Research of thermal oxygen ageing on tensile properties of rubber based on Peck-Yeoh model

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Abstract
Vulcanized natural rubber (NR) is widely used in the industrial areas for absorbing vibrations and shock due to their excellent elastic stability. However, with the increase of exposing to sunlight and oxygen and the change of temperature in their working environment, NR tends to be hardened and lose damping properties. Therefore, the thermal aging effects on the mechanical properties of vulcanized NR need to be considered. In the present work, the effect of thermal oxygen aging on tensile properties of NR is experimentally investigated. Dumbbell-type specimens of different hardness (45/55/65HA) are selected and subjected to thermal oxygen ageing tests at different ageing temperatures (60/70/80/90 °C) for 5, 12, 24, 48 and 72 h. The nominal stress and strain can be measured and recorded by the computer in the process of uniaxial tensile test of aged NR. In the process of analyzing the results of uniaxial tensile test of aged rubber, the modulus of elasticity is chosen as the aging evaluation index, and the hardness, ageing time and temperature are analyzed qualitatively with the aid of the Yeoh hyperelastic constitutive model, while the Peck-Yeoh model is combined to calculate the modulus of elasticity after ageing for the quantitative analysis of the influencing factors. The results of qualitative and quantitative analysis reveal that the NR hardness, ageing temperature and ageing time have a descending order effect on the modulus of elasticity of aged NR. The conclusions drawn from this paper not only provide a basis for the study of the influence of ageing phenomena on the static stiffness properties of rubber elements, but also can give some reference to the design and optimization of the ageing resistance of vulcanized NR.

1. Introduction
As a renewable and reusable polymer material, rubber is widely used for vibration isolation, sealing, insulation, connection and transmission of industrial products due to its excellent mechanical properties and relatively lower cost [1, 2]. However, NR and their products are inevitably corroded during production, processing, transportation, storage and usage process by a combination of environmental factors such as heat, oxygen, humidity, salt spray and mechanical stress, as well as intrinsic factors produced by the formulation and vulcanization process of the rubber material. Thus, the performance of rubber gradually declines until failure [3, 4]. Rubber products are usually subjected to alternating loads during the process of servicing, whether they can continue to undertake the corresponding work is determined by the mechanical properties. The ageing of rubber materials affects the mechanical properties of the parts, and the tensile properties of rubber parts are one of the most important mechanical properties to ensure that they can work normally [5]. In the previous work [6–8], apart from the intuitive characterization of test data, no unified qualitative and quantitative characterization and calculation methods have been developed for the effects of ageing on the tensile properties of rubber, therefore, a systematic method for the assessment of the effects of ageing on the tensile properties is urgently needed.

Indoor accelerated and natural environment ageing of rubber have been extensively studied in this field [9]. Natural environment ageing tests make full use of environmental conditions and the test conditions are very
close to the actual working conditions. While the artificial accelerated ageing tests simulate and enhance the ageing factors in the natural environment, such as light, heat, oxygen and ozone, aimed to accelerate the ageing process through ageing test equipment. As one of the most commonly used accelerated testing methods, hot air accelerated ageing not only has the advantages of convenient operation and low cost, but also being the closest to natural ageing, which has been verified in the previous research on natural ageing and artificial accelerated ageing, for rubber materials, temperature is the key factor affecting the thermal oxygen ageing rate, and high temperature is often used as the accelerating stress. The accelerated test is theoretically based on the principle of time-temperature equivalent superposition, whereby the rate of reaction is accelerated by an elevated temperature, reducing the time required for rubber degradation [10]. Currently research on rubber ageing is mainly concerned with aging life prediction [11], accelerated test methods (mechanistic consistency verification [12–15], modelling of degradation trajectories [16–21], accelerated model building [22–25] and optimal design of tests [26–30], fewer researches have been carried out on the degradation of performance of rubber components due to ageing. The ageing process of rubber is a process of breaking and reorganization of the main chains, side chains and cross-linked bonds of the rubber molecular chain. Depending on the working environment, the factors that inducing ageing in rubber products are quite complex, including physical factors such as light, electricity and stress, chemical factors such as oxygen, ozone, acid and alkali salts, metal ions and biological factors such as micro-organisms. After ageing, the physical, chemical, acousto-optic performance and macro-micro surfaces of the material change [7, 8, 31]. In the term of appearance, rubber materials and their products may become deformed, hardened, brittle, crack, moldy, sticky, lose their luster and change color. Some performance degradation occurs in the aspects of mechanical performance, such as material elastic modulus, tensile strength, compression set, rebound rate and hardness [32]. The glass transition temperature, thermal degradation onset temperature etc are subject to change. In the microstructure, rubber polymer chains are cross-linked and long chains are broken, and new substances are formed and precipitated inside the rubber, accompanied by the expansion of pores and cracks. In order to evaluate the performance of rubber after ageing, the corresponding evaluation indexed are selected according to the macroscopic performance and microstructure changes of rubber material products.

