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Viscoelastic and damping properties of ethylene vinyl acetate (EVA) and its dicumyl peroxide (DCP) cross-linked variants

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ABSTRACT

Uncontrolled vibrations reduce safety, durability, efficiency, comfort, and overall performance in engineering systems; therefore, effective vibration damping is essential. Viscoelastic materials play a crucial role in vibration damping due to their ability to dissipate energy, their tunable properties, and their broad range of applications. Ethylene vinyl acetate (EVA), a thermoplastic copolymer with inherent viscoelastic properties, is widely used in vibration-damping applications. However, its damping capacity can be further improved through cross-linking. This study investigates the damping performance of ethylene vinyl acetate with 18 wt.% vinyl acetate content (EVA-18) modified with 1-4 wt.% dicumyl peroxide (DCP) as a cross-linking agent. Mechanical properties were measured through tensile testing, and viscoelastic behaviour was characterized using Dynamic Mechanical Analysis (DMA). Damping performance was evaluated by Experimental Modal Analysis (EMA) in free-layer damping (FLD) and constrained-layer damping (CLD) configurations. Frequency-dependent system loss factors were predicted using B.C. Nakra's analytical formulations and compared with experimental results. In FLD, EVA-1 showed the highest average loss factor (0.034), whereas in CLD, EVA-0 exhibited the highest loss factor (0.069). These

results clarify how controlled DCP cross-linking modifies the viscoelastic and damping behaviour of EVA-18 and indicate its potential for use in vibration-control applications in automotive, aerospace, and structural engineering.

Keywords: Viscoelastic Damping, EVA-18, Cross-linked polymers, Dynamic Mechanical Analysis (DMA), Experimental Modal Analysis (EMA).

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1. Introduction

Vibration damping is crucial in engineering and industrial applications to enhance the performance, safety, and longevity of structures, machinery, and mechanical systems. Effective damping contributes to increased efficiency, reduced mechanical fatigue, improved system performance, enhanced durability, and increased comfort and reliability across diverse sectors, including automotive, aerospace, manufacturing, and electronics. Damping refers to a material's ability to dissipate energy, usually in the form of heat, when subjected to dynamic loading.

Polymers exhibit inherent viscoelastic behaviour, which makes them effective in vibration damping, as they can absorb and dissipate vibrational energy [1-4]. In industries where vibration and noise reduction are critical, such as the automotive industry, controlling noise, vibration, and harshness (NVH) is imperative. Similarly, in the aerospace industry, minimizing structural vibrations is crucial. The demand for materials with higher damping capabilities has increased in various sectors, particularly in applications where minimizing noise and vibrations is vital for optimal performance and longevity [5-9]. This growing demand for high-performance damping materials has stimulated research into polymeric systems with tailored viscoelastic behaviour.

Ethylene vinyl acetate (EVA) is a widely used thermoplastic copolymer with notable viscoelastic properties [10-12]. This copolymer is a member of the polyolefin family, synthesized by the copolymerization of ethylene and vinyl acetate (VA). The copolymer is available in various forms and has diverse applications across multiple industries [13-14]. EVA's viscoelastic

properties allow it to dissipate vibrational energy effectively through internal friction, converting it to heat when subjected to deformation, thereby reducing vibration amplitude. EVA maintains its damping performance across a wide temperature range, making it suitable for various environmental conditions. Its unique combination of flexibility, durability, toughness, chemical resistance, impact resistance, environmental resistance, and excellent energy-absorbing capacity makes EVA particularly suitable for engineering applications involving vibration control. Moreover, blends of EVA with other elastomers have been extensively studied for their applications in structural vibration damping [15-27].

Vinyl acetate (EVA-18) EVA, with 18 wt.%, is particularly noted for its balanced properties, making it useful in a range of industrial applications, from packaging and films to footwear, wire and cable, and vibration-damping materials [28-36]. Despite this versatility, EVA's damping properties have garnered increasing attention, particularly for applications involving dynamic mechanical stresses, such as those in the automotive, aerospace, and mechanical systems [37-39].

However, EVA's inherent damping capability may not be sufficient for applications requiring higher vibration attenuation. This limitation can be addressed through material modifications, such as cross-linking. In addition to enhancing damping, cross-linking also improves the polymer's dimensional stability, overall durability under mechanical stresses, mechanical strength, creep resistance, and thermal durability [40-45].

Cross-linking with dicumyl peroxide (DCP) is a well-established method to improve the mechanical and viscoelastic properties of polymers, including EVA [46-55]. Through DCP, permanent covalent bonds form between polymer chains, creating a more rigid, stable molecular network that enhances the material's ability to dissipate vibrational energy [56-58]. The degree of cross-linking, modulated by varying DCP concentrations, significantly influences the material's viscoelastic behaviour and, consequently, its vibration-damping efficiency. However, the relationship between cross-linking

percentage and damping performance remains an area that requires further exploration. Moreover, comprehensive analytical-experimental correlation of DCP-cross-linked EVA under both FLD and CLD configurations has not been reported.

This study addresses this gap by presenting a detailed mechanical and viscoelastic characterization of ethylene-vinyl acetate containing 18 wt.% vinyl acetate (EVA-18), cross-linked with varying concentrations (1-4 wt.%) of dicumyl peroxide (DCP). In the present work, DCP concentrations of 1-4 wt.% were selected based on previous studies that have demonstrated that peroxide contents above 4 wt.% often result in over-crosslinking, material embrittlement, and deterioration of mechanical and damping properties. The vibration-damping behaviour of cross-linked EVA 18 is systematically evaluated using both free-layer damping (FLD) and constrained-layer damping (CLD) configurations, which represent practical design approaches for vibration control. In the FLD method, the polymer is applied directly to a vibrating substrate.

In contrast, the CLD technique involves constraining the polymer layer between the substrate and a rigid constraining layer, thereby forming a sandwich structure that enhances energy dissipation under vibratory loading [59-65]. The choice of EVA treatment, FLD, or CLD techniques depends on the specific requirements of the application, as each treatment imparts unique damping characteristics. While EVA's damping properties are well reported, systematic studies on how controlled DCP cross-linking affects its performance under both FLD and CLD configurations, with analytical and experimental validation, remain scarce. Accordingly, the present study aims to elucidate how DCP-induced cross-linking influences the viscoelastic and damping behaviour of EVA-18 using DMA, EMA, and Nakra's analytical model. This work presents an analytical and experimental framework for understanding how DCP-induced cross-linking affects the damping behaviour of EVA-18. The study provides new insight into structure-property

correlations in peroxide-cross-linked EVA for vibration mitigation in engineering structures.

2. Material and Sample Preparation

Ethylene-vinyl acetate-18 (EVA; 18 wt.% vinyl acetate) and dicumyl peroxide (DCP; 99% purity) were used to prepare EVA sheets. EVA-18 granules were melted in a Brabender WinMix hot mixer for 2–3 minutes at 95 °C. This temperature was selected below the onset of DCP decomposition (≈ 130 °C) to ensure uniform dispersion before cross-linking. The cross-linking agent (DCP) was then added, and the compound was mixed for an additional 5 minutes to ensure homogeneous distribution. The compounded EVA was compression moulded into sheets using a preheated mild steel mould with cavity dimensions of $150 \times 150 \times 2$ mm. Four cross-linked formulations were prepared by adding 1, 2, 3, and 4 wt.% DCP, designated as EVA-1, EVA-2, EVA-3, and EVA-4, respectively. A control sample without DCP was designated as EVA-0. After moulding, sheets were thermally cured at 160°C for 10 min to complete peroxide decomposition and cross-link formation.

Curing parameters were determined using a moving die rheometer (MDR).

In both free-layer and constrained-layer damping configurations, the viscoelastic coating was mounted on the mild steel substrate and the constraining layer using a cyanoacrylate-based adhesive to ensure uniform bonding and structural integrity. The adhesive was applied as an ultra-thin interfacial bond, primarily to ensure proper bonding between the layers. It acts as a kinematically rigid link. In practice, it is not possible to measure the adhesive thickness accurately; hence, it was not possible to use a mathematical approach to determine the equivalent damping properties of the adhesive-coated VEM. In practice, accurate measurement of the adhesive thickness is not feasible; consequently, the mathematical determination of the equivalent damping properties of the adhesive-coated VEM could not be performed.

