

Mechanical Performance Degradation of Naturally Aged Nitrile Butadiene Rubber in Low Frequency Range

Syam Prasad Ammineni^{1,2*}, Ch. Nagaraju³, D. Linga Raju⁴

Abstract

For good mechanical design, damping is often still an invisible requirement. Nitrile Butadiene Rubber (NBR) has a wide range of applications as a damping and sealing material. To offer the long-term service of NBR, it is important to estimate the degradation of modal properties under complex mechanical and environmental loading. The present work aims to correlate the experimental data with generalized higher-order Maxwell models and curve fitting techniques to find the damping characteristics of NBR in low-frequency ranges with age. Nitrile Butadiene Rubber (NBR) is assumed to be homogeneous and isotropic, and it is allowed to age naturally in the oxidative environment with no load. Mechanical tests are performed to find hardness, true stress-strain behavior, and failure stress of virgin NBR and the naturally aged NBR. Deterioration of damping ability of NBR is studied by Dynamic Mechanical Analysis (DMA) tests to relate the complex properties of naturally aged material at an operating temperature of 40°C, with virgin material in the frequency domain. The developed curve fitting techniques are well acceptable with experimental data and higher-order maxwell models. Relaxation modulus in shear mode is calculated for virgin and aged NBR. Based on experimental results, it has been observed that the Mechanical properties, such as yield strength, tensile strength, Elastic modulus are deteriorated with natural oxidative aging. Modal properties of NBR namely storage modulus by 52%, loss modulus by 66%, loss factor by 31%, relaxation modulus by 43.9%, and damping coefficient by 31.25%, as well as damping ability has deteriorated with age.

Keywords: Damping, DMA, Frequency, Maxwell model, NBR.

INTRODUCTION

Viscoelastic materials, due to their versatility in nature, are having a wide range of applications. The nitrile butadiene rubber (NBR) is one of the most serviceable viscoelastic materials due to its good mechanical and physical properties. It is manufactured by emulsion polymerization of butadiene and acrylonitrile and is widely used as a sealing element to prevent leakage and avoid transferring vibration to sensitive components at low natural frequencies. Apart from many other physical damping mechanisms, isotropic homogeneous viscoelastic materials exhibit damping behavior which is a function of time and temperature. During the service period, NBR is subjected to complex mechanical loading and environmental conditions. However, to ensure reliability and safety during the long-term process, it is inevitable to estimate the degradation of mechanical characteristics [1] such as tensile strength [2, 3], elongation break [4], Hardness [5], and damping performance [6, 7]. Especially in damping applications used in the mounting of electronic components, deterioration of NBR's viscoelastic nature with aging will raise to loss in

*Author for Correspondence

Syam Prasad Ammineni

¹Research Scholar, Department of Mechanical Engineering, JNTUK, Kakinada, India

²Assistant Professor, Department of Mechanical Engineering, Maturi Venkata Subba Rao (MVSRR) Engineering College, Hyderabad, Telangana, India

³Professor, Department of Mechanical Engineering, Velagapudi Ramakrishna Siddhartha Engineering College, Kanuru, Vijayawada, Andhra Pradesh, India

⁴Assistant Professor, Department of Mechanical Engineering, JNTUK, Kakinada, India

Received Date: March 08, 2022

Accepted Date: March 23, 2022

Published Date: April 19, 2022

Citation: Syam Prasad Ammineni, Ch. Nagaraju, D. Linga Raju. Mechanical Performance Degradation of Naturally Aged Nitrile Butadiene Rubber in Low Frequency Range. Journal of Polymer & Composites. 2022; 10(1): 68–79p.

performance which leads to devastating failure of the components. When the material is subjected to external loading, the viscous portion in the material utilizes the energy to deform in shear mode and create an opposing force by dissipating the heat energy [8]. Complex shear modulus G' is a measurement that describes the energy dissipation of viscoelastic material in shear or compression mode and is determined by dynamic mechanical tests. From the fundamentals of viscoelasticity, it is fact that, when the viscoelastic material is subjected to harmonic stress, the resulting strain is also harmonic by the same frequency with a phase lag [9]. It is because of the dissipation of energy during deformation by viscous element. In recent years very little research is originated to study the degradation of damping characteristics of viscoelastic materials with ambient oxidative aging.

Y. S. Ko et al. [10] modified the Weissenberg rheogoniometer to estimate the loss and storage modulus of viscoelastic solids under free and forced vibrations. C. S. Woo et al. [11] predicted the useful lifetime of NBR and EPDM rubbers by accelerated aging technique in the thermo-oxidative environment from various temperature and time ranges. The results show that the stiffness of polymers increases with aging time. The activation energy also changes with time and temperature and the polymeric properties of NBR changes highly than EPDM. M. Vašina et al. [7] work is focused on the dissipation of heat energy during cyclic loading and its relation with damping. It is observed that the loss factor significantly affects the excitation frequency for rubbers. Y. Qian et al. [12] investigated NBR aging tests systematically under compression at operating temperatures in transformer oil and proposed an evaluation index to predict the service lifetime. B. Musil et al. [13] in his research paper proposed a continuum mechanical model to predict the aging behavior of the NBR in air and oil environment. Nait et al. [14] worked on new developments in the area of fracture of rubbers and the influence of aging on mechanical properties. The stress limiter and the energy limiter approaches are used to find the failure stress and strain in elastomers under uniaxial tension. J. Liu et al. [15] concluded that aging is caused for surface damage of NBR and makes the material inhomogeneous [6].