In this paper, based on the hot air ageing test, uniaxial tensile test of aged rubber and the rubber constitutive model [33], the effects of hardness, ageing time and temperature on the tensile properties of aged rubber are studied qualitatively, afterwards, by calculating the initial modulus of elasticity after ageing using the Peck-Yeoh model, quantitative analysis of the experimental factors is carried out based on the calculated initial modulus of elasticity, the research not only provide a basis for the study of the influence of ageing phenomena on the static stiffness properties of rubber elements, but also can give some reference for the design and optimization of the ageing resistance of vulcanized NR.
2. Evaluation of tensile properties of aged rubber

2.1. Rubber materials and samples
The type of dumbbell rubber sample is used for the test, with three hardness of 45, 55, 65 HA. The different hardness of the rubber samples has different carbon black content, but contained the same proportion of antioxidant, as shown in table 1. The rubber materials were provided by LUOSHI Shock Absorbing Parts Co of China, and the amount of carbon black was specially formulated by the company for our test.

2.2. Test equipment and method
In accordance with the requirement of the national standard GB/T 3512-2014 accelerated hot air ageing and heat resistance test for vulcanized rubber or thermoplastic rubber from China. A hot air ageing chamber is used for the test. The total volume of the test pieces should be controlled within 10% of the effective volume of the chamber and the distance between each piece be outside 10mm, the air in the chamber needs to be circulated and the air flow rate is between 0.5 and 1.5 m s\(^{-1}\), meanwhile, the minimum surface area of the sample should be facing the direction of the air flow in order to reduce the disturbance to the air flow rate.

The test program is set up by setting three variables: temperature, accelerated ageing and rubber hardness, and the ageing program for the rubber hot air ageing test is determined according to the results of the pre-test as shown in table 2. The uniaxial tensile test is carried out on a tensile test rig, and the tensile strength and elongation at break are calculated by measuring the change of tensile force and displacement during the rubber stretching process. The physical and dimensional drawings are shown in the figure 1.

2.3. Tensile test results of aged rubber
The tensile test results of the aged rubber are characterized in the form of elongation at tear, and the subsequent evaluation indexes can be calculated according to the results in the table 3. With the increase of aging time, tear elongation retention rate decreases, the retention rate of elongation at tear at measurement points 2 and 3 is greater than 100%, which may be due to the secondary vulcanization of rubber with incomplete vulcanization in a short period of exposure to 60/70 °C, or it may be an anomaly caused by measurement error. The ‘-‘ in measurement point 6 indicates that the value of tensile elongation retention could not be measured because the sample was damaged prematurely due to improper stretching method during the measurement of tensile elongation, and the elongation retention rate at tear characterizes the change of the aging degree of the rubber. As the aging time increases, the elongation retention rate decreases, indicating that the aging of the rubber increases. As the temperature increases, the decay rate of the elongation at tear of rubber specimens with different hardness increases, which indicates that the aging rate of rubber increases with the increase of temperature.
3. Analysis of the decline in tensile properties of aged rubber

