nm (Schollwnberger, 1973). There are two reasons for the yellowing of the color:

(1) When the wavelength is between 0 nm and 340 nm, it stimulates the aromatic chromophiles to undergo photofries reaction, and the product contains primary aromatic amines.

(2) In the range of 330 to 400 nm, the initial photofries reaction product is further photo-oxidized to form a new substance containing benzoquinone diimine hydrogen peroxide (Gaudette & Lemaire, 1984).

In summary, the polyurethane elastomer undergoes the following changes during ultraviolet aging:

(1) Breaking of chemical bonds: The high energy of ultraviolet light breaks the chemical bonds in the polyurethane molecular chain, resulting in a decrease in molecular weight.

(2) Photochemical reactions: Ultraviolet light causes photoinduced Ferris rearrangement and free radical oxidation reactions, resulting in yellowing and reduced performance of the material.

(3) Oxidation reaction: An oxidation reaction caused by the combined action of ultraviolet light and oxygen, resulting in hardening and embrittlement of the material surface.

(4) Cross-linking reaction: The cross-linking reaction triggered by ultraviolet light leads to a decrease in the material's flexibility.

(5) Microstructure changes: UV aging causes molecular chain rearrangement and surface hardening, affecting the overall performance of the material.

These changes eventually lead to reduced tensile strength, changes in elongation at break, yellowing and discoloration of polyurethane elastomers.

4. Test the principle of improvement

The ignition part of the artificial climate aging (xenon arc lamp) (Nan, Du, Zhu, Wang, Zhao, & Zhang, 2019) test is considered the best test to simulate the full solar spectrum because it produces ultraviolet, visible, and infrared light. Because of this, it is considered the most widely used method at home and abroad. However, this method also has its limitations, namely the stability of xenon arc light sources and the complexity of the test system that comes with it. Xenon arc light sources must be filtered in order to reduce unnecessary radiation. There are multiple types of filter glass to choose from to achieve different irradiance distributions. The choice of glass depends on the type of material being tested and its end use. Replacing the filter glass can change the type of short-wave ultraviolet light passing through, thereby altering the rate and type of damage to the material.

UV lamp exposure aging tests use fluorescent UV lamps to simulate the destructive effect of sunlight on durable materials. Unlike the xenon arc lamps mentioned earlier, fluorescent UV lamps are electrically similar to ordinary cold fluorescent lamps, but produce more ultraviolet than visible or infrared light. Fluorescent UV lamps are low-pressure mercury arc lamps. The radiation emitted by the mercury arc is converted into longer wavelengths of ultraviolet radiation through a phosphorus coating, and the spectral energy distribution depends on the emission spectrum of the mercury arc and the ultraviolet radiation transmittance of the glass tube. The internal spectral stability of fluorescent UV lamps simplifies the control of irradiance. All light sources weaken with age. But fluorescent UV lamps are different from other types of lamps because their spectral energy distribution does not change over time. This feature enhances the repeatability of test results, and therefore fluorescent UV lamps have a rather unique advantage in durability test studies.

The difference between artificial climate aging (xenon arc lamp) and fluorescent UV lamp is that xenon lamp irradiation test chamber simulates the entire solar spectrum, including ultraviolet, visible and infrared light, with the aim of simulating sunlight. UV aging tests do not attempt to imitate sunlight, but only the destructive effects of sunlight. The principle behind it is that durable materials exposed outdoors for a long time are more damaged by short-wave ultraviolet light than by visible light and infrared light. As long as there is ultraviolet, infrared and visible light, the aging damage can be ignored. Therefore, when designing test conditions, only ultraviolet light should be designed to cover all aging damage caused by sunlight.

5. Selection mechanism for fluorescent UV lamps

There are three types of fluorescent UV lamps in GB/T 14522-2008:

(1) UVA-340 fluorescent UV lamp: The relative spectral energy distribution of this type of lamp should comply with the situation in Table 1. The total radiation percentage below 300 nm is less than 2%, and the peak radiation energy is at a wavelength of 340 nm. This type of lamp is generally used to simulate medium and short wave ultraviolet light in daylight.