Nevertheless, many studies [16–23] are there with accelerated aging techniques under various environmental conditions, very rare studies are found on damping performance degradation of naturally aged NBR and comparison with virgin material. In this paper, to investigate the performance degradation of NBR, it is allowed to age naturally for about two years in the laboratory in oxidative environmental conditions. A virgin sample of the same mechanical, physical, and chemical properties is taken for comparison. Mechanical tests are conducted to get elongation break, tensile strength, elastic modulus, and hardness of virgin and naturally aged samples. Complex dynamic properties of the naturally aged and virgin samples are obtained by conducting DMA tests at low frequency ranges. Prony series values are evaluated from DMA data to define viscoelastic material characteristics (used in Computer Aided Engineering (CAE) software tools) for dynamic analysis of NBR material further. Nonlinear curve fitting is also carried out to fit with experimental data in frequency and time domain.

Theory of Viscoelastic damping

For most polymers developed strain by the application of stress is typically dependent on stress time history [8]. For example, if stress is suddenly applied and held at a fixed value, the strain will begin from zero unlike at a rapid rate in elastic solids. In the case of cyclic shear loading, the relation between time-dependent stress-strain [9] can be written as

$$\tau(t) = G\phi(t) \pm G\eta\sqrt{\phi_o^2 - \phi(t)^2} \quad (1)$$

Where $\tau(t)$ is shear stress at time t , G is Shear modulus of the material, $\phi(t)$ is time-dependent shear strain, ϕ_o is maximum strain amplitude in a cycle.

For sinusoidal steady-state harmonic response, strain response can be written as

$$\phi(t) = \phi_o \sin(\omega t) \quad (2)$$

Here ω is the sinusoidal frequency in rad/sec, and substitute the equation 1 in equation 2

$$\tau(t) = G\phi(t) \pm G\eta\phi_o |\cos(\omega t)| \quad (3)$$

$$\tau(t) = G\phi(t) \pm \frac{G\eta}{|\omega|} \frac{d\phi(t)}{dt} \quad (4)$$

$$\tau = G\phi \pm \frac{G\eta}{|\omega|} \frac{d\phi}{dt} \quad (5)$$

The first term in equation 5 represents elastic nature and the second term represents the rate of strain or work done by the stress in phase with strain. It also shows the phase lag ' δ ' between stress and strain with loading frequency and can be represented as follows

$$\tau(t, \omega) = \tau_0 \sin(\omega t + \delta) \quad (6)$$

$$\tau(t, \omega) = \tau_0 \sin(\omega t) \cos \delta + \tau_0 \cos(\omega t) \sin \delta \quad (7)$$

$$\tau(t, \omega) = \phi_0 [G'(\omega) \sin(\omega t) + G''(\omega) \cos(\omega t)] \quad (8)$$

$$\frac{\tau(t, \omega)}{\phi_0} = [G'(\omega) \sin(\omega t) + G''(\omega) \cos(\omega t)] \quad (9)$$

$$G^*(\omega) = G'(\omega) + i G''(\omega) \quad (10)$$

Where $G'(\omega)$ is storage modulus and $G''(\omega)$ is loss modulus, and the ratio of loss modulus and storage modulus gives loss factor η

$$\eta = \frac{G''}{G'} = \tan \delta \quad (11)$$

When polymers are used as vibration isolators, the dynamic response of a single degree of freedom of viscoelastic materials in the time domain can be written as [9]

$$y(t) = \frac{F \exp(i(\omega t - \eta))}{\sqrt{(k - m\omega^2)^2 + k^2\eta^2}} \quad (12)$$

Where 'F' is excitation force, 'k' is stiffness, and 'm' is the equivalent mass of viscoelastic material. Even though, the k and η are frequency-dependent parameters; stiffness can be measured at static conditions whereas measuring loss factor based on static amplitude may mislead to an incorrect viscoelastic response. In such cases, the accurate measurement may be estimated at the resonance frequency (ω_0) or nearer. The stiffness k and loss factor η don't vary with frequency rapidly, that is at low values of η , two different random frequencies ($\omega_1 < \omega_0, \omega_2 > \omega_0$) may be taken in such a way that the ratio (N) of peak amplitude at resonance frequency to the amplitude at operating frequency should be greater than unity and is used to calculate stiffness and loss factor. The stiffness at resonance frequency can be calculated by using $\omega_0 = \sqrt{k/m}$, and the ratio of frequency difference ($\Delta\omega = \omega_2 - \omega_1$) to the resonance frequency from 3dB method can be written as

$$\frac{\Delta\omega}{\omega_0} = \sqrt{1 + \eta\sqrt{N^2 - 1}} - \sqrt{1 - \eta\sqrt{N^2 - 1}} \quad (13)$$

From the above equation, loss factor η can be derived as

$$\eta = \sqrt{\frac{1 - \left[1 - \frac{1}{2} \left(\frac{\Delta\omega}{\omega_0}\right)^2\right]^2}{N^2 - 1}} \quad (14)$$

The variation of loss factor (η) with frequency ratio for various values of N is shown in Figure 1. For low values of η (in the linear zone $\frac{\Delta\omega}{\omega_0} < \sqrt{2}$) the relation between resonance frequency and the operating frequency of viscoelastic material can be written as

$$\eta = \tan \delta = \frac{\Delta\omega}{\omega_0} = 2\xi \quad (15)$$

Values of loss factor (η) and stiffness (k) of viscoelastic material are known, the amplitude of vibration at resonance can be measured by using equation 12.

From Figure 1, at $\frac{\Delta\omega}{\omega_0} = \sqrt{2}$, there is an abrupt change in trend and is difficult to find the damping ratio ξ and loss factor η to define the type of system.