3.1. Section of constitutive model for aged rubber materials

In order to investigate the effects of ageing phenomena on the tensile properties of rubber, further research is carried out with the help of the hyperelastic constitutive model. The strain tensor invariants in the three directions of rubber deformation can be expressed in the form of equations (1)–(3). The relationship between the strain energy function and the strain tensor invariance can be expressed in the Mooney-Rivlin model as equation (4), in the Yeoh model as equation (5) and in the Arruda-Boyce model as equation (6). As the properties of the rubber material change after ageing, the hyperelastic constitutive model is fitted to the ageing rubber material again. Figure 2 shows the fitting results of the hyperelastic constitutive model for rubber samples with hardness of 65 HA at 90 °C after ageing for 48 h.

\[ I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \]  
\[ I_2 = \lambda_1^4 \lambda_2^2 + \lambda_1^2 \lambda_2^4 + \lambda_1^2 \lambda_3^4 \]  
\[ I_3 = \lambda_1^4 \lambda_2^4 \lambda_3^4 \]  
\[ W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \]  
\[ W = \sum_{i=1}^{3} C_{i0}(I_1 - 3)^i \]  

Table 3. Tensile elongation retention recession data of different hardness under different temperature aging conditions of rubber.

| Hardness (HA) | T (°C) | point1/ (%) | point2/ (%) | point3/ (%) | point4/ (%) | point5/ (%) | point6/ (%) |
|--------------|-------|-------------|-------------|-------------|-------------|-------------|-------------|
| 45           | 90    | 100         | 96.25       | 90.90       | 94.65       | 85.74       | 81.47       |
|              | 80    | 100         | 98.65       | 95.87       | 91.43       | 92.75       | 89.63       |
|              | 70    | 100         | 100.93      | 95.66       | 95.49       | 95.62       | 94.43       |
|              | 60    | 100         | 97.83       | 100.38      | 97.04       | 95.06       | 94.66       |
|              | 90    | 100         | 97.74       | 93.08       | 89.42       | 82.98       | —           |
| 55           | 80    | 100         | 95.93       | 93.83       | 93.40       | 92.63       | 88.51       |
|              | 70    | 100         | 95.98       | 97.35       | 94.62       | 95.05       | 94.27       |
|              | 60    | 100         | 100.34      | 100.73      | 98.44       | 96.90       | 95.41       |
|              | 90    | 100         | 95.42       | 88.17       | 88.16       | 85.61       | —           |
| 65           | 80    | 100         | 97.53       | 97.17       | 92.47       | 91.83       | 86.94       |
|              | 70    | 100         | 99.10       | 100.31      | 95.96       | 94.23       | 93.49       |
|              | 60    | 100         | 101.06      | 96.92       | 96.78       | 92.32       | 92.49       |

Figure 2. Fitted curve of hyperelastic constitutive model of aged materials.
Based on the result of fitting, shown in the figure 2, it can be judged that both the third order Odgen model and the Yeoh model are accurate for the ageing rubber material. With reference to previous studies, the Yeoh model is used to evaluate the tensile properties of the ageing rubber material.

\[ W = \mu \sum_{i=1}^{\infty} \frac{C_i}{\lambda_3^{2i-2}} (I_1 - 3) \]  

Figure 3. Curves of experimental and fitting results based on Yeoh model.
3.2. Identification of Yeoh model parameters for aged rubber materials

Based on the expression of the Cauchy stress from the uniaxial tensile test and the strain energy function of the principal tensile model, the Cauchy stress–principal tensile ratio function of the Yeoh hyperelastic constitutive model can be derived as shown in equation (7).

![Stress-principal tensile ratio curves for ageing rubber with different hardness at 60 °C.](image)

Figure 4. Stress–principal tensile ratio curves for ageing rubber with different hardness at 60 °C.

