Defence Science Journal, Vol. 75, No. 4, July 2025, pp. 504-511, DOI : 10.14429/dsj.20781

Investigation on Short Carbon Fibre-Filled NBR Composites for Fabrication of Low-Frequency Vibration Isolator

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ABSTRACT

Vibrations generated by onboard machinery in marine vessels can result in several adverse consequences, including reduced equipment lifespan, interference with communication systems, and compromised stealth capabilities in strategic applications. Passive anti-vibration mounts are a viable solution to mitigate these issues by isolating equipment operating above a specified frequency. This study investigates the material properties of short carbon fibre-filled nitrile rubber (NBR) compounds and their effectiveness in vibration isolation for low-frequency applications. The materials were characterized for their physico-mechanical properties using various instrumental techniques, followed by a comparative analysis. Damping properties were assessed through Dynamic Mechanical Analysis (DMA) and the time-temperature superposition method. Among the series of compositions, NBR with 2 parts per hundred rubber (2 phr) fibre loading exhibited optimal performance for low-frequency applications, demonstrating superior tear strength and the lowest compression set. The tan δ value with broad curve for the 2 phr fibre composition ratified with hysteresis values of mount made out of this also. Mounts fabricated with this composition exhibited a resonance frequency of 15 Hz under a 190 kg load. This study encompasses the design of rubber compounds and the characterization of materials in both raw and mounted forms.

Keywords: Vibration-isolation; Composite-mount; Transmissibility; Low-frequency; Short-carbon fibre

1. INTRODUCTION

Anti-vibration mounts are effective in mitigating the adverse effects of vibrations produced by various equipment. The development of such mounts requires extensive investigation into material formulation and mount design. Factors such as load rating, type of loading, required isolation frequency, and the operating environment play critical roles in mount development. These aspects fall outside the scope of the present study. This work focuses on the effect of incorporating short carbon fibre to enhance the damping characteristics, stiffness, and hardness of the mount design. The importance of achieving low compression set, good ageing properties, and other relevant characteristics for elastomeric and plastic composites has been well-documented in the literature[1-11]. Furthermore, the distribution of fibre within the matrix is crucial to attaining the desired material properties, also investigated in this study using Scanning Electron Microscopy (SEM). The deformation behaviour of the mount under rated load is another key factor, as it enables energy conversion through hysteretic damping. The objective of this study was to develop a short carbon fibre-filled elastomeric composite anti-vibration mount with a load rating of 220 kg, capable of effectively isolating vibrations above 25 Hz. A thorough literature review revealed that such a study has not been previously conducted.

Received : 20 January 2024, Revised : 26 January 2025
Accepted : 27 January 2025, Online published : 26 June 2025

2. METHODOLOGY

The materials and fibre were selected based on damping requirements, hardness, and the environmental conditions in which the mount is designed to operate. Nitrile rubber containing 34 % acrylonitrile content was utilized along with short carbon fibre of an average length of 3 mm at varying loading percentages. Compositions including neat rubber and formulations with 0.5, 1, 2, and 4 phr (parts per hundred rubber) of carbon fibre were prepared using a two-roll mill. Cure characteristics were analysed using a rubber process analyser (RPA) at 160 °C. The distribution of fibres within the matrix was examined using scanning electron microscopy (SEM).

Material testing was conducted to evaluate the mechanical and damping characteristics. Dynamic mechanical analysis (DMA) was performed at a single frequency to determine the tan δ (loss factor) and the glass transition temperature (Tg). Multi-frequency DMA experiments were also carried out to measure tan δ over a range of frequencies, utilizing the Time-Temperature Superposition (TTS) principle. Thermo Gravimetric Analysis (TGA) was employed to assess the filler content, while Differential Scanning Calorimeter (DSC) was used to determine the glass transition temperature and cure characteristics.