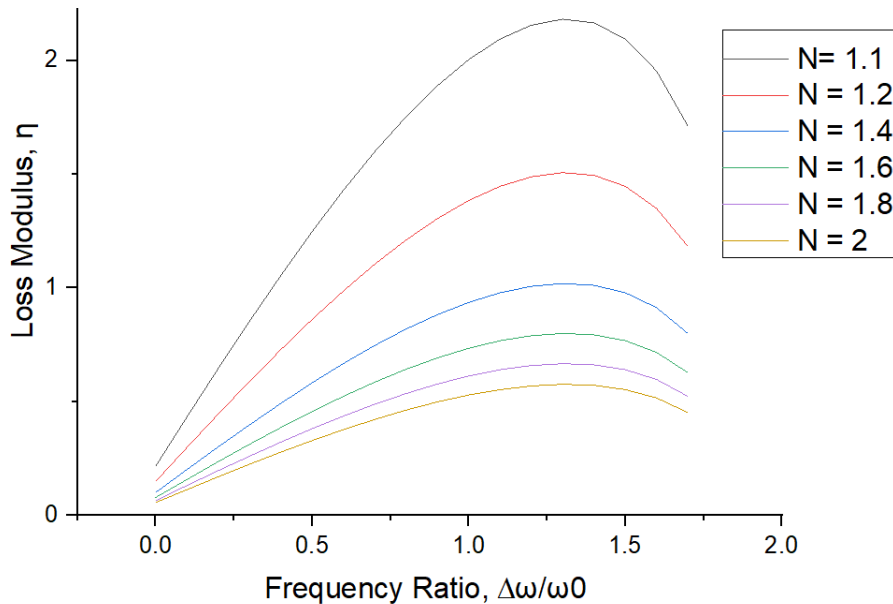


Figure 1. Loss factor vs Frequency ratio of viscoelastic material.

For $\frac{\Delta\omega}{\omega_0} < \sqrt{2}$ conditions, i.e at lower frequency applications, without performing any vibration tests, the equation can be used to determine whether a viscoelastic damping system is underdamped, overdamped, or critically damped.

In steady-state harmonic excitation, Specific damping capacity (φ) is the factor that measures the damping ability of the viscoelastic isolator, defined as the ratio of energy dissipation to energy stored in a cycle. Specific damping capacity at any frequency for steady-state linear inertia systems can be written as [24]

$$\varphi = 2\pi \tan (\delta) \quad (16)$$

The above equation 16 is In the absence of reliable data, equation 16 will help the design engineer to select and design a suitable viscoelastic isolator.

Models of viscoelastic behavior

Maxwell and Kelvin-Voigt models are two basic mechanical models that are used to predict the viscoelastic behavior of polymers, which are represented with spring (elastic nature) and dashpots (viscous nature) as shown in Figure 2. In the present work, the generalized Maxwell model [25] in which elements are connected parallel is used to determine the relaxation modulus which is a function of time and given by the equation

$$G(t) = \sum_{i=1}^n G_i e^{-t/\tau_i} \quad (17)$$

For elastic materials $t \rightarrow \infty$, $G(t) = G_e$ a finite value; whereas for viscous materials $t \rightarrow 0$, $G(t) = 0$; and for viscoelastic materials, the equation 17 can be written as [26]

$$G(t) = G_e + \sum_{i=1}^n G_i e^{-t/\tau_i} \quad (18)$$

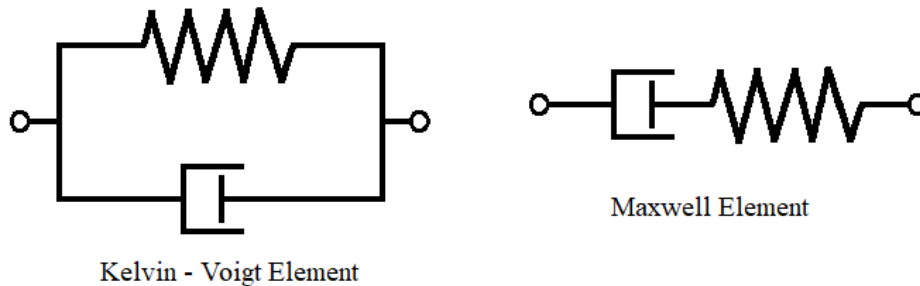


Figure 2. Viscoelastic Mechanical Models.

The above equation is used to define viscoelastic behavior in CAE software popularly known as Prony Series. Estimating the maxwell model parameters (G_e, G_i, τ_i) in the time domain is difficult, so the above time-domain equations can be written in the frequency domain for storage modulus ($G'(\omega)$) and loss modulus ($G''(\omega)$) separately and is given by Tschoegl et al. [27].

$$G'(\omega) = G_e + \sum_{i=1}^n \frac{G_i \omega^2 \tau_i^2}{1 + \omega^2 \tau_i^2} \quad (19)$$

$$G''(\omega) = \sum_{i=1}^n \frac{G_i \omega \tau_i}{1 + \omega^2 \tau_i^2} \quad (20)$$

The model parameters G_e , G_i and τ_i evaluated in the frequency domain and time domain are the same. To get precise curve fitting for the experimental data at lower frequencies, first, second, and third-order are taken ($i=3$) [28] in the present work.

EXPERIMENTATION

NBR sheet is supplied by Kumar rubber moulding Pvt. Ltd., Hyderabad, India with a thickness of 5mm. The samples are cut into 30mm wide by 300mm long beams and aged naturally in the laboratory for two years under no-load conditions. Virgin samples of the same specifications and compositions are taken to conduct the experiments for comparison.

Tensile and Hardness Tests

Dog-bone shape specimens as shown in Figure 3. are punched from the aged and virgin (of same composition and hardness) beams as per ISO 37:2011 Tensile tests are performed at KELVN Labs, Hyderabad (NABL certified) at a rate of 50mm/min at room temperature to find elastic modulus, elongation break, %of elongation, tensile strength, and yield strength. Shore – A hardness tests are performed as per ISO 7619-1:2010 to find the hardness of naturally aged NBR and virgin NBR at five different locations and an average is taken to get reliable results.



Figure 3. Dog-bone Specimens of NBR.