| T/℃ | Hardness/HA | Ageing time/h | \(c_{10}\)   | \(c_{20}\)  | \(c_{30}\)     |
|-----|--------------|---------------|--------|--------|----------------|
| 60  | 45           | 24            | 0.5846631908 | 0.0356548611 | 0.0000016183 |
| 60  | 45           | 72            | 0.6159453387 | 0.0441555717 | −0.0000834300 |
| 60  | 55           | 5             | 0.9877763184 | 0.0775520706 | −0.0009115819 |
| 60  | 55           | 12            | 0.9932369535 | 0.0933160370 | −0.0014652612 |
| 60  | 65           | 24            | 1.6870193257 | 0.1481448808 | −0.0044258324 |
| 60  | 65           | 48            | 1.8822664231 | 0.1610072649 | −0.0058422502 |
| 70  | 45           | 12            | 0.5611513017 | 0.0317122025 | 0.0001300699 |
| 70  | 45           | 72            | 0.6207755478 | 0.0487970160 | −0.0003308751 |
| 70  | 55           | 5             | 0.9838104333 | 0.0669662944 | −0.0003277818 |
| 70  | 55           | 12            | 1.0290281298 | 0.0798039145 | −0.0008066614 |
| 70  | 65           | 24            | 1.8970566438 | 0.1443643457 | −0.005790419 |
| 70  | 65           | 48            | 1.9202432043 | 0.1552365335 | −0.0050209952 |
| 80  | 45           | 48            | 0.6027407778 | 0.0481259477 | −0.001244859 |
| 80  | 45           | 72            | 0.6119774502 | 0.0517016646 | −0.0001766798 |
| 80  | 55           | 5             | 1.0616204931 | 0.0921376535 | −0.001999448 |
| 80  | 55           | 12            | 1.1036261925 | 0.0958995036 | −0.0013903567 |
| 80  | 65           | 12            | 1.8614543292 | 0.1546865343 | −0.005426469 |
| 80  | 65           | 24            | 1.8425630729 | 0.1560122319 | −0.0051305729 |
| 90  | 45           | 48            | 0.6451122389 | 0.0480681628 | −0.000042369 |
| 90  | 45           | 72            | 0.628591707 | 0.0667562670 | −0.0004313059 |
| 90  | 55           | 12            | 1.1539091122 | 0.0943180462 | −0.0013500104 |
| 90  | 55           | 24            | 1.3316285698 | 0.0860502032 | −0.0009091653 |
| 90  | 65           | 24            | 2.1354963147 | 0.2075286212 | −0.0114524176 |
| 90  | 65           | 48            | 2.2832338524 | 0.1394234084 | −0.0049872172 |
Due to the large amount of sample data, the non-linear least squares method is used to identify the parameter of Yeoh model in MATLAB software, that is, $c_{10}, c_{20}, c_{30}$, and the degree of fitting is determined by calculating the coefficient of determination (also known as the coefficient of determination or goodness of fit) between fitted stress and test stress value. The closer of $R^2$ with 1, the higher the accuracy of the fit and the higher the reference of the model. The formula for the coefficient of determination is shown in equation (8).

$$R^2 = 1 - \left( \frac{\hat{y} - y}{\bar{y} - \hat{y}} \right)^2$$

Where $y_i$ and $\hat{y}_i$ are test and predicted stress value respectively, $\bar{y}$ is the average test stress at the sample point.

Figure 3 shows the fitting of Yeoh model for aged rubber specimens with different hardness under different test conditions. The parameters of the average filled curve is the average values of the parameters obtained by fitting three rubber specimens under the same test conditions. According to the calculation, the coefficients of determination for each sample are above 0.99, which verified the high fitting accuracy.

Table 4 lists the average Yeoh model parameters obtained by fitting under some ageing test conditions.

### 3.3. Qualitative analysis of ageing on the deterioration of the tensile properties of rubber

In order to study the tensile property degradation caused by hardness, ageing time and temperature respectively, tensile modulus is used as the evaluation index. The hardness of rubber is firstly chosen as the independent variable, figure 4 shows the stress–principal tensile ratio curves under different hardness at three aging times at 60 °C, where the reference value is based on the stress–principal tensile ratio of unaged 45HA rubber material at room temperature, the slope of each curve is the tensile modulus of the rubber under different accelerated stress conditions. The curve shows that the tensile modulus of rubber materials increases significantly with increasing hardness under the condition of the same temperature and ageing time. And the elongation at break tends to decrease with the increase of hardness, which means that the higher the hardness of the rubber, the worse the tensile properties.