3. Characterization

3.1 Tensile Test

Material samples were subjected to tensile testing to evaluate their mechanical properties. Tensile tests were conducted according to ASTM D412, which specifies procedures for elastomeric materials [66-67]. Tensile specimens were punched from the moulded sheets using an ASTM Die. A tabletop dual-column universal testing machine (Hounsfield 50K, UK) was used to apply tensile loading at a constant crosshead speed. The machine had calibrated load cells rated at 1 kN (100 kgf) to measure the applied force, and an extensometer to measure the specimen's elongation. The dumbbell-shaped test specimens were cut from a flat sheet, with a gauge length of 25 mm, a width of 4 mm, and a thickness of 2 mm. The crosshead speed (the rate at which the machine pulls the specimen) was set to 500 mm/min. The preload applied to the specimen was 1 N. The tensile test results provide insights into the material's mechanical properties, such as its strength and flexibility.

3.2 Dynamic Mechanical Analysis (DMA)

Dynamic Mechanical Analysis (DMA) was performed in tensile mode using the RSA-G2 of TA Instruments (USA) to study the viscoelastic behaviour and thermal transitions of EVA-18 (Ethylene Vinyl Acetate) and its cross-linked variants [68-70]. The analysis was conducted in accordance with ASTM D4065 [71].

Rectangular specimens with uniform dimensions-length 25 mm, width 5 mm, and thickness 1 mm-were prepared. Each sample was carefully mounted in the tensile clamp without applying pre-strain, ensuring proper alignment.

Two types of DMA tests were conducted: a temperature sweep and a frequency sweep. In the temperature sweep, a constant oscillation frequency of 1 Hz was employed. Since EVA softens with increasing temperature, the test was conducted over a temperature range of -80°C to $+120^{\circ}\text{C}$. The analysis begins at -80°C using liquid nitrogen cooling and proceeds to 120°C at a controlled heating rate of $2^{\circ}\text{C}/\text{min}$. A sinusoidal strain was applied in single-frequency mode during the test.

For the frequency sweep, the temperature was maintained at 30°C, and the frequency was varied logarithmically from 0.1 Hz to 100 Hz. Oscillatory tensile loads were applied, and the corresponding displacement response was measured. TRIOS software (TA Instruments) was used for data acquisition and master-curve construction.

The master curves were constructed by horizontally shifting the isothermal frequency-dependent data along the $\log(f)$ axis, following the time-temperature superposition (TTS) principle. The WLF (Williams-Landel-Ferry) equation was applied to determine the shift factor α_T , which relates the viscoelastic response at a reference temperature to that at other temperatures:

$$\log(\alpha_T) = -\frac{C_1(T - T_{ref})}{[C_2 + (T - T_{ref})]} \quad (1)$$

Where T is the temperature, T_{ref} is the reference temperature (30 °C in this study), and C_1 and C_2 are material-specific constants typically derived from experimental data. The shift factors obtained from the WLF equation allow the construction of smooth, continuous master curves without vertical shifting, indicating thermorheologically simple behaviour.

The objective of this analysis was to evaluate the material's viscoelastic properties - storage modulus (E'), loss modulus (E'') and damping factor ($\tan \delta$) - as functions of temperature and frequency.

3.3 Calculation of cross-linking density

The crosslink density (ν) was estimated using rubber elasticity theory based on the storage modulus in the rubbery region:

$$\nu = \frac{E'}{3RT} \quad (2)$$

Where ν is the cross-link density (mol/m³), E' is the storage modulus in the rubbery plateau region (Pa), R is the universal gas constant, 8.314 J/mol·K and T is the absolute temperature (K). Crosslink density was calculated using storage modulus values at 90°C. At these temperatures, the EVA samples are

in a rubbery state, and the crosslinked network predominantly governs the modulus.

4. Experimental Modal Analysis

Experimental Modal Analysis (EMA) is a crucial technique for characterizing the dynamic behaviour of structures and materials. The damping characteristics of EVA-18 and its crosslinked variants were analyzed using experimental modal analysis (EMA). In this study, an electrodynamic shaker (DS-1000 system with a 100 kg capacity) was employed to excite the system (bare MS beam, FLD system, and CLD system), and the resulting vibrations were measured using accelerometers (Type 4507 B004; mass - 2 g; sensitivity of 100 ± 3 mV/g). Excitations were measured using an exciter transducer. The EMA was conducted at a frequency resolution of 0.5 Hz to capture the frequency response functions accurately.

The dimensions of the base beam, viscoelastic layer, and constraining layer were in accordance with the ASTM E756 standard [72]. The thickness of the base beam was 3.15 mm, the width was 10 mm, and the length was 225 mm, while the thickness of the viscoelastic layer was 2 mm and the thickness of the constraining layer was 3.15 mm. The clamping distance for the base beam was kept at 25 mm. FLD readings were taken with the shaker for all samples. Then, on the same assembly, a constraining layer was applied to form CLD samples. The base beam and constraining layer were made of mild steel.

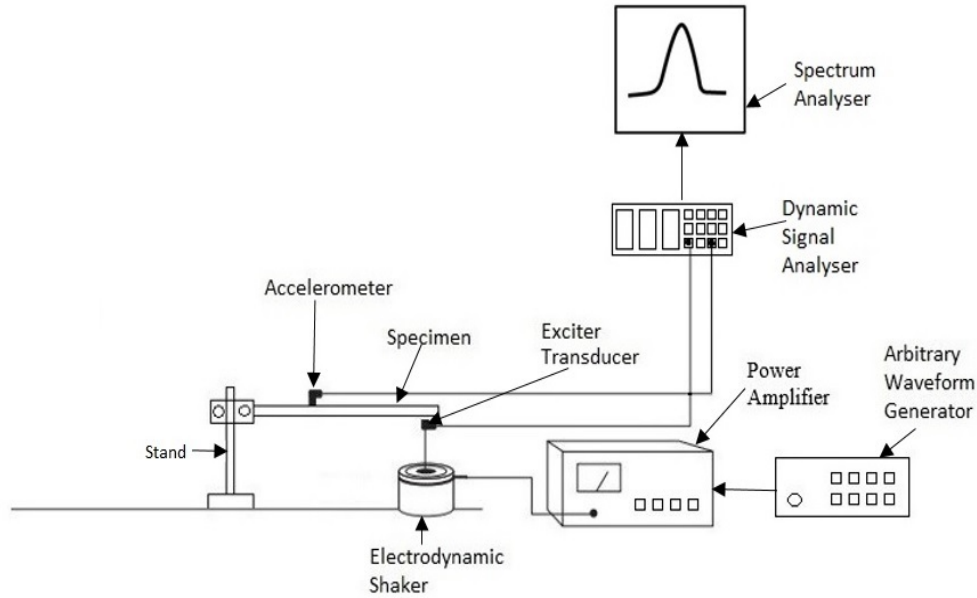


Fig. 1. Schematic of experimental setup for modal testing

The experimental setup, as depicted in Figure 1, consists of a beam specimen mounted on a stand and connected to an electrodynamic shaker through a stinger, with an exciter transducer positioned between the beam and the stinger. A stinger is a thin, flexible rod used to connect an electrodynamic shaker to a test structure. The shaker was driven by a power amplifier, controlled by an arbitrary waveform generator to provide a precise excitation signal. The excitation frequency was swept from 1 Hz to 5000 Hz. An accelerometer was attached to the beam to measure its vibrational response, with the data being processed by a dynamic signal analyzer (Brüel & Kjær, eight-channel data acquisition system) and subsequently analyzed using a spectrum analyzer. Each test was repeated three times to ensure measurement repeatability.

Data acquisition was performed using a digital signal processing system that recorded the accelerometers' responses in real-time. The frequency response functions (FRFs) were computed from the input force and output acceleration signals. FRFs with coherence values close to unity were selected to ensure high data reliability. Data acquisition and processing were

performed using DEWESoft X3 software. It is used to record, visualize, and process experimental data.

Analysis of EVA as a damping material was conducted through experimental modal analysis (EMA) using the Oberst beam technique, in which one end of the test specimens is clamped and the other is free [73-76]. The damping performance of the material is quantitatively analyzed by calculating the loss factor [77-80]. The loss factor is a measure of the material's ability to dissipate vibrational energy, where a higher loss factor indicates better damping capacity. The loss factor in this study was calculated using the 3 dB method, commonly employed in experimental modal testing. The loss factor was additionally estimated using the analytical model proposed by B. C. Nakra, which facilitates the theoretical evaluation of damping behaviour from the material's viscoelastic parameters [81-83].