Dynamic Mechanical Analysis (DMA)

The majority of viscoelastic material behavior tests are performed in the frequency domain, because interpreting the results in time-dependent behavior is difficult and requires advanced equipment. The vibration response of viscoelastic materials is affected by shear history, hence the tests are carried out

in compression mode. DMA (SII EXSTAR 6000) tests in compression mode are performed to measure storage modulus (G'), loss modulus (G'') and phase lag ($\tan \delta$) at an operating temperature range of 40°C with a frequency range of 0.1hz, 0.5hz, 1hz, 5hz, and 10hz, and $\pm 0.5\text{mm}$ amplitude of oscillations.

RESULTS AND DISCUSSIONS

The mechanical properties of naturally aged NBR and virgin NBR are evaluated from a Uniaxial tensile testing machine and shore – A hardness tester, the results are shown in Table 1.

Table 1. Mechanical Properties of naturally aged NBR and virgin NBR.

Material Property	Naturally aged NBR	Virgin NBR
Yield tensile strength (MPa)	3.03	5.26
Maximum tensile strength (MPa)	6.65	11.35
Elastic Modulus (MPa)	1.17	2.18
%age of Elongation	424.16	478.2
Shore – A Hardness number	83.4	84.6

Table 1 shows that mechanical properties deteriorate significantly with age, even at no load oxidative environment. With aging, the yield tensile strength of NBR decreases by about 43.4%, the maximum yield strength decreases by about 41.4%, the elastic modulus decreases by about 46.3%, the percentage of elongation break by about 11.3%, and hardness do not decrease significantly.

With aging, changes in viscoelastic properties are largely controlled by crosslink reactions and crosslink density; as the rubber ages at no load, there are no significant changes in polymer crosslink reactions, resulting in a minimal drop in hardness. The percentage of elongation breaks has decreased, but not significantly; due to natural oxidative aging, there are few changes in chain orientation; on the other hand, testing has been done at a slower rate, allowing the material to relax. Major mechanical properties such as yield tensile strength, maximum tensile strength, and elastic modulus deteriorate by more than 40% after two years of age. This implies that the crosslink density of NBR increases with age and reaches a critical value, at which the molar mass between two adjacent crosslink points decreases, as does the effective mobility of chains, resulting in stress concentration and a decrease in basic mechanical properties viz. tensile strength and elastic modulus [15, 29].

For structural damping applications, to find the structural integrity, the frequency-dependent modulus is necessary and can be obtained by DMA. Variation of loss modulus (G''), storage modulus(G'), and loss factor ($\tan \delta$) at lower frequencies of naturally aged NBR and virgin NBR. Nonlinear curve fitting analysis is carried out using power function [26] to fit the data and compared with experimental data and maxwell models ($n=1,2,3$) are shown in Figures 4 and 5.

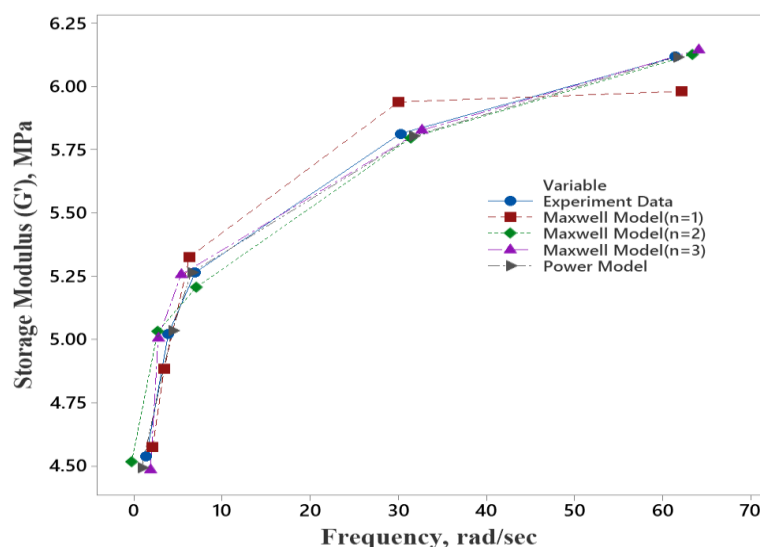


Figure 4. Storage Modulus vs frequency of Naturally aged NBR at 40°C .

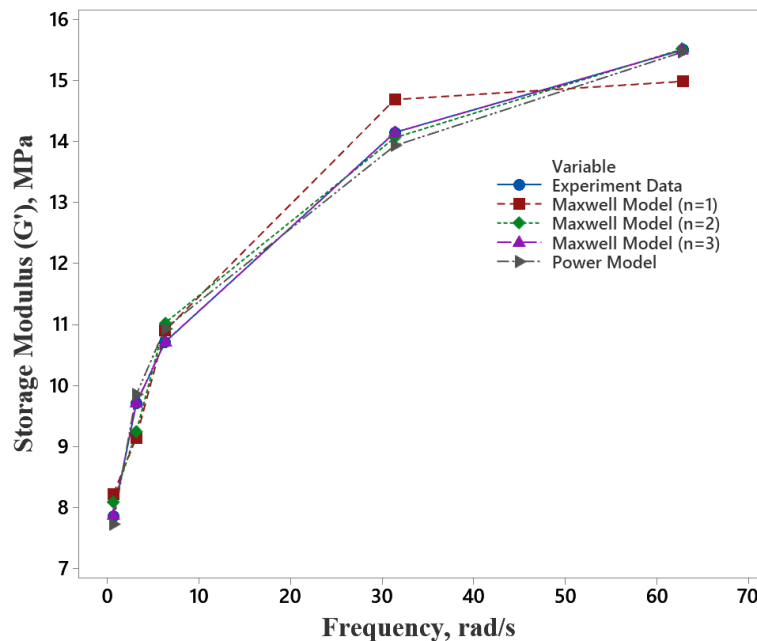


Figure 5. Storage Modulus vs frequency of Virgin NBR at 40°C.