(2) UVA-351 fluorescent ultraviolet light: The relative spectral energy distribution of this type of lamp should conform to the situation in Table 2, where wavelengths below 300 nm account for less than 2% of the total radiation, and its peak radiation energy is at 351 nm. This type of lamp is generally used to simulate medium and short-wave ultraviolet light in daylight.

(3) UVA-313 fluorescent UV lamp: The relative spectral energy distribution of this type of lamp should conform to the situation in Table 3, less than 300 nm wavelength accounted for less than 2% of the total radiation, and its radiation energy peak at 351 nm wavelength. This type of light is generally used to simulate the middle and short wave ultraviolet in daylight.

Table 1. Relative spectral energy distribution of UVA-340 fluorescent UV lamp

Wavelength passband/nm	Minimum %	Maximum value
Lambda <290	/	0.01
290 or less lambda 320 or less	5.9	9.3
320 < lambda 360 or less	60.9	65.5
360 < lambda 400 or less	26.5	32.8

Note(s): The data in the table is the cumulative irradiance in the given wavelength passband as a percentage of the total irradiance, and the wavelength passband of the total irradiance is 290–400 nm

Source(s): GB/T 14522-2008

Table 2. Relative spectral energy distribution of UVA-351 fluorescent UV lamp

Wavelength passband/nm	Minimum %	Maximum value
Lambda <290	/	0.2
290 or less lambda 320 or less	1.1	3.3
320 < lambda 360 or less	60.5	66.8
360 < lambda 400 or less	30.0	38.0

Note(s): The data in the table is the cumulative irradiance in the given wavelength passband as a percentage of the total irradiance, and the wavelength passband of the total irradiance is 290–400 nm

Source(s): GB/T 14522-2008

Table 3. Relative spectral energy distribution of UVA-313 fluorescent UV lamp

Wavelength passband/nm	Minimum %	Maximum value
Lambda <290	1.3	5.4
290 or less lambda 320 or less	47.8	65.9
320 < lambda 360 or less	26.9	43.9
360 < lambda 400 or less	1.7	7.2

Note(s): The data in the table is the cumulative irradiance in the given wavelength passband as a percentage of the total irradiance, and the wavelength passband of the total irradiance is 290–400 nm

Source(s): GB/T 14522-2008

The relative spectral energy distribution data is calculated by rectangle integration. Equation 3-1 is the equation using rectangular integral to determine the relative spectral energy distribution. Other integration methods can also be used to calculate the relative spectral energy distribution, but different values may be obtained. The rectangular integral is used when comparing the relative spectral energy distribution of a fluorescent UV lamp with the spectral energy analysis specified in this standard (Gaudette & Lemaire, 1984).

To determine whether a fluorescent UV lamp meets the requirements of Tables 1–3, measure its spectral energy distribution between 250 and 400 nm. Usually, measurements should be taken at wavelength intervals of 2 nm. If the manufacturer’s spectral measuring instrument cannot measure wavelengths as low as 250 nm, the lowest wavelength measured should be reported. The lowest wavelength measured must not be greater than 270 nm. To determine whether the spectral energy distribution of the fluorescent ultraviolet lamp UVB-313 meets the requirements, a measurement range of 250 to 400 nm is required. Calculate the cumulative irradiance between each wavelength bandpass, then divide by the given total UV irradiance as shown in Formula A. When applying Formula, it is required to use the same wavelength interval (step size) within the spectral range of the application, such as 2 nm (General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China and the Standardization Administration of China, 2008).

$$I_R = \frac{\sum\limits_{\lambda_i=A}^{\lambda_i=B} E_{\lambda_i}}{\sum\limits_{\lambda_i=C}^{\lambda_i=400} E_{\lambda_i}} \times 100$$

In the formula:

I_R – Relative irradiance expressed as a percentage, %;

E_{λ_i} – Irradiance at the wavelength (the order of all wavelengths should be equal), in watts per square meter (λ_i W/m^2);

A – Lower limit of wavelength band pass, in nanometers (nm);

B – Upper limit of wavelength bandpass, in nanometers (nm);

C – Lower limit of total UV band pass for calculating relative spectral irradiance (290 nm for UVA-340 lamp and 250 nm for UVB-313 lamp), in nanometers (nm);

λ_i – Measured irradiance wavelength in nanometers (nm).