The theoretical loss factors of the developed compositions were systematically compared with the experimentally determined values to assess the accuracy of the theoretical model. The comparison of FLD and CLD further adds to the novelty of this study, offering practical insights into the most effective damping configurations for EVA-18. This dual approach enables a comprehensive understanding of the material's damping behaviour across varying cross-linking percentages.

5. Analytical Prediction of Damping Performance

Calculation of System Loss Factor had been carried out for Free Layer Damping and Constrained Layer Damping using equations developed by B. C. Nakra [83].

5.1 Free layer damping (FLD)

Structural vibrations can be damped by a passive damping layer coating on the substrate, without any CL on top. It is the simplest damping treatment on a substrate.

The system loss factor was calculated from the ratio of stiffness of the composite to the base structure using the following expression:

Nakra et al. [83] gave an expression of the system loss factor for an FLD treatment as

$$\eta_s = \frac{\eta_2 h e (3 + 6h + 4h^2)}{1 + e h (3 + 6h + 4h^2)} \quad (3)$$

Where η_2 is $\tan \delta$ of a viscoelastic material obtained by DMA.

Here, $e = \frac{E_2'}{E_1}$ and $h = \frac{H_2}{H_1}$

With the following assumptions:

$eh \ll 1$ and $\eta_2 E_2' H_2 \ll E_1 H_1$, which are true for almost all cases of VEM coating on metals.

5.2 Constrained Layer Damping (CLD)

Nakra [83] suggested an expression for the system loss factor for a beam with a CLD arrangement.

The expressions for the shear parameter and the system loss factor are given as follows.

Shear parameter:

$$\psi_{23} = \frac{G^*}{E_3 h^2 \left(\frac{n\pi}{L} \right)^2} \quad (4)$$

And system loss factor:

$$\eta_s = \frac{H \eta_0}{(1 + \alpha_{13} H_{13}^3) (M^2 + \eta_0^2) + HM} \quad (5)$$

Where η is the modal number, L is the length of the sandwich beam, G^* , η_0 the complex shear modulus and loss factor of the VEM, $\alpha_{13} = E_1/E_3$, $H_{13} = t_c/h$, $H_{23} = t/h$ and $E_i = \text{Young's modulus of the } i^{\text{th}} \text{ layer}$.

Since the DMA tests were performed in tensile mode, the measured complex extensional modulus E^* was converted to complex shear modulus G^* using the relation $G^* = \frac{E^*}{2(1+\nu)}$, where $\nu = 0.49$, a Poisson's ratio of EVA.

$$H = \frac{3\psi_{23}}{H_{23}} (1 + H_{13} + 2H_{23})^2 (1 + \eta_0^2) \quad (6)$$

$$M = 1 + \frac{\psi_{23}}{H_{23}} \left(\frac{1}{\alpha_{13} + H_{13}} + 1 \right) (1 + \eta_0^2) \quad (7)$$

6. Results and Discussion

6.1 Tensile Test

Table 1 presents the results of tensile tests performed on five EVA-18 (Ethylene Vinyl Acetate) samples with varying DCP (dicumyl peroxide) concentrations (DCP 0 wt.% to DCP 4 wt.%). All results reported were based on the average values of three measurements. The result is summarised and discussed below:

Table 1: Tensile properties

Sample	Modulus @10% elongation (MPa)	Modulus @100% elongation (MPa)	Ultimate tensile strength (MPa)	Ultimate elongation (%)
EVA-0	37.5	5.53	23.2	718
EVA-1	34.8	5.62	33.4	647
EVA-2	36.7	6.29	18.9	369
EVA-3	36.9	6.58	9.45	189
EVA-4	12.1	5.86	7.76	219

The modulus at 100% elongation increased with increasing DCP content up to 3 wt.%. EVA-0 showed a modulus of 5.53 MPa, which rises to 6.58 MPa for EVA-3. The trend indicates that the addition of DCP increases the material's ability to resist deformation at larger elongations due to enhanced cross-linking. EVA-3 has the highest modulus (6.58 MPa), indicating it is the stiffest at 100% elongation. The modulus slightly decreases for EVA-4 (5.86 MPa), suggesting that excessive cross-linking starts reducing the material's elasticity.

EVA-1 exhibited the highest ultimate tensile strength (33.4 MPa). At DCP concentrations above 1 wt.%, ultimate strength decreased markedly,

indicating embrittlement due to excessive cross-linking. The reduction in tensile strength at higher DCP contents correlates with the narrowing of the glass transition peaks, indicating restricted segmental mobility, reduced energy dissipation, and consequent embrittlement. In addition, the ultimate elongation decreases with increasing DCP concentration.

Figure 2 shows the stress-strain relationship for five different EVA samples. Initially, all samples have a similar linear region, indicating elastic behaviour.

EVA-1 shows the highest UTS of 33.4 MPa, indicating it is the strongest material in the set. EVA-4 exhibited the lowest tensile strength (7.76 MPa) and elongation, indicating brittleness. EVA-0 has a lower slope than other samples, indicating it is less stiff or more flexible, yet it has the highest elongation, indicating it is more ductile.

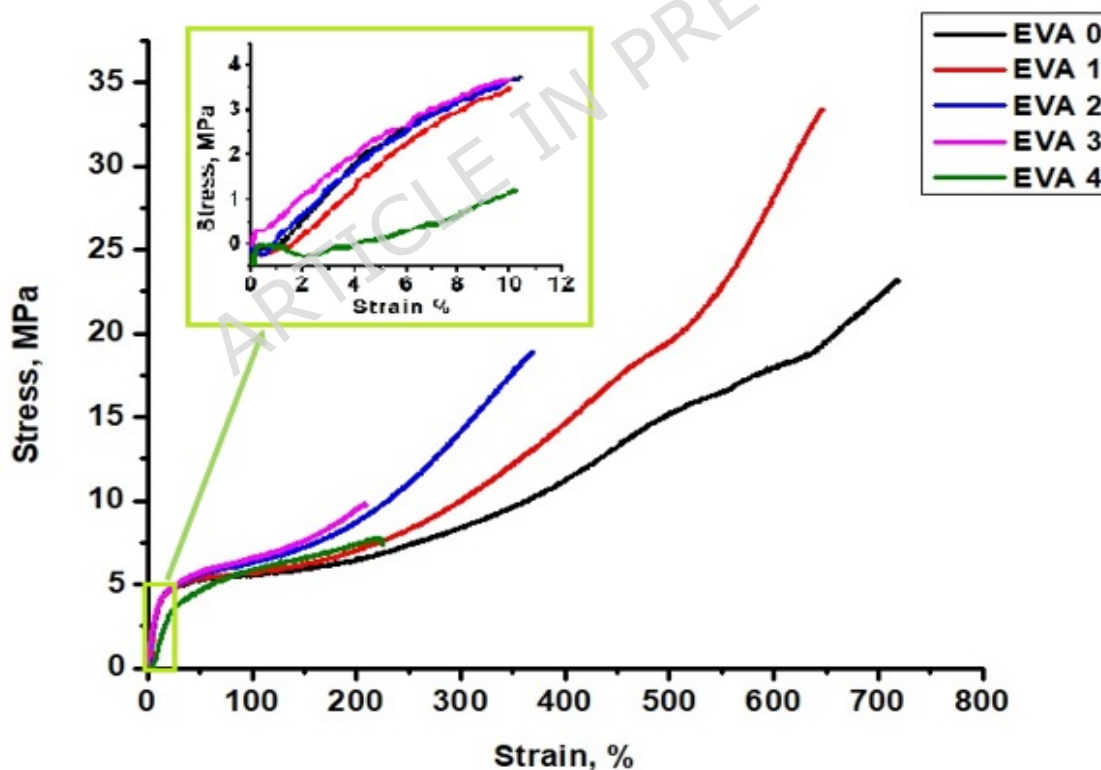


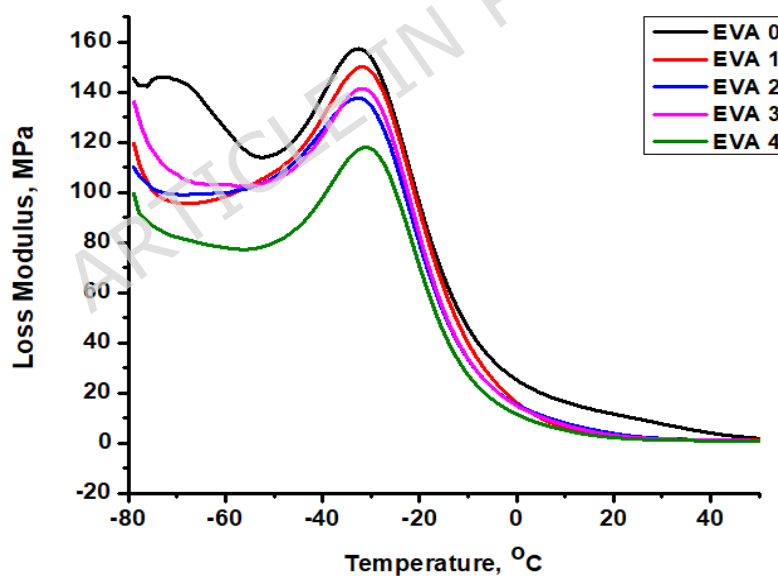
Fig. 2. Stress-Strain curves of EVA samples