Then, using ageing time as independent variable, the stress–principal tensile ratio curves for rubber materials of three hardness at 70 °C through different ageing times is shown in figure 5. According to the curves in figure 5, it can be obtained that rubber materials of the same hardness show a small overall increase in modulus of elasticity with increasing ageing time after ageing for the same time. At the early stage of ageing, the tensile modulus of the rubber materials grows faster, but at the later stage of ageing, the stress–principal elongation ratio grows slower.
curve at different ageing time are relatively close, indicating that the growth rate of the elastic modulus of the rubber aging slows down at the later stage. The deviation of the rubber aging stress-strain curve from the reference curve in figure 5 is \((c) - (b) - (a)\) in descending order, and this result also proves the correctness of the conclusion that the modulus of elasticity increases with increasing stiffness obtained in figure 4. Figure 5(a) shows that the change of elastic modulus with aging time in the tensile test for the aged rubber parts of 45HA is not very regular, and the elastic modulus of the rubber aged 48 h is even higher than that of the rubber aged 72 h. In the later stage of tensile, the elastic modulus of the unaged rubber specimens is even higher than that of the aged 5 h and 12 h. The reason for this phenomenon may be due to the aging test and the accumulation of errors in the tensile test of the aged specimens, and the results in figures 5(b) and (c) show that the change of elastic modulus with aging time is more regular.

Finally, using temperature as an independent variable, figure 6 illustrates the stress-principle tensile ratio curves of the 45HA rubber material at different temperatures for three ageing times. The curves show that the modulus of elasticity of rubber with same hardness increases with increasing temperature over the same ageing time. As the ageing time increases, the difference in the effect of ageing at different temperatures becomes more and more conspicuous. The results in figure 6 also show that the difference in elastic modulus between the same hardness rubber specimens at the same aging time is not significant in the pre-stretching period, but becomes more and more obvious as the stretching progresses, and the phenomenon is also very correlated with the temperature, the higher the temperature, the faster the difference is produced. According to the comparison of (a)/(b)/(c) in figure 6, it is found that the change of elastic modulus at 60 °C is greater than that at 70 °C at that stage as the aging time proceeds. The reason for this phenomenon may be due to the complexity of the reaction mechanism of rubber materials or the error of test measurement. And the same aging time, for aging 5 h and 24 h rubber specimens tensile results show that the elastic modulus at 80 °C is even higher than the elastic modulus at 90 °C, proving that the temperature has a certain insensitivity to the tensile properties of aging rubber in this aging stage.

In summary, the increase of material hardness, temperature and ageing time will lead to an increase in the modulus of elasticity of the rubber material, with material hardness having the most pronounced effect on the modulus of elasticity of the rubber. The sensitive analytical method based on the deviation degree between aged rubber and unaged rubber specimens is qualitative. In the next section, the influence of three factors on the tensile properties of rubber will be analyzed quantitatively to determine whether the qualitative analysis is correct or not. Take rubber mounts as an example, the increasing elasticity modulus represents an increase in the stiffness of the mount. According to the performance requirement of rubber mounts, the rubber mounts should have greater stiffness and damping at low frequencies and large amplitudes, and smaller stiffness and damping at high frequencies and small amplitudes. Under the same deformation conditions, the modulus of elasticity of the
ageing rubber increases and the suspension stiffness increases accordingly, which will lead to the deterioration of the NVH performance of the vehicle.

4. Peck-yeoh modelling and quantitative analysis of parameter influencing factors

4.1. Peck-yeoh modelling and fitting

In order to comprehensively consider the effects of the three parameters of test temperature, ageing time and hardness on the tensile properties of rubber materials in the process of hot air accelerated ageing test, i.e. the effects on the parameters of the Yeoh hyperelastic constitutive model, the Peck-Yeoh model is established with the aid of the Peck model, and equation (9) is the mathematical functional relationship of the Peck-Yeoh model.

\[
f(HA, T, t) = m_1 HA^{m_2} e^{m_3 t/m_4}
\]

Where, HA represents the hardness of the rubber, T is the temperature of accelerated ageing test, t represents the ageing time of the rubber specimen, \(c_{i0}\) represents the Yeoh model parameter, \(i = 1, 2, 3, m_1, m_2, m_3, m_4\) are the Peck-Yeoh model parameters.