The UVA-340 fluorescent UV lamp was chosen as the test light source in the design of this experiment because the relative spectral energy distribution of the UVA-340 fluorescent UV lamp is closest to the ultraviolet energy of midday sunlight.

6. Test section

6.1 Test materials

Three different components of polyurethane elastomer samples, numbered 1# to 7#. The samples before and after aging are shown in Figures 1 and 2.

6.2 Testing instruments

The UV aging samples were processed using the UVYEST/SPRAY UV fluorescence aging test chamber from Russ Materials Testing Technology Asia Pacific.

Tensile strength and elongation tests were performed using the Z010 high and low temperature electronic universal material testing machine, as shown in Figure 3.

Figure 1. Samples of 7 different components before and after ultraviolet aging. Source: Author's own work

Figure 2. Samples of seven different components before UV aging. Source: Author’s own work

Figure 3. Zwick high and low temperature electronic universal material testing machine. Source: Author’s own work

6.3 Test methods

Ultraviolet treatment of samples in accordance with GB/T 14522-2008 “Weathering Test Method for Artificial Fluorescent Ultraviolet Lamps” – Plastic, coating and rubber materials products for mechanical industry Appendix C: Exposure type 5(GB/T 14522-2008,2008), the sample treatment time is 30 days.

Tensile strength and elongation were tested in accordance with provisions 6.4.14 and 6.4.15 of TG/GW120-2013 “Interim Technical Conditions for Expansion Joints of Railway Concrete Bridge Elastomers” (Jiang, Yang, & Guo, 2010).

(1) Tensile test: Use dumbbell specimens of type 2 for tensile stress-strain performance of vulcanized or thermoplastic rubber as stipulated in GB/T528-2009, with a standard distance of 20 mm and a speed of 500 mm/min, with the final test result as the median.

(2) Ultraviolet aging test:

- According to customer requirements, the test uses type 5 exposure period, with a cumulative test time of 30 days
- Test exposure period type 5: UV fluorescent lamp UVA-340; Cycle condition: Light exposure temperature at 50 °C (blackboard temperature), for
- Irradiance of 0.76 W/m2@340 nm at 8 h; Spray time 0.25 h; Setting time 3.75 h, temperature 50 °C (blackboard temperature).
- For specimen installation, cut the sample pieces into rectangular specimens of appropriate size (about 115 mm long * 75 mm wide), and sprinkle talcum powder on the backlit side

The powder (to prevent sample sticking) is attached to the sample holder of the UV box.

After the exposure period ends, take out the samples as per the customer’s requirements and lower them for 24 hours under conditions of 23 °C ± 2 °C and 50% ± 10% RH.

Then proceed with the test. When cutting the sample, sample the part exposed to ultraviolet light.

6.4 Test results and analysis

Based on the data shown in Table 4, the test results meet the standard requirements.

As shown in Table 5, the tensile strength of the seven groups of polyurethane elastomers decreased to varying degrees after UV aging, with the sixth group having the largest decrease of 54.76% and the first group having the smallest decrease of 25.45%. The elongation at break increased and decreased. The elongation at break increased in groups 1/2/5/5/6 after UV aging, with group 2 showing the greatest change of 94% (%). After UV aging in 4/7 groups, the elongation at break decreased, with 7 groups having the greatest decrease of 17 (%).

It can be seen that UV aging significantly reduces the tensile strength of polyurethane elastomers, but there is no significant change in elongation at break.

In addition, the performance changes of different formulations of polyurethane elastomers under ultraviolet aging are also different. For example, specimens with added UV absorbers and antioxidants (such as Specimen 3#) showed relatively small performance degradation after UV aging. This indicates that the UV resistance of polyurethane elastomers can be effectively enhanced through reasonable formulation design and the use of additives.