6.2 Viscoelastic Characterization

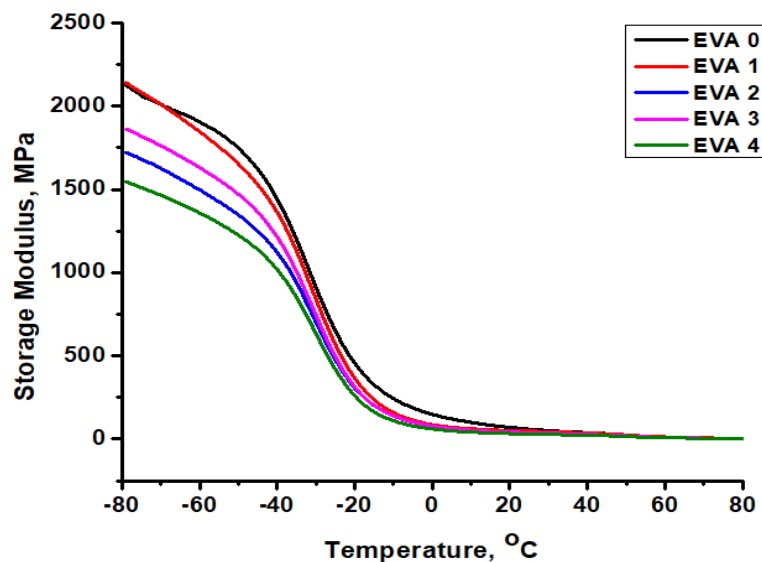
6.2.1 Viscoelastic properties as a function of temperature

Figure 3 shows the Loss Modulus (MPa), Storage Modulus (MPa) and $\tan \delta$ as a function of Temperature ($^{\circ}\text{C}$) for five different EVA samples: EVA-0, EVA-1, EVA-2, EVA-3, and EVA-4.

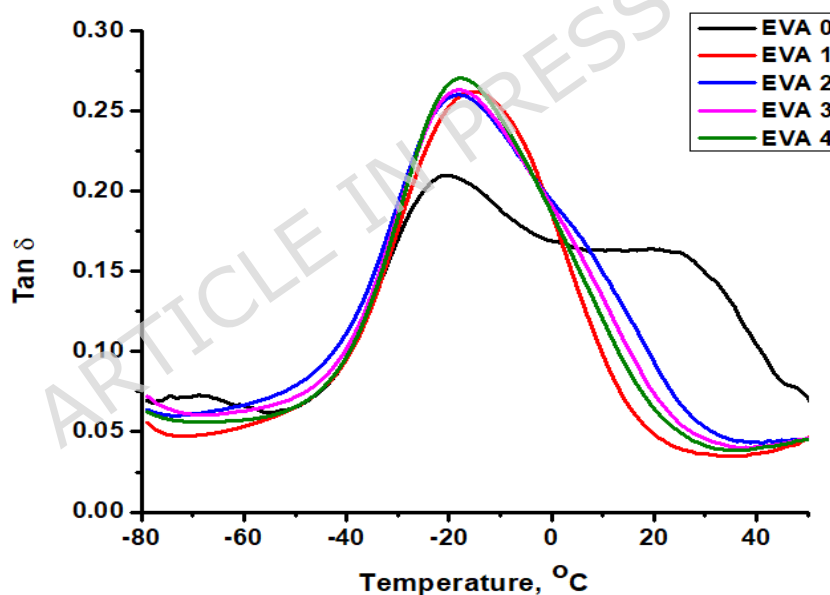
The loss modulus represents the material's ability to dissipate energy. EVA-0 exhibits the highest loss modulus, with a peak at approximately 157 MPa at a temperature of about -32.51°C . The peak of EVA-1 is slightly lower than EVA-0, at 150.22 MPa at -31.22°C . EVA-4 has the lowest loss modulus peak, at 118.413 MPa at -30.697°C , which is significantly lower than that of the other samples. A higher loss modulus means more energy is lost as heat due to internal friction. The trends indicate that increasing the DCP content in EVA decreases the loss modulus. This data helps determine the suitability of different EVA formulations for applications that require energy absorption at varying temperatures.



a) Loss Modulus vs Temperature



b) Storage Modulus vs Temperature



c) Tan d vs Temperature

Fig. 3. Viscoelastic properties as a function of temperature

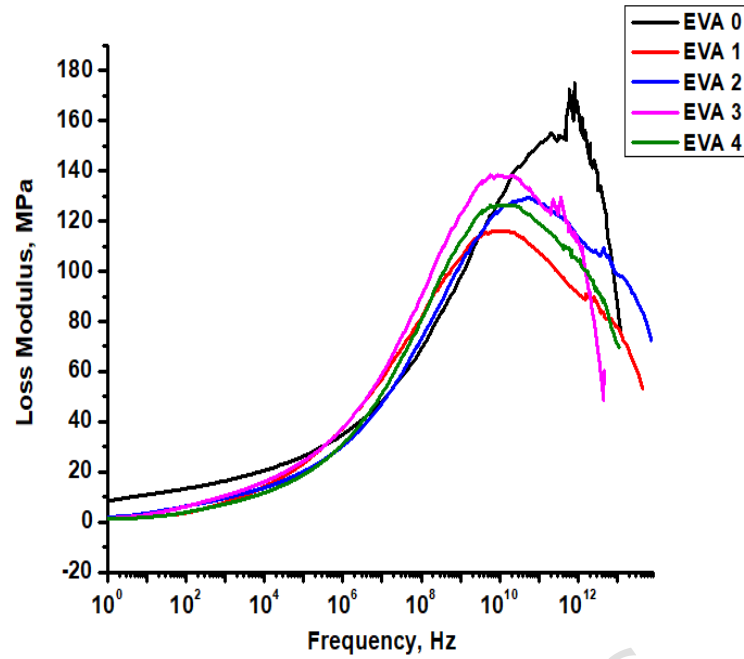
EVA-0 exhibits the highest storage modulus across the entire temperature range, reaching 2143.198 MPa at -78.61°C , indicating it is the stiffest material. The higher storage modulus observed for EVA-0 is attributed to its greater crystallinity, which contributes to stiffness. The introduction of DCP disrupts crystalline regions, and the resulting reduction in crystallinity

outweighs network stiffening, leading to a decrease in the storage modulus. EVA-4 has the lowest modulus among all samples (1551.283 MPa at -79.07°C), indicating the softest behaviour across the entire temperature range. The slope of the graph suggests that EVA is initially stiff but softens rapidly as temperature increases.