Based on the 60 sets of Yeoh model parameters obtained from the parameter identification in section 3.2, the non-linear least squares method is used to determine the fitness of the model by calculating the \(R^2\) between the predicted Yeoh model fit and original test values, with temperature, ageing time and hardness as variables, and Peck model is used to fit the Yeoh model parameters for the ageing material. The results are shown in figure 7. The coefficients of determination between the original and fitted values are satisfied the accuracy requirement, where the determination coefficients of \(c_{i0}\) and \(c_{30}\) are above 0.93, while the \(R^2\) of \(c_{20}\) is 0.87, indicating that the Peck-Yeoh model is useful in describing the effects of temperature, ageing time and material hardness on the parameters of the Yeoh model for aged rubber.

Based on the fitting results, the values of the parameters of the Peck-Yeoh model can be obtained as shown in table 5.

![Figure 7. Peck-Yeoh model fitting results.](image)

| Table 5. Peck-Yeoh model parameter fitting results values. |
|-------------|----------------|----------------|----------------|----------------|
| i           | Yeoh parameters | \(m_1\)         | \(m_2\)         | \(m_3\)         | \(m_4\)         |
| 1           | \(c_{i0}\)      | 5.9169e-06      | 3.0625          | −22.2187        | 0.0595          |
| 2           | \(c_{i0}\)      | 1.1233e-07      | 3.4773          | −42.4395        | 0.0698          |
| 3           | \(c_{30}\)      | −2.0729e-14     | 6.5367          | −115.0000       | 0.1459          |

![Figure 7. Peck-Yeoh model fitting results.](image)
Substituting the values in the above table into the Peck-Yeoh model, the functional relationship can be obtained as equations (10)–(12).

\[
\begin{align*}
\alpha_0 &= 5.9159 \times 10^{-6} H A^{3.0625} e^{-22.2187 t^{0.0595}} \\
\alpha_1 &= 1.1232 \times 10^{-7} H A^{3.4773} e^{-42.4395 t^{0.0698}} \\
\alpha_2 &= -2.0729 \times 10^{-14} H A^{5.5567} e^{-115 t^{0.1459}}
\end{align*}
\]

4.2. Quantitative analysis of tensile property decline of aged rubber based on Peck-Yeoh model

Based on the stress-main tensile ratio curves of the rubber materials, a qualitative analysis of the tensile property degradation due to material hardness, ageing time and hardness is presented in section 3.2 of this paper. In this section, a further quantitative analysis of the tensile property degradation due to ageing or rubber will be carried out based on the established Peck-Yeoh model, together with a parametric influence analysis of the Peck-Yeoh model.

According to the constitutive model relationship of the reduced polynomial of rubber material, the initial shear modulus of rubber material is equal to two times of the model parameters \(\alpha_0\), while for materials such as rubber with Poisson’s ratio close to 0.5 and approximately incompressible properties, the initial modulus of elasticity is approximately equal to three times of the initial shear modulus when small deformation occurs, as shown in equation (13), thus we get that the initial modulus of elasticity of rubber is linearly related to the \(\alpha_0\).
The Peck-Yeoh model expression for the initial modulus of elasticity and the fitted graphs are shown in equation (14) and figure 8 respectively.

\[
E \approx 3\mu_0 = 3 \times 2G_0 \approx 6G_0
\]

Based on the fitted Peck-Yeoh model for the initial modulus of elasticity, the graph is divided into four periods of 60, 70, 80 and 90 °C, with each period divided into three segments of 45, 55 and 65 HA, each segment containing five data points at 5, 12, 24, 48 and 72 h. As shown in figure 9, the data sets for the three hardness of the initial modulus of elasticity and four temperatures are fitted linearly again to obtain the functions shown in equations (15) and (16) respectively.

\[
\begin{align*}
45HA: y &= 0.0109x + 3.3767 \\
55HA: y &= 0.0201x + 6.1367 \\
65HA: y &= 0.0301x + 10.1502
\end{align*}
\]

\[
\begin{align*}
60 ^\circ C: y &= 0.6451x + 1.7375 \\
70 ^\circ C: y &= 0.6840x - 8.6876 \\
80 ^\circ C: y &= 0.6946x - 19.2323 \\
90 ^\circ C: y &= 0.8389x - 36.6198
\end{align*}
\]