Table 4. Changes in test requirements

Test items		Technical metrics
Tensile strength and retention	Standard conditions (MPa)	≥3.0
	Ultraviolet aging (%)	≥90
Elongation at break and retention rate	Standard conditions (%)	≥900
	UV aging (%)	≥90

Source(s): Author’s own work

Table 5. Tensile strength and elongation at break of seven groups of specimens

	Pre-ultraviolet aging		Post-UV aging	
Serial numbers	Tensile strength (MPa)	Elongation at break (%)	Tensile strength (MPa)	Elongation at break (%)
1	5.5	1,202	4.1	1,276
2	3.0	1,430	2.1	1,524
3	5.1	1,229	3.5	1,286
4	5.2	1,232	3.2	1,215
5	3.8	1,323	2.5	1,345
6	4.2	1,418	1.9	1,482
7	4.6	1,402	2.4	1,385

Note(s): Reset the new technical indicators to the standard

Source(s): Author’s own work

7. Conclusions

In material aging performance research, a single aging test method often has certain limitations. For example, although natural aging tests can truly reflect the aging situation of materials in actual environments, they are time-consuming and significantly affected by natural conditions such as geography and season, making it difficult to meet the demand for rapid evaluation of material performance; The thermal oxidative aging test mainly focuses on the effects of temperature and oxygen on materials, but neglects the influence of key environmental factors such as light; However, a simple UV aging test, although able to highlight the damage of UV radiation to materials, lacks comprehensive simulation of other environmental parameters such as temperature and humidity.

By systematically comparing and analyzing the advantages and disadvantages of these different aging test methods, the research team proposed a test plan combining artificial climate aging and ultraviolet aging. Artificial climate aging tests can accurately regulate various environmental factors such as temperature, humidity, and rain, simulating the comprehensive environmental conditions of different climate regions; the ultraviolet aging test can enhance the degradation effect of ultraviolet radiation on materials in a targeted manner. The organic combination of the two can cover the synergistic effects of various environmental factors and highlight the role of key destructive factors. To verify the effectiveness of the combination scheme, the research team selected polyurethane elastomer as the research object and conducted comparative experiments using a single test method and a combination test scheme. Through the detection and analysis of various indicators such as appearance changes, mechanical property degradation, and chemical structure evolution of the material, the results fully demonstrate that the combination test scheme can more accurately simulate the complex aging effects of polyurethane elastomer in actual use environments, and its aging behavior is more consistent with the material changes under natural use. This achievement not only provides a more scientific and reliable experimental basis for the performance evaluation of polyurethane elastomers, but also provides important technical references for their rational application in engineering practice, which helps to improve the accuracy of service life assessment of related products and the rationality of engineering design.

Looking ahead to the future, there are still potentials for further research on aging of polyurethane elastomers. At the material formulation level, further exploration can be conducted on the formulation design of new polyurethane elastomers. By introducing UV resistant additives, optimizing molecular chain structure, and using new cross-linking agents, the UV resistance and comprehensive mechanical properties of the material itself can be improved, and the aging resistance of the material can be enhanced from the source.

In terms of experimental methods, in addition to the existing combination of artificial climate and ultraviolet aging, other typical aging factors such as thermal oxygen aging, hydrolysis aging, salt spray aging, etc. can also be combined to design a multi factor coupled composite aging test, which can more comprehensively simulate the various aging conditions that materials may encounter in complex practical environments, and thus more systematically evaluate the performance changes of materials. At the same time, with the continuous deepening of material science theory and the rapid development of modern analytical techniques, such as the application of advanced characterization methods such as scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), etc., the study of the aging mechanism of polyurethane elastomers will be more in-depth, which can reveal the chemical changes and structural damage mechanisms during the aging process at the molecular level, providing stronger theoretical support and technical guidance for the precise modification and efficient application of materials, and promoting the safe and stable use of polyurethane elastomer materials in the field of railway bridges.

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Further reading

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