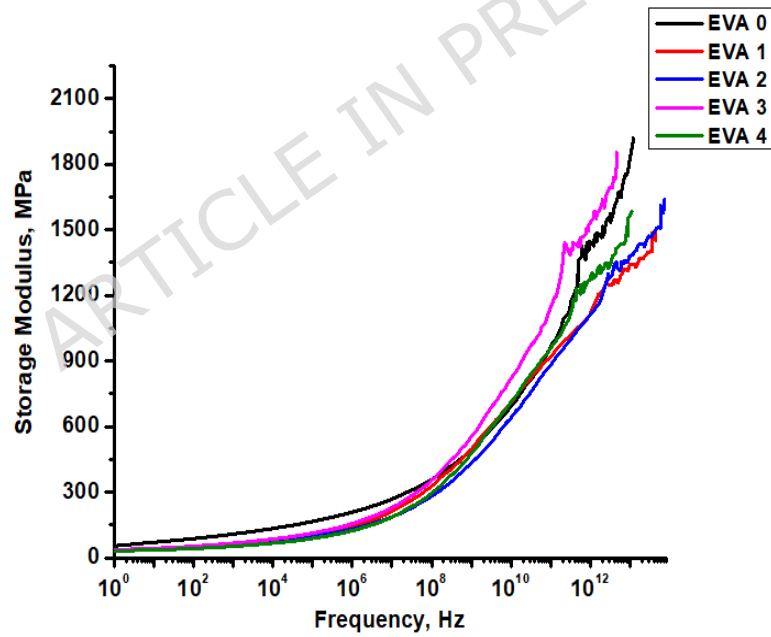
Each $\tan \delta$ curve exhibits a peak between -40°C and 0°C, which corresponds to the glass transition temperature (T_g) of the materials. EVA-4 shows the highest peak values of $\tan \delta$ (0.27), while EVA-0 shows the lowest peak value (0.21). EVA-0 shows a broader peak, suggesting a wider temperature range over which the glass transition occurs. It also depicts that it is suitable for a wider temperature range for damping. All cross-linked samples generally exhibit similar trends, with a clear peak at T_g ; however, EVA-0 stands out due to its secondary slope beyond 20°C, suggesting a unique secondary transition or different molecular relaxation behaviour. The pristine EVA exhibited clear phase separation, with two distinct relaxation peaks: one at -20 °C, attributed to ethylene, and another at approximately 27 °C, corresponding to vinyl acetate. This phase separation becomes suppressed upon cross-linking, and all DCP-modified EVA samples show a single, sharper $\tan \delta$ peak due to improved phase homogeneity and restricted chain mobility caused by covalent cross-links.

6.2.2 Viscoelastic properties as a function of frequency

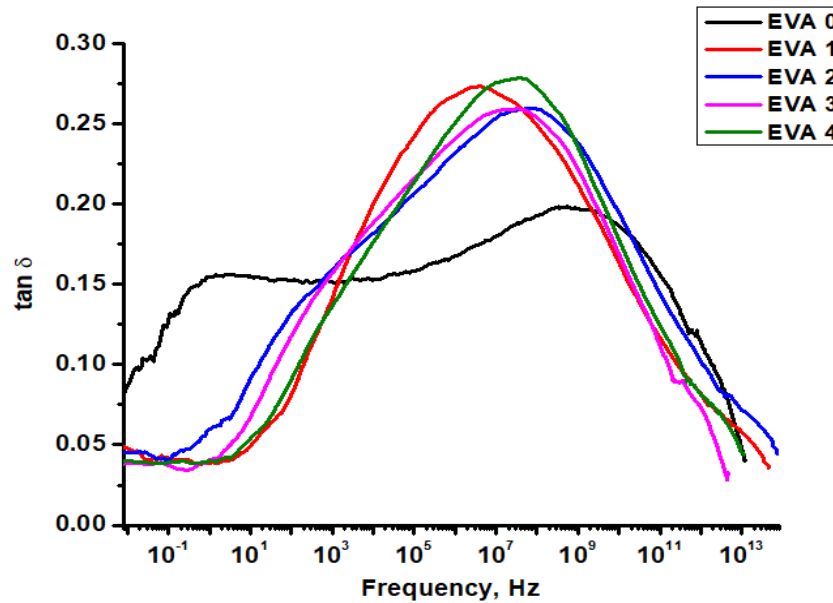
Figure 4 shows the Loss Modulus (MPa), Storage Modulus (MPa) and $\tan \delta$ as a function of frequency (Hz) for five different EVA samples EVA-0, EVA-1, EVA-2, EVA-3, and EVA-4.



a) Loss Modulus vs frequency



b) Storage Modulus vs frequency



c) Tan d vs frequency

Fig. 4. Viscoelastic properties as a function of frequency

EVA-0 shows the highest peak of loss modulus (156 MPa), while EVA-1 has the lowest peak (117 MPa). While EVA-2, EVA-3 and EVA-4 have intermediate peaks. EVA-0, with a higher loss modulus at high frequencies, may be suited for applications requiring higher energy dissipation.

EVA-0 achieves the highest storage modulus (1920 MPa), indicating that it is the stiffest material and has the greatest elastic energy storage capacity. EVA-1 exhibits the lowest values of storage modulus (1500 MPa) at high frequencies, indicating that it is the most flexible and suitable for damping applications. Materials with higher storage modulus at high frequencies, such as EVA 0 and EVA-3, are ideal for applications requiring stiffness and high energy storage capacity (e.g., structural components, impact-resistant materials).

EVA-0 has the lowest peak value of $\tan \delta$ (0.19), indicating that it exhibits the least energy dissipation among the samples and is therefore more elastic. EVA-4 exhibits the highest peak value (0.27), indicating that this material has the best damping characteristics at its peak frequency. The general trend of a single peak is consistent for all samples, but the peak frequency and height

vary. As EVA-0 shows a broader peak, suggesting a wider frequency range of damping. Materials like EVA-1 and EVA-4 exhibit higher $\tan \delta$ peaks, suggesting they are better suited for damping applications, as they can dissipate more energy and reduce vibrations more effectively.

6.2.3 Cross-link Density and Structure-Property Relationship

The cross-link density (ν) is a critical structural parameter that governs the mechanical, viscoelastic, and damping behaviour of polymeric materials. In the present study, the cross-link density of EVA-18 and its dicumyl peroxide (DCP) cross-linked variants was evaluated using the rubbery plateau storage modulus (E') obtained from dynamic mechanical analysis (DMA). Table 2 presents the storage modulus (E') in the rubbery region and the corresponding cross-link density (ν) values for EVA-18 samples with varying DCP content.

Table 2. Crosslink density for EVA Samples

Sample	E' (MPa)	Crosslink Density (mol/m ³)
EVA-1	1.29	142.479
EVA-2	1.68	185.554
EVA-3	2.37	261.764
EVA-4	2.48	273.913

A clear increase in cross-link density with increasing DCP concentration is observed, confirming the formation of an effective polymer network through peroxide-induced cross-linking. Consistent with rubber elasticity theory, this increase in ν is accompanied by a rise in the storage modulus (E'), indicating enhanced material stiffness.

The increase in cross-link density significantly influences the mechanical behaviour of EVA. At lower cross-link densities, the polymer chains retain higher mobility, resulting in improved flexibility and enhanced elongation. However, at higher cross-link densities, network saturation occurs. This

behaviour suggests that additional cross-links restrict chain mobility and reduce network extensibility. This observation is consistent with the tensile results, which show that excessive cross-linking leads to reduced elongation and increased brittleness.

The cross-link density also plays a critical role in governing the viscoelastic and damping behaviour of EVA. Damping in viscoelastic materials arises from molecular friction and segmental motion; therefore, it is strongly dependent on chain mobility. At lower cross-link densities, higher molecular mobility facilitates greater energy dissipation, thereby improving damping performance. It explains the superior free-layer damping (FLD) behaviour observed for EVA-1.

6.2.4 WLF Parameters and Time-Temperature Superposition (TTS) Analysis

The temperature-dependent viscoelastic behaviour of the EVA composites was analyzed using the Williams-Landel-Ferry (WLF) equation. The shift factors ($\log \alpha_T$) were evaluated over the investigated temperature range, and the WLF constants (C_1 and C_2) were determined to characterize the temperature-frequency dependence of the viscoelastic response. Table 3 summarizes the WLF constants (C_1 , C_2) and corresponding shift factors ($\log \alpha_T$) for EVA-18 and its DCP cross-linked variants over the investigated temperature range.

Table 3. WLF constants (C_1 , C_2) and corresponding shift factors ($\log \alpha_T$) for EVA-18 and DCP cross-linked samples at different temperatures.