Figures 4 and 5 show the variation of storage modulus of naturally aged NBR and virgin NBR with frequency at 40°C and reveal that the experimental data are well-matched with maxwell models and power models. Nonlinear Curve fitting is carried out by minimizing the sum of the square of residuals (SSR). Table 2 shows that the value of R^2 (correlation coefficients) converges to unity as the order of the Maxwell model increases. However, because the loss modulus values are very small in comparison to the storage modulus, and $\tan\delta$ values are also closer to zero, a good approximation of prony series values may be obtained from the storage modulus data of order 3 and this is taken into account in the current work.

Table 2. R^2 (correlation coefficients) of Maxwell models, Power model vs. experimental data.

Sample		Maxwell model			Power model
		$n=1$	$n=2$	$n=3$	
Naturally Aged NBR	R^2	0.966	0.976	0.999	0.995
Virgin NBR		0.974	0.989	0.999	0.990

Table 3. Maxwell parameters with $n=3$ (G:MPa, τ :sec).

Sample	G_e	G_1	τ_1	G_2	τ_2	G_3	τ_3
Naturally Aged NBR	4.443	0.941	0.034	0.611	0.601	0.289	0.191
Virgin NBR	7.660	3.077	0.419	4.236	0.045	1.291	0.028

The obtained maxwell parameters from storage modulus $G'(\omega)$ for naturally aged NBR and virgin NBR are listed in Table 3, by substituting these values in equation 19 gives

$$G'(\omega)|_{\text{Naturally aged NBR}} = 4.443 + \frac{0.941\omega^2(0.034)^2}{1 + \omega^2(0.034)^2} + \frac{0.611\omega^2(0.601)^2}{1 + \omega^2(0.601)^2} + \frac{0.289\omega^2(0.191)^2}{1 + \omega^2(0.191)^2} \quad (21)$$

$$G'(\omega)|_{\text{Virgin NBR}} = 7.66 + \frac{3.077\omega^2(0.419)^2}{1 + \omega^2(0.419)^2} + \frac{4.236\omega^2(0.045)^2}{1 + \omega^2(0.045)^2} + \frac{1.291\omega^2(0.028)^2}{1 + \omega^2(0.028)^2} \quad (22)$$

The same parameters can be substituted in equation 18 gives the relaxation modulus, which is a function of time.

$$G(t)|_{\text{Naturally aged NBR}} = 4.443 + 0.941 e^{-t/0.034} + 0.611 e^{-t/0.601} + 0.289 e^{-t/0.191} \quad (23)$$

$$G(t)|_{\text{Virgin NBR}} = 7.66 + 3.077 e^{-t/0.419} + 4.236 e^{-t/0.045} + 1.291 e^{-t/0.028} \quad (24)$$

The time-dependent relaxation behavior of naturally aged NBR and virgin NBR is plotted in Figure 6. It demonstrates that when a load is applied for a long time, the modulus approaches G_e . It shows that the load is applied for a long time, modulus tends approaches to G_e , and also observed that natural aged NBR took less time to relax than virgin NBR on the application of load, due to deterioration in viscous nature and tends to act as an elastic material.

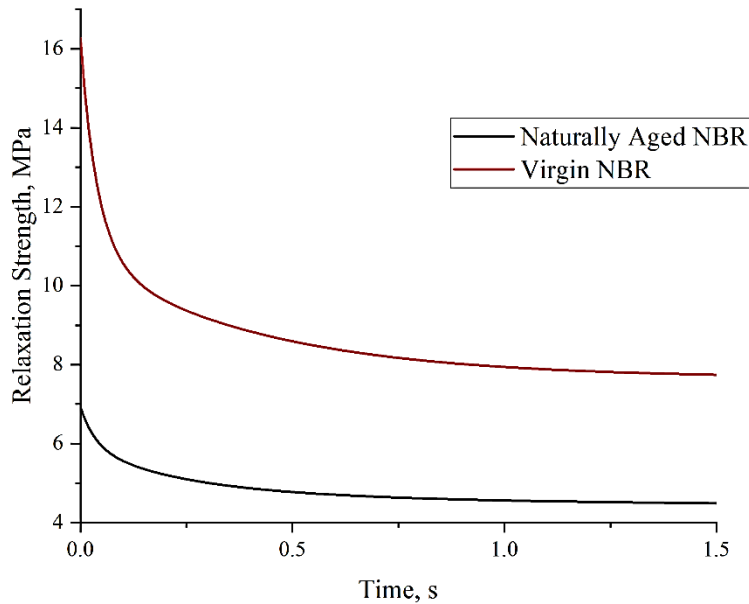


Figure 6. Relaxation modulus vs time for naturally aged NBR and virgin NBR.

To describe the relaxation modulus and evaluate the Prony series, viscoelastic isolators exposed to low frequencies, the maxwell 3rd order model is adequate and the percentage of errors with experimental data are shown in Table 4. It is also proven that the power model is a quick and convenient method for obtaining the dynamic parameters at intermediate points of experimental data with a minimum percentage of error.

Table 4. Error calculation of Maxwell model, power model with experimental DMA data.

Sample	Frequency, Hz	Storage modulus, MPa			%ge error = $\frac{\text{mod}(DMA - \text{Model})}{DMA} \times 100$	
		DMA	Maxwell Model n=3	Power model	Maxwell Model n=3	Power model
Naturally aged NBR	10	6.113	6.113	6.103	0	0.163
	5	5.835	5.835	5.832	0	0.051
	1	5.226	5.226	5.247	0	0.401
	0.5	5.008	5.008	5.014	0	0.119
	0.1	4.524	4.524	4.512	0	0.265
Virgin NBR	10	15.496	15.496	15.465	0	0.203
	5	14.148	14.148	13.932	0	1.528
	1	10.713	10.7137	10.933	0	2.05
	0.5	9.708	9.709	9.849	0	1.453
	0.1	7.863	7.864	7.729	0	1.706

To define the viscoelastic behavior of polymers in CAE solvers, Prony series values (g_i , τ_i , and k_i) are required. When the viscoelastic isolators are subjected to harmonic loads with low frequencies, volumetric changes in the material are negligible. Thus, in CAE packages, the volumetric Prony

constant (k_i) is claimed to be frequency independent. The Prony constants a_i and τ_i are essential to finding the time-dependent shear response to define the deviatoric behavior of viscoelastic material and are determined as follows [30]

$$a_i = \frac{G_i}{G_0} \quad (25)$$

Where G_0 is relaxation modulus in shear when time $t \rightarrow 0$. For Naturally aged NBR and virgin NBR, values of G_0 are calculated from equations 23 and 24.