The slope of the hardness curve allows us to obtain that the initial modulus of elasticity gradually doubles as the hardness increases and the growth rate becomes significantly larger. And for different hardness of rubber materials, the modulus range is different. The greater the hardness, the greater the initial modulus of elasticity of rubber material on the condition that other things are equal. For this type of rubber, the difference in initial modulus of elasticity \( \Delta E \) is around 4MPa for a 10HA difference in hardness. Among the test influencing factors, the magnitude of rubber hardness is the dominant factor affecting the magnitude of the initial modulus of elasticity of rubber.

The slope of the temperature curve shows that the initial modulus of elasticity of the ageing rubber material increases gradually with the increasing of temperature, meanwhile the rate of increase is also gradually increasing, but the rate of change of the ageing growth rate with increasing temperature is not as obvious as the rate of change due to hardness. In addition, the initial modulus of elasticity of the ageing rubber material also increases gradually with increasing temperature, according to the comparison of scatter value for the same hardness and ageing time. To investigate the effect of test time on the ageing or rubber materials, the initial modulus elasticity of the ageing rubber is reordered and the graph is divided into three cycles according to 45, 55 and 65 HA, each cycle further divided into five segments according to 5, 12, 24, 48 and 72 h. Each segment contained four data points at 60, 70, 80 and 90 °C. The Peck-Yeoh model expression for the initial modulus of elasticity of the ageing rubber is fitted as shown in equation (17).

\[
E = 33.0099HA^{0.0596}e^{-\frac{170.3743}{T}}e^{-0.3141}
\]
According to equation (17), the fitting result can be obtained as shown in figure 10, and the magnitude of the coefficient of determination is 0.9749. The linear fitting is then carried out for the five data sets under the ageing time in the fitted value E of the initial modulus of elasticity, and the function relationship as shown in equation (18) is obtained. By the slope of the ageing time curve, the initial modulus of the elasticity of the aged rubber is also gradually increased with the extension of the ageing time and its growth rate is also gradually increased, with the change in the ageing rate with the extension of the ageing time being the first to increase and then decrease, but again without the rate of change due to hardness being significant.

\[
\begin{align*}
5 \ h: & \ y = 0.1713x + 2.8225 \\
12 \ h: & \ y = 0.1806x + 2.0212 \\
24 \ h: & \ y = 0.1966x + 1.2380 \\
48 \ h: & \ y = 0.1981x + 0.7861 \\
72 \ h: & \ y = 0.2025x - 0.1765
\end{align*}
\]  

(18)

5. Conclusion

In this paper, by means of hot air accelerated ageing test, the elastic modulus is selected as the ageing evaluation index based on the vibration isolation of rubber mount, and the uniaxial tensile test is carried out on the aged rubber specimens, and the test influencing factors of hardness, ageing time and temperature are analyzed qualitatively with the help of Yeoh hyperelastic constitutive model, after that, the quantitative analysis of the experimental influencing factors is carried out with the aid of Peck-Yeoh model according to the calculation of initial elastic modulus of aged rubber. The main findings of this study include the following.

(1) Increases in material hardness, ageing temperature and ageing time all result in an increase in the modulus of elasticity of the rubber material.

(2) The ageing growth rate of the initial modulus of elasticity of rubber increases rapidly with increasing hardness, with material having the most significant effect on the modulus of elasticity of rubber and its growth rate.

(3) A small increase in the ageing growth rate of the initial modulus of elasticity of rubber with increasing temperature.

(4) As the ageing time increases, the ageing growth rate of the initial modulus of elasticity of rubber increases to a certain extent, but the ageing growth rate first changes quickly and then slows down.

The next step in the research could be to investigate the effects of rubber ageing on other aspects of the performance of rubber components, taking into account the role of multi-factor ageing, i.e. the investigation of multiple properties due to multiple stresses. This research could be carried out in order to provide better theoretical support for the reliability of the use of rubber components and their timely replacement.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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