EVA-0				EVA-1			EVA-2			EVA-3			EVA-4		
T	f ₃₀ : 6 Hz to 10 ⁶ Hz			f ₃₀ : 6 Hz to 9x10 ⁴ Hz			f ₃₀ : 6 Hz to 2x10 ⁵ Hz			f ₃₀ : 6 Hz to 9x10 ⁴ Hz			f ₃₀ : 7 Hz to 1.2x10 ⁵ Hz		
°C	C1	C2	log(α_T)	C1	C2	log(α_T)	C1	C2	log(α_T)	C1	C2	log(α_T)	C1	C2	log(α_T)
-5	11.87	105	5.927	9.764	108	4.675	10.29	104	5.217	9.88	106	4.868	10.11	106	4.977
0	12	105	4.79	9.98	107.8	3.841	10.36	104	4.188	9.91	106	3.908	10.14	106	3.997
5	12.3	104	3.885	10	107.2	3.04	10.44	104	3.3	9.85	106	3.037	10.18	105	3.178

1 0	12.5 3	10 3	3.021	10.3 7	106. 1	2.403	10.4 5	10 4	2.49	9.93	10 6	2.306	10.4 3	10 4	2.476
1 5	12.6 7	10 2	2.182	10.7 9	105	1.793	10.6 3	10 2	1.827	10.1 1	10 4	1.701	10.9 3	10 2	1.88
2 0	12.8 9	10 1	1.415	11.6 2	102	1.257	10.8 6	10 0	1.201	10.1 6	10 0	1.129	11.1 9	98	1.27
2 5	13.3	10 0	0.695	13.6	98	0.723	12.0 4	98	0.647	12.6	97	0.682	13.6 5	94	0.764

For all compositions, $\log \alpha_T$ decreases systematically with increasing temperature, indicating reduced horizontal shifting as the system approaches the reference temperature and confirming the validity of time-temperature superposition. The WLF constants exhibit relatively narrow variations across all samples, suggesting thermorheologically simple behaviour. Pristine EVA (EVA-0) shows comparatively higher C_1 values, reflecting greater temperature sensitivity of the viscoelastic response, whereas cross-linked samples exhibit slightly lower C_1 values, indicating reduced sensitivity due to restricted chain mobility. A gradual decrease in C_2 with increasing temperature is observed, which is attributed to reduced free volume and enhanced network constraints in the cross-linked systems.

The evolution of C_1 , C_2 , and $\log(\alpha_T)$ indicates that crosslinking progressively shifts the viscoelastic response from free-volume-dominated behavior to network-controlled dynamics. These results confirm the applicability of the WLF equation and support the construction of reliable master curves for long-term viscoelastic prediction.

6.3 Damping Characteristics

6.3.1 EVA FLD system

The graph in Figure 5a displays the frequency responses of various EVA materials (EVA-0 to EVA-4) obtained using the FLD method, along with the bare beam response. The bare beam experiences significant resonance and higher vibration levels across the frequency spectrum, peaking at multiple points. It suggests that without EVA damping, the system is prone to more vibration. Frequency response function (FRF) analysis validated the damping

effectiveness of the tested materials. EVA-1 exhibits the greatest attenuation, with the lowest amplitudes across most of the frequency range, particularly below 3000 Hz. It reduces peaks more significantly than other EVA materials, indicating superior vibration damping, which may be attributed to an optimal cross-linking density.

Fluctuations in the loss factor in Figure 5b indicate a complex viscoelastic behaviour. EVA-2 and EVA-3 exhibit higher loss factors up to 800 Hz, making them the best performers in low-frequency energy dissipation. EVA-2 exhibits more consistent behaviour across the frequency spectrum, indicating balanced energy dissipation over a wide frequency range. The higher loss factor of EVA-2 for a wide frequency range is preferable in applications where high energy dissipation is desired.

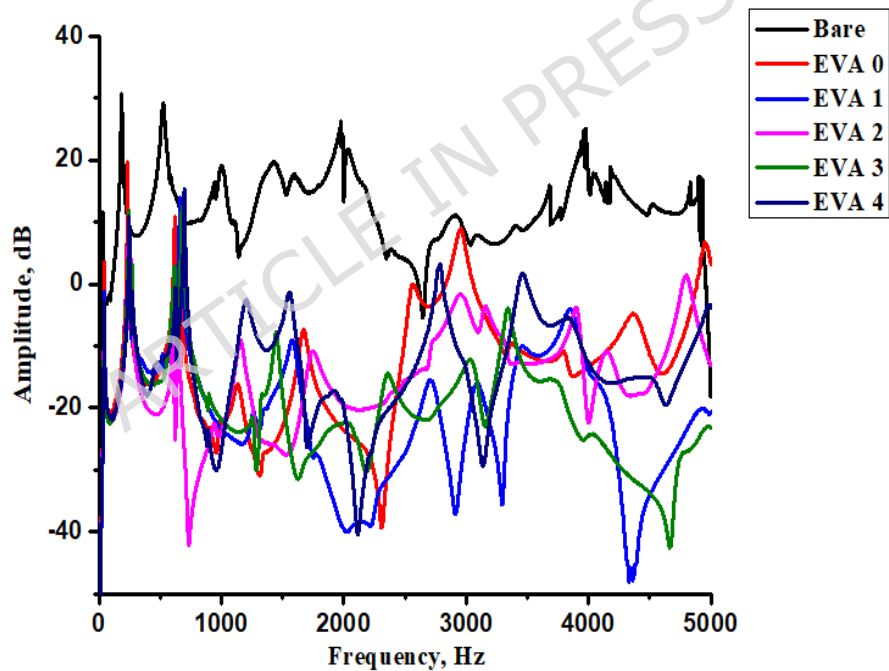


Fig. 5. a) Frequency response function (FRF) of bare beam and EVA DCP samples, obtained experimentally in FLD mode

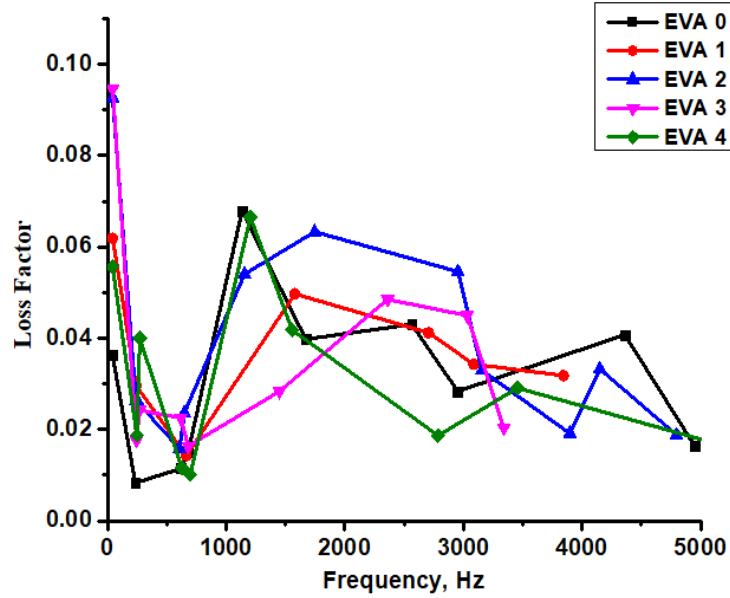
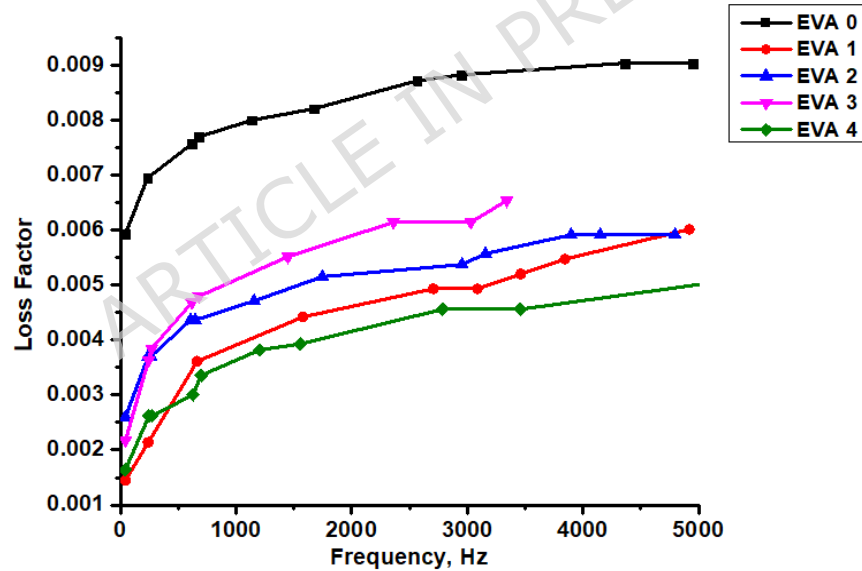


Fig. 5. b) FLD system loss factor obtained by 3 dB method of the frequency response



c)

Fig. 5. c) FLD system Loss Factors obtained by Nakra calculations.