Rubber samples with specific compositions were prepared and moulded into sheets of 150 mm × 150 mm × 2 mm thickness, as well as button samples with a diameter of 29 mm and thickness of 12.5 mm. These samples were moulded at 160 °C for an optimized duration determined through rheometric studies and subsequently used for various testing procedures by relevant ASTM standards[12-15].

2.1 Design of Rubber Compositions

The Nitrile rubber matrix with 34 % acrylonitrile content was chosen for its suitability in hostile environments involving oil, heat, and humidity. To enhance protection against oxygen, heat, and ozone-induced cracking under dynamic conditions, a combination of polymerized 2,2,4-trimethyl-1,2-dihydroquinoline (Vulcanox HS) and N-isopropyl-N'-phenyl-p-phenylenediamene (Vulcanox 4010) was utilized. Reinforcement was achieved through the addition of carbon blacks, specifically semi-reinforcing furnace (SRF), fast extruding furnace (FEF), and medium thermal (MT) grades.

To minimize compression set and creep, Bis (1-methyl-1-phenylethyl) peroxide and Bis (α,α-dimethylbenzyl) peroxide (DCP) were employed as curing agents, with Zinc dimethyl acrylate (ZDMA) used as a coagent. Standard naphthenic oil and a plasticizer, Bis (2-ethylhexyl) phthalate, were incorporated into the formulation to improve processability.

A series of five compositions was prepared with varying dosages of short carbon fibre, ranging from 0 to 4 phr, as detailed in Table 1.

Table 1. Compositions of rubber used in the present study

Ingredients	1	2	3	4	5
NBR(Kosyn 35L)	100	100	100	100	100
ZnO	5.0	5.0	5.0	5.0	5.0
Valcanox HS	1.5	1.5	1.5	1.5	1.5
Vulkanox 4020	1.5	1.5	1.5	1.5	1.5
Carbon short fibre~3mm	-	0.5	1.0	2.0	4.0
Carbon black SRF	35.0	35.0	35.0	35.0	35.0
Carbon black MT	40.0	40.0	40.0	40.0	40.0
FEF	20	20	20	20	20
Naphthenic oil	8	8	8	8	8
DOP	5	5	5	5	5
Dicumyl peroxide	3	3	3	3	3
ZDMA	5	5	5	5	5
Batch weight	224.0	224.5	225.0	226.0	228.0

2.2 Material Characterization

The properties of the material, such as density, hardness, modulus of elasticity, ultimate tensile strength, tear strength, and compression set, were characterized by relevant ASTM and other standards[12-15]. Hardness is a crucial property for rubber materials, providing an approximate indication of the elastic modulus, which, in turn, relates to the static deflection of the final intended mount. The modulus of elasticity provides insight into the stiffness of the material, while the ultimate tensile strength determines the mechanical strength of the material before failure.

Since the compound is intended for continuous cyclic deformations, tear strength must be sufficiently high to prevent tearing through incidental cracks. Compression set is a key property for anti-vibration mounts, as the material must withstand continuous static loading from machinery; the lowest permanent set is desirable for such applications. The density of the material was measured using standard densimeter equipment, while hardness was assessed using a Bareiss Shore-A durometer. Tensile and tear specimens were punched from the 2 mm thick sheets by ASTM D412 using a die, and testing was conducted using a universal testing machine. The data obtained from these tests were utilized to determine various mechanical properties, including ultimate tensile strength, percentage elongation, modulus of elasticity at various elongations, and tear strength.

Characterization techniques such as Dynamic Mechanical Analysis (DMA), Scanning Electron Microscopy (SEM), and thermal analyses (TGA and DSC) were also employed. The material's resistance to liquids was evaluated through water absorption and diesel absorption tests.

Finally, mounts moulded with compositions containing neat rubber and 0.5-4 phr carbon fibre were evaluated for their hysteresis, vibration transmissibility at 190 kg, fatigue performance over 100,000 cycles, and load-deflection behaviour. Vibration transmissibility of mounts before and after diesel ageing was also compared.