$G_0|_{\text{Naturally aged NBR}} = 6.008 \text{ MPa}$; $G_0|_{\text{Virgin NBR}} = 14.863 \text{ MPa}$, then the Prony values are calculated by using equation 25 and shown in Table 5.

Table 5. Prony series for naturally aged NBR and virgin NBR.

Sample	a_1	τ_1	a_2	τ_2	a_3	τ_3
Naturally aged NBR	0.156	0.034	0.107	0.601	0.048	0.191
Virgin NBR	0.237	0.419	0.285	0.045	0.087	0.028

Prony coefficients a_3 , a_2 , a_3 are dimensionless, and τ_1 , τ_2 , τ_3 in seconds

Under harmonic excitation, viscous elements in the maxwell model dissipate the energy and subside the vibrations. As discussed earlier damping behavior of viscoelastic isolators is majorly determined by viscous elements i.e loss modulus and $\tan \delta$. Detoriation of these dynamic parameters with age is shown in Figures 7 to 9. However, at resonance conditions, the amplitude of vibrations of naturally aged NBR and virgin NBR is calculated from equation 12.

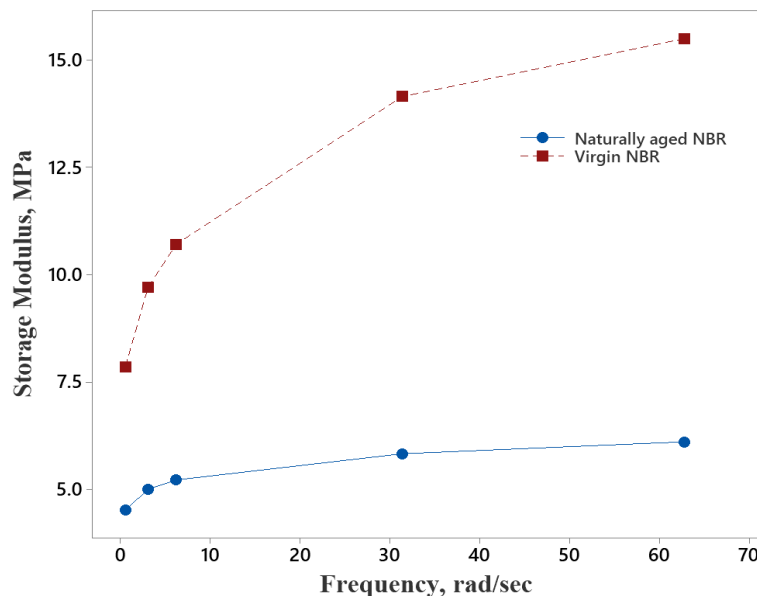


Figure 7. Storage modulus vs frequency of naturally aged NBR and virgin NBR at 40°C temperature.

Figures 8 and 9 show that the Daming ability of viscoelastic isolators deteriorates with age. The loss modulus of NBR material deteriorates by 66% and $\tan \delta$ by 31% in two years at no-load conditions. Loss modulus and loss factor increase slightly with frequency in both naturally aged NBR and virgin NBR, but much less than storage modulus, indicating that at lower frequencies there are no significant changes in loss modulus and loss factors with frequency even after aging.

Table 6. Variation of specific damping capacity for different frequencies at 40°C.

Sample	0.1Hz	0.5hz	1hz	5hz	10hz
Naturally aged NBR	0.63	0.64	0.69	0.76	0.81
Virgin NBR	0.96	0.99	1.02	1.05	1.08

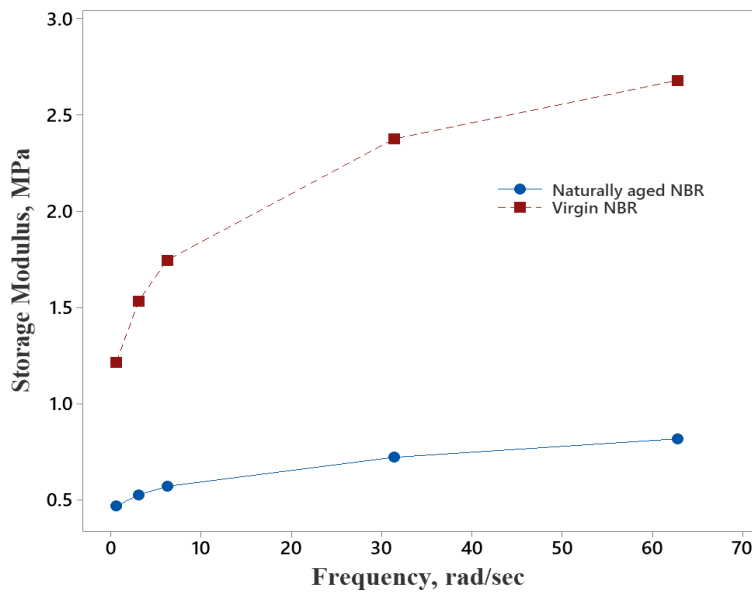


Figure 8. Loss modulus vs frequency of naturally aged NBR and virgin NBR at 40°C temperature.