All EVA treatments (EVA-0, EVA-1, EVA-2, EVA-3, EVA-4) exhibit a general trend of increasing loss factor with increasing frequency, as shown in Figure 5c. It indicates that the materials become more effective in dissipating energy at higher frequencies. EVA-0 shows the highest loss factor values consistently

across all frequencies, peaking at 0.009. EVA-4 has the lowest loss factor, starting at 0.0016 and increasing to 0.0045 by the end of the frequency range. EVA-0, exhibiting the highest loss factor, provided the most efficient vibration damping. EVA-4, on the other hand, has the least damping efficiency.

6.3.2 EVA CLD system

The graph in Figure 6a shows the frequency responses of different EVA materials (EVA-0 to EVA-4) obtained using the CLD method, along with the bare beam response. All EVA CLD treatments demonstrate a significant reduction in amplitude compared to the Bare condition. It indicates that the CLD treatments effectively attenuate vibrations.

EVA-1, with superior damping properties, exhibits the lowest amplitudes across all datasets. The bare dataset, showing high amplitude, suggests that without damping, the system resonates freely. In contrast, EVA CLD-treated samples (especially EVA-1) effectively suppress these resonances, thereby reducing vibrational energy. EVA-1 exhibits smoother, more consistent behaviour across most of the frequency range, while EVA-2 shows better attenuation for the low-frequency range up to 1000 Hz.

The datasets in Figure 6b exhibit fluctuations in loss factor values, indicating a more complex behaviour of EVA CLD treatment. The graph's irregular pattern suggests that the loss factor does not increase or decrease linearly with frequency. Instead, the loss factor values vary, resulting from material behaviour at different frequencies. There is a non-linear relationship between Loss Factor and Frequency for all datasets.

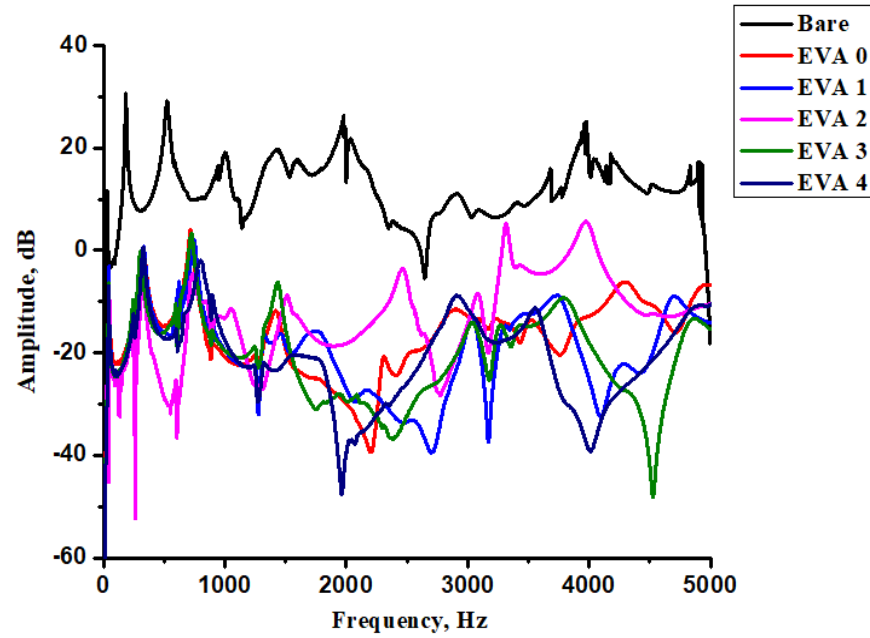


Fig. 6. a) Frequency response function (FRF) of bare beam and EVA DCP samples, obtained experimentally in CLD mode

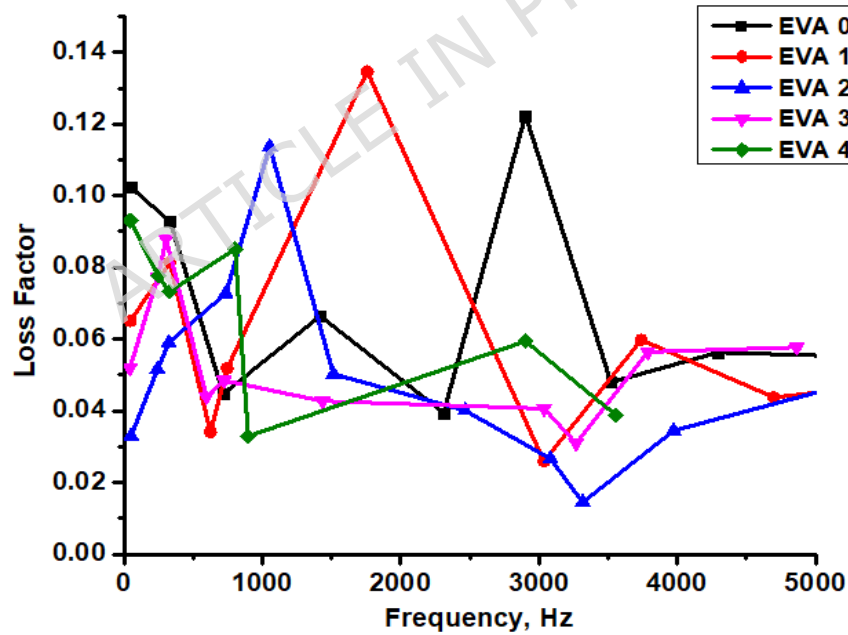


Fig. 6. b) CLD system loss factor obtained by the 3 dB method of the frequency response

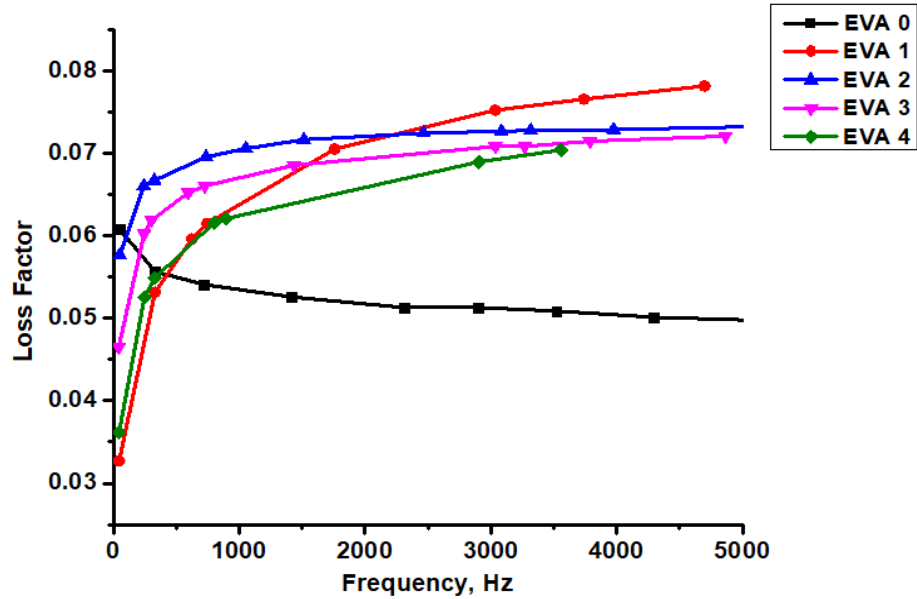


Fig. 6. c) CLD system Loss Factors obtained by Nakra calculations.

As frequency changes, the internal friction and energy dissipation properties of the materials change, leading to varying loss factors. The inherent properties of the materials, including internal damping mechanisms and viscoelastic behaviour, affect their ability to dissipate energy. The differences in loss factor trends can be attributed to the inherent material properties of each EVA type, including viscoelasticity and damping.

EVA-1 displays the highest loss factor at 1757 Hz with a value of 0.14. It suggests that at this frequency, EVA-1 experiences maximum energy dissipation. EVA-2 has its highest loss factor at 1052 Hz with a value of 0.11363. It indicates significant damping performance at this frequency. EVA-1 has the highest overall loss factor, indicating the best damping performance. EVA-0 also exhibits good damping characteristics up to 800 Hz.

All datasets in Figure 6c exhibit a rapid increase in the loss factor as the frequency increases from 1 Hz to approximately 500 Hz. Beyond this initial steep rise, the curves begin to level off between 500 Hz and 5000 Hz. It indicates a threshold frequency of 500 Hz, beyond which the materials' damping capacity stabilizes.