2.3 Evaluation of Rubber Composites for Anti-Vibration Mounts

To assess the suitability of rubber composites for vibration-damping applications, a series of anti-vibration mount designs were fabricated using compression moulding.

As illustrated in Fig. 1(a), the composite anti-vibration mounts consist of five key components:

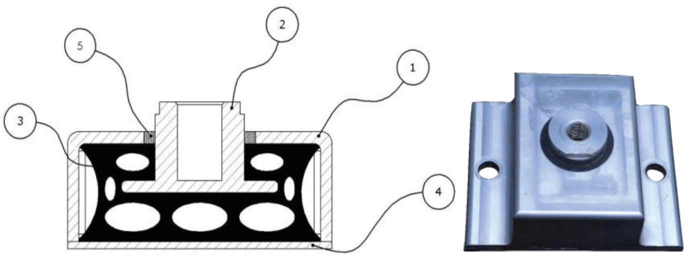
- **Casing:** Encloses the assembly and provides structural integrity.
- **Loading Plate:** Extends to the top with an internal threaded section for fastening to the machinery or equipment base.
- **Composite Stack:** Composed of a cured elastomeric-fibre composite, the stack surrounds the loading plate up to its neck, providing the primary damping mechanism.
- **Bottom Plate:** Forms the base of the assembly, bonded to the composite stack.
- **Encapsulation Sealant:** A specialized polyurethane-based insitu sealant that provides environmental protection and encapsulation.

The top and bottom interfaces between the elastomer and metal are bonded using a high-strength elastomer-based adhesive to ensure durability and structural stability.

The mount operates by fastening the machinery base to the top of the float. Under static conditions, the float moves downward to a stable position, resulting in the static deflection of the mount. When subjected to dynamic loading from machinery-induced vibrations, the float oscillates around its neutral position, transferring the load to the elastomeric composite stack.

The unique design of the rubber-fibre composite stack, combined with specifically engineered elliptical holes and adhesive-bonded interfaces, allows for effective vibration damping through hysteretic energy dissipation. The shear forces exerted by the float during its movement are absorbed and dissipated by the elastomeric material, thereby reducing vibration transmission.

This innovative design highlights the potential of elastomeric-fibre composites for high-performance anti-vibration applications, offering superior damping properties and durability in demanding industrial environments.



(a) (b)

Figure 1. Views of mount, (a) Schematic; and (b) Mount.

2.4 Evaluation of Prototype Mounts

Five anti-vibration mounts were fabricated using elastomer compositions filled with 0–4 phr fibre, and their performance was evaluated through mechanical and dynamic testing. A photograph of the prototype moulded mount is shown in Fig. 1(b).

2.4.1 Mechanical Testing

Mechanical testing was conducted using a Universal Testing Machine (UTM). The parameters evaluated included:

- **Static deflection:** Determined by applying a compressive load at a speed of 5 mm/min to measure the deflection at the rated load.
- **Hysteresis loss:** Assessed through cyclic loading between 0–220 kg for 10 cycles. The hysteresis loop area from the 10th cycle was used to calculate energy dissipation.
- **Creep behaviour:** Evaluated by monitoring the deformation under constant load over time.

2.4.2 Dynamic Testing

Dynamic performance testing was performed using an electrodynamic shaker[15]. The mount was secured on top of the shaker, and dead weights were added to simulate real-world operating conditions. The tests were conducted under the following conditions:

- **Load capacities:** Due to the exciter's capacity limitations (Model SDL 2.5k), tests were performed with loads of 152 kg and 190 kg.
- **Vibration input:** Random and harmonic vibration signals within a frequency range of 10–1000 Hz were applied.
- **Measured parameters:** Resonance frequency, peak transmissibility, and isolation frequency were recorded.

2.4.3 Diesel Ageing

The durability of the mounts under chemical exposure was evaluated through diesel immersion testing. The mounts were immersed in a diesel bath for 72 hrs and subsequently removed for analysis.