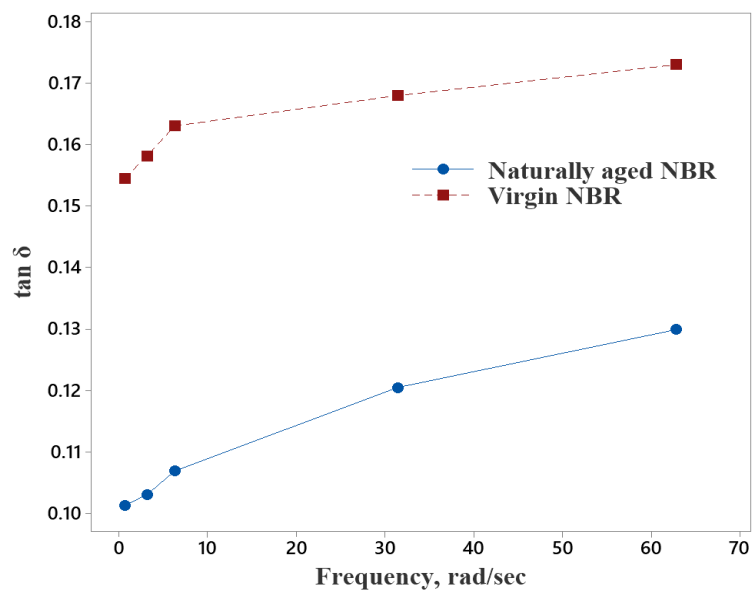


Figure 9. $\tan\delta$ vs frequency of naturally aged NBR and virgin NBR at 40°C.

Before aging, virgin NBR viscous damping coefficient (ξ) at resonance frequency is 0.0816 ($\xi < 1$) and allowed to aging for two years it is decreased to 0.0561 ($\xi < 1$). The specific damping capacity of naturally aged NBR and virgin NBR is given in Table 6. Specific damping capacity of naturally aged rubber is deteriorated by 34% at 0.1hz and 25% at 10hz frequency. At lower frequencies, the damping capacity of aged NBR is deteriorated more and shows less performance. As the maxwell model is the second-order system, the viscous damping coefficient of NBR is between 0 to 1 ($0 < \xi < 1$), the sensitive electronic components mounted on NBR isolators will be stable at the resonance frequency. The proposed method (by using equation 12) suits well to eliminate the difficulty of measuring the amplitude at the resonance frequencies once the elastic (k) and viscous (η) quantities under dynamic conditions are known.

CONCLUSIONS

In this paper, mechanical performance degradation of NBR material in the natural oxidative aging condition is studied. Several mechanical performance characterization tests including Tensile, hardness,

dynamic mechanical analysis at low frequency ranges, are conducted on two years of naturally aged NBR and virgin NBR. Experiment data is well fitted with a higher-order ($n=3$) of the Maxwell model and power model to obtain dynamic characteristics at lower frequencies. The following are the significant conclusions:

1. With age, basic mechanical properties such as yield strength (41.4%), tensile strength (43.4%), and elongation break (11.3%) have deteriorated.
2. The third order of the Maxwell model is sufficient for satisfactory results in low-frequency applications.
3. Ambient oxidative aging significantly reduces the modal, mechanical properties of NBR, namely storage modulus by 52%, loss modulus by 66%, loss factor by 31%, relaxation modulus by 43.9%, and damping coefficient by 31.25%, as well as damping ability.
4. Frequency domain DMA testing data is sufficient to obtain time-dependent viscoelastic parameters, i.e. Prony series, for modeling viscoelastic behavior in CAE software.
5. Power model approximation curve-fitting also offers lesser computation time for obtaining dynamic parameters between given intervals of testing data.
6. The energy dissipation capacity of NBR material deteriorated significantly with age, as did the specific damping capacity by 34%.
7. With age, specific damping capacity at low frequencies (34%) deteriorates more than at higher frequencies (25%).

REFERENCES

1. Q. Peng, Z. Zhu, C. Jiang, H. Jiang, Effect of stress relaxation on accelerated physical aging of hydrogenated nitrile butadiene rubber using time-temperature-strain superposition principle, *Adv. Ind. Eng. Polym. Res.* 2 (2019) 61–68. <https://doi.org/10.1016/j.aiepr.2019.03.002>.
2. C. Bendjaouahdou, S. Bensaad, Aging studies of a polypropylene and natural rubber blend, *Int. J. Ind. Chem.* 9 (2018) 345–352. <https://doi.org/10.1007/s40090-018-0163-2>.
3. J. Feng, Q. Zhang, Z. Tu, W. Tu, Z. Wan, M. Pan, H. Zhang, Degradation of silicone rubbers with different hardness in various aqueous solutions, *Polym. Degrad. Stab.* 109 (2014) 122–128. <https://doi.org/10.1016/j.polymdegradstab.2014.07.011>.
4. S.-S. Choi, J.-C. Kim, Lifetime prediction and thermal aging behaviors of SBR and NBR composites using crosslink density changes, *J. Ind. Eng. Chem.* 18 (2012) 1166–1170. <https://doi.org/10.1016/j.jiec.2012.01.011>.
5. P. Lyu, W. Li, Y. Ma, Y. Cui, Effect of ageing on constrained damping structure of viscoelastic material, *AIP Conf. Proc.* 2036 (2018) 030003. <https://doi.org/10.1063/1.5075656>.
6. T. Ge, X.-H. Huang, Y.-Q. Guo, Z.-F. He, Z.-W. Hu, Investigation of Mechanical and Damping Performances of Cylindrical Viscoelastic Dampers in Wide Frequency Range, *Actuators*. 10 (2021) 71. <https://doi.org/10.3390/act10040071>.
7. M. Vašina, M. Pöschl, P. Zádrapa, A Study of Significant Factors Affecting Viscoelastic Damping Properties of Polymer Materials, *Manuf. Technol.* 18 (2018) 523–529. <https://doi.org/10.21062/ujep/132.2018/a/1213-2489/MT/18/3/523>.
8. R. Lakes, R.S. Lakes, *Viscoelastic Materials*, Cambridge University Press, 2009.
9. D.I.G. Jones, *Handbook of Viscoelastic Vibration Damping*, John Wiley & Sons, 2001.
10. Y.S. Ko, W.C. Forsman, Dynamic Mechanical Testing of Viscoelastic Solids in Free and Forced Oscillation: Experiments with a Modified Weissenberg Rheogoniometer, *Int. J. Polym. Mater. Polym. Biomater.* 8 (1980) 53–63. <https://doi.org/10.1080/00914038008077934>.
11. C.S. Woo, S.S. Choi, S.B. Lee, H.S. Kim, Useful Lifetime Prediction of Rubber Components Using Accelerated Testing, *IEEE Trans. Reliab.* 59 (2010) 11–17. <https://doi.org/10.1109/TR.2010.2042103>.
12. Y. Qian, H. Xiao, M. Nie, Y. Zhao, Y. Luo, S. Gong, Lifetime Prediction and Aging Behaviors of Nitrile Butadiene Rubber under Operating Environment of Transformer, *J. Electr. Eng. Technol.* 13 (2018) 918–927. <https://doi.org/10.5370/JEET.2018.13.2.918>.
13. B. Musil, M. Jöhltz, A. Lion, On the ageing behaviour of NBR: chemomechanical experiments, modelling and simulation of tension set, *Contin. Mech. Thermodyn.* 32 (2020) 369–385. <https://doi.org/10.1007/s00161-018-0728-5>.