According to the Loss Factor obtained using the Nakra Equation for EVA CLD treatment, EVA-1 and EVA-2 are the most effective materials for energy dissipation, making them suitable for applications requiring high damping. EVA-2 shows the highest loss factor values up to 2500 Hz, reaching around 0.072 at around 3000 Hz. EVA-1 exhibits the highest loss factor values above 2500 Hz, reaching approximately 0.078 at around 5000 Hz. The highest value is observed for EVA-1 at 4697 Hz with a loss factor of roughly 0.078. EVA-0 displays the lowest loss factor, which stabilizes at around 0.055 at 4291 Hz after an initial decrease at lower frequencies.

6.3.3 Average Loss Factor Comparison

The average loss factor was calculated for all EVA compositions (EVA-0 to EVA-4) of both Free Layer Damping (FLD) and Constrained Layer Damping (CLD) configurations. Figure 7 compares the average loss factors for both experimental measurements and analytical predictions. The CLD experimental results consistently exhibit higher loss factors across all compositions compared to FLD, with EVA-0 showing the highest value, 0.069.

In the FLD experimental results, EVA-1 exhibits the highest average loss factor (~ 0.034), likely due to its partially cross-linked structure, which offers an optimal balance of stiffness and damping. It makes EVA-1 the preferred choice for applications that utilize free-layer damping. Additionally, EVA-1 shows strong agreement between experimental and theoretical values under CLD, indicating reliable and consistent damping behaviour. Notably, equation-based predictions, particularly for FLD, significantly underestimate experimental values, suggesting that the current theoretical model may not fully capture the complex viscoelastic behaviour and structural interactions in FLD systems. Furthermore, the experimental setup inherently includes additional energy dissipation mechanisms, such as material nonlinearity, interfacial effects, etc., which are not considered in the analytical model.

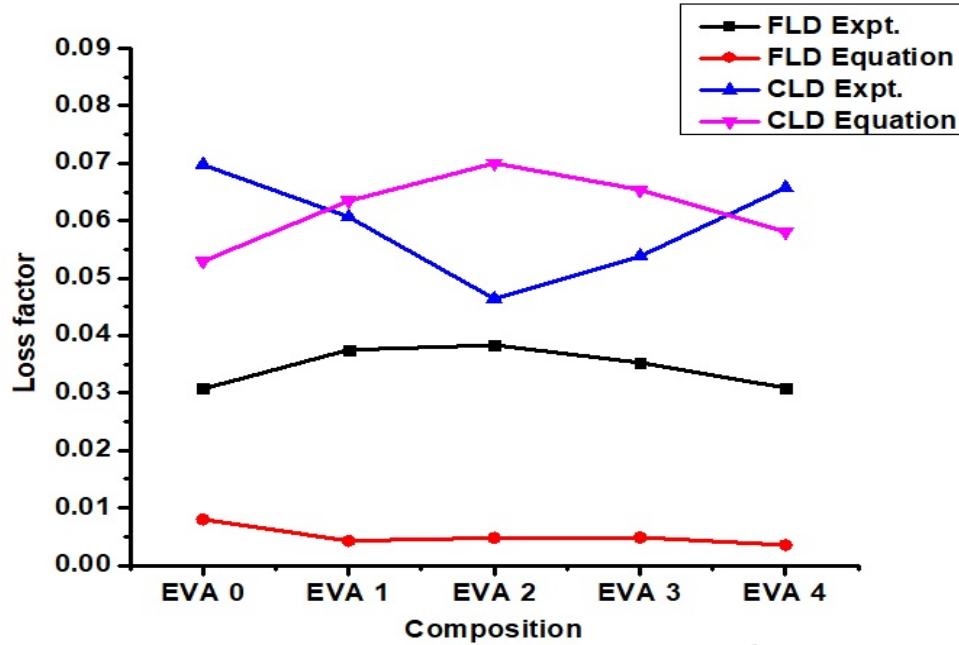


Fig. 7. Comparison of average system loss factors (experimental vs. Nakra predictions) for FLD and CLD configurations across EVA formulations.

Furthermore, the CLD equation-based results show relatively better alignment with the experimental data. The difference in behaviour between FLD and CLD treatments reflects distinct damping mechanisms: FLD performance is more dependent on the inherent material stiffness, whereas CLD benefits from viscoelastic shear effects between the constrained and base layers, thereby maximizing energy dissipation.

The data suggest that, for maximum energy dissipation, CLD treatment of unmodified EVA compositions, such as EVA-0, is most effective, while partially cross-linked variants, such as EVA-1, offer an optimal balance of stiffness and damping for practical design. This evaluation also highlights the need to refine predictive models, especially for FLD, to improve their accuracy and practical applicability in dynamic damping design. These findings highlight the importance of selecting suitable damping configurations tailored to material composition and specific application requirements. Additionally, these findings are crucial for guiding material selection in vibration-sensitive applications, where choosing the optimal

combination of damping configuration and polymer formulation directly impacts system performance. The competitiveness of the EVA-18/DCP system against other damping polymers should not be assessed only by the loss factor magnitude. The significance of the EVA-18/DCP system lies in its balanced combination of damping efficiency, thermoplastic processability, crosslinked network stability, and mechanical integrity, robustness, and manufacturing feasibility, making it a competitive, practically viable material.

7. Conclusion

This study comprehensively investigated the mechanical, viscoelastic, and damping characteristics of EVA-18 and its cross-linked variants, developed by varying concentrations (0 wt.% to 4 wt.%) of dicumyl peroxide (DCP). Tensile testing and DMA revealed that DCP-induced cross-linking significantly alters the stiffness, flexibility, and viscoelastic and damping properties of EVA-18. Experimental Modal Analysis, coupled with theoretical modelling using B.C. Nakra equations enabled an in-depth comparative evaluation of frequency-dependent system loss factors in free-layer damping (FLD) and constrained-layer damping (CLD) configurations across a wide frequency range.

EVA-0 exhibited the highest ductility, making it suitable for applications requiring large deformation and flexibility. EVA-1 offers the most favourable balance of strength, stiffness, and elongation, demonstrating an optimal cross-link density beyond 1 wt.% DCP: excessive cross-linking reduces ductility and toughness, leading to a stiffer, more brittle response. This gradient in properties facilitates the tailored selection of EVA grades for specific design requirements.

The study highlights EVA's potential for targeted vibration reduction and structural damping. The results demonstrate that damping performance is highly dependent on both the degree of cross-linking and the damping configuration employed. In FLD, EVA-1 exhibited the highest average experimental loss factor (0.034), attributed to its balanced stiffness and internal friction from partial cross-linking. FLD relies on the material's

inherent ability to dissipate energy through internal friction, primarily from stretching and compressing with the substrate. Conversely, CLD's effectiveness is derived from the shear deformation of the viscoelastic layer between the base and constraining layers. The tensile test results show that unmodified EVA-0 is the most ductile and flexible of all samples, with the highest ultimate elongation (718%) and the lowest modulus at 100% elongation (5.53 MPa). This inherent flexibility allows maximum shear deformation, which, in turn, leads to the highest energy dissipation in the CLD setup. Therefore, in CLD, unmodified EVA-0 exhibited the highest loss factor (0.069), which was attributed to its greater inherent flexibility, allowing greater shear deformation. Theoretical predictions aligned more closely with experimental results in the CLD setup than in the FLD setup, highlighting the limitations of existing classical analytical models, such as Nakra's formulation, in capturing the complex behaviour of unconstrained viscoelastic systems. These observations highlight the need to refine analytical models further to improve their predictive capabilities across diverse damping scenarios.

Overall, the damping performance is strongly configuration-dependent, with EVA-1 exhibiting optimal performance in FLD due to its balanced stiffness and energy dissipation, while EVA-0 demonstrates superior performance in CLD due to its greater flexibility and enhanced shear deformation. The results establish clear structure-property relationships and provide guidelines for selecting appropriate EVA materials for applications in fields such as acoustics, automotive, and aerospace engineering, as well as industrial machinery and transportation systems where energy dissipation is crucial.

The applicability of the present analytical and experimental framework is limited to the investigated compositions and configurations. Moreover, the adopted Nakra-based model assumes ideal interfacial bonding and linear viscoelastic behaviour and cannot fully predict complex service loading conditions encountered in practical engineering applications.

Declaration:**Ethical approval:**

Not Applicable. This study did not involve human participants, animals, or any biological materials.

Consent to participate:

Not Applicable. This study did not involve human participants.

Consent to publish:

All authors have reviewed and approved the final version of the manuscript for publication.

Declaration of competing interests:

The authors have no competing interests to declare that are relevant to the content of this article.

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During the preparation of this work, the author(s) used ChatGPT (OpenAI) to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the publication's content.

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