14. M. Nait Abdelaziz, G. Ayoub, X. Colin, M. Benhassine, M. Mouwakeh, New developments in fracture of rubbers: Predictive tools and influence of thermal aging, *Int. J. Solids Struct.* 165 (2019) 127–136. <https://doi.org/10.1016/j.ijsolstr.2019.02.001>.
15. J. Liu, X. Li, L. Xu, P. Zhang, Investigation of aging behavior and mechanism of nitrile-butadiene rubber (NBR) in the accelerated thermal aging environment, *Polym. Test.* 54 (2016) 59–66. <https://doi.org/10.1016/j.polymertesting.2016.06.010>.
16. Q.Y. Tang, W.F. Zhang, Environmental Factors on Aging of Nitrile Butadiene Rubber (NBR) - A Review, *Adv. Mater. Res.* 1033–1034 (2014) 987–990. <https://doi.org/10.4028/www.scientific.net/AMR.1033-1034.987>.
17. Y. Xiong, G. Chen, S. Guo, G. Li, Lifetime prediction of NBR composite sheet in aviation kerosene by using nonlinear curve fitting of ATR-FTIR spectra, *J. Ind. Eng. Chem.* 19 (2013) 1611–1616. <https://doi.org/10.1016/j.jiec.2013.01.031>.
18. T. Nakagawa, T. Toya, M. Oyama, Ozone Resistance of Highly Saturated Nitrile Rubber (HNBR), *J. Elastomers Plast.* 24 (1992) 240–261. <https://doi.org/10.1177/009524439202400307>.
19. W. Zheng, X. Zhao, Q. Li, T.W. Chan, L. Zhang, S. Wu, Compressive stress relaxation modeling of butadiene rubber under thermo-oxidative aging, *J. Appl. Polym. Sci.* 134 (2017). <https://doi.org/10.1002/app.44630>.
20. A. Plota, A. Masek, Lifetime Prediction Methods for Degradable Polymeric Materials—A Short Review, *Materials*. 13 (2020) 4507. <https://doi.org/10.3390/ma13204507>.
21. Review of Accelerated Ageing Methods and Lifetime Prediction Techniques for Polymeric Materials, National Physical Laboratory, 2005.
22. T. Ozawa, A New Method of Analyzing Thermogravimetric Data, *Bull. Chem. Soc. Jpn.* 38 (1965) 1881–1886. <https://doi.org/10.1246/bcsj.38.1881>.
23. M. Hussain, S. Yasin, H. Memon, Z. Li, X. Fan, M.A. Akram, W. Wang, Y. Song, Q. Zheng, Rheological and Mechanical Properties of Silica/Nitrile Butadiene Rubber Vulcanizates with Eco-Friendly Ionic Liquid, *Polymers*. 12 (2020) 2763. <https://doi.org/10.3390/polym12112763>.
24. E.J. Graesser, C.R. Wong, The Relationship of Traditional Damping Measures for Materials with High Damping Capacity., David Taylor Research Center Bethesda MD Ship Materials Engineering DEPT, 1991. <https://apps.dtic.mil/sti/citations/ADA235347> (accessed February 15, 2022).
25. J.D. Ferry, *Viscoelastic Properties of Polymers*, John Wiley & Sons, 1980.
26. M.L. Williams, P.J. Blatz, R.A. Schapery, *Fundamental Studies Relating to Systems Analysis OF Solid Propellants*., Defense Technical Information Center, Fort Belvoir, VA, 1961. <https://doi.org/10.21236/AD0256905>.
27. N.W. Tschoegl, *The Phenomenological Theory of Linear Viscoelastic Behavior: An Introduction*, Springer-Verlag, 1989.
28. M. Baumgaertel, H.H. Winter, Determination of discrete relaxation and retardation time spectra from dynamic mechanical data, *Rheol. Acta.* 28 (1989) 511–519. <https://doi.org/10.1007/BF01332922>.
29. R. Han, Y. Wu, X. Quan, K. Niu, Effects of crosslinking densities on mechanical properties of nitrile rubber composites in thermal oxidative aging environment, *J. Appl. Polym. Sci.* 137 (2020) 49076. <https://doi.org/10.1002/app.49076>.
30. C. Tzikang, Determining a Prony Series for a Viscoelastic Material From Time Varying Strain Data, NASA Langley Technical Report Server, 2000.