This comprehensive testing approach enabled the evaluation of static and dynamic performance characteristics,

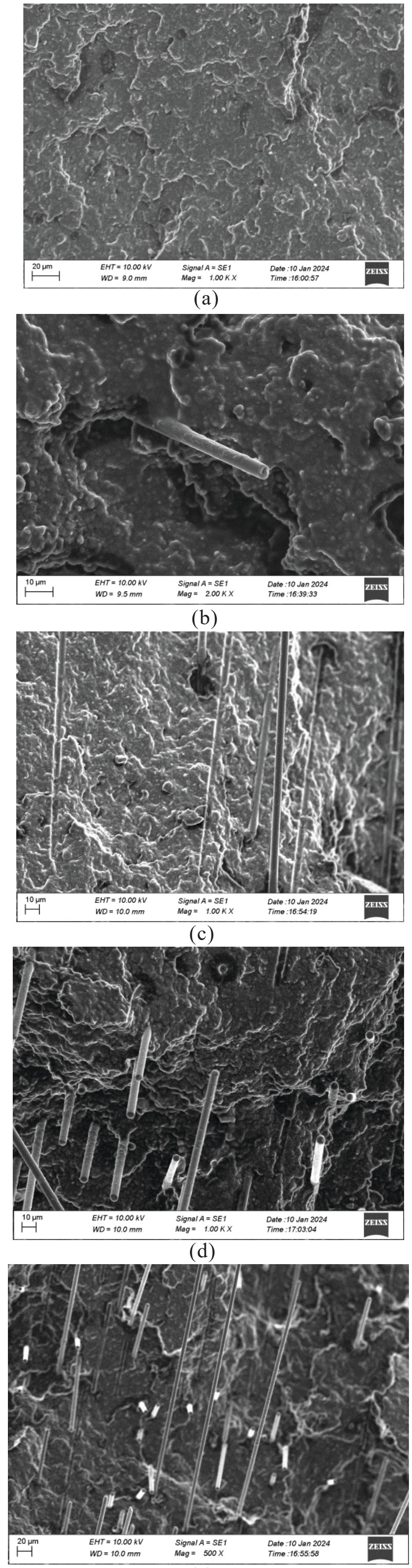


Figure 2. SEMs of NBR Compounds, (a) Neat; (b) 0.5 Phr; (c) 1 Phr; (d) 2 Phr; and (e) 4 Phr.

as well as the chemical resistance of the mounts, providing valuable insights into their suitability for anti-vibration applications.

3. RESULTS AND DISCUSSION

The distribution of fibres and the fibre-matrix interaction play a critical role in determining the mechanical properties of the composite. These aspects were analysed using scanning electron microscopy (SEM). SEM images (Fig. 2(a)–2(d)) revealed a uniform distribution of fibres within the matrix, indicating effective dispersion and compatibility.

The uniform fibre distribution observed aligns with findings reported elsewhere.[16,18-23], further supporting the significance of proper fibre dispersion in enhancing mechanical performance.

3.1 Mechanical Properties and Resistance to Liquids

Table 2 presents the effect of fibre loading on the mechanical properties of the material. As the fibre content increased from 0 to 4 phr, the hardness of the material increased from 72 Shore A to 80 Shore A, a trend consistent with the findings of Qiang[17], *et al.*

Figure 5 illustrates the elongation versus tensile strength behaviour of neat and fibre-filled compositions (0.5–4 phr). The tensile strength initially increased with fibre loading, reaching a maximum at 2 phr, before exhibiting a decline at higher fibre contents. A similar trend was reported by Kavita[18], *et al.*.

The modulus of the compositions showed a linear increase with fibre addition, with the highest modulus observed at 4 phr loading. Conversely, the elongation at break was found to be highest for the neat composition and lowest for the 4 phr fibre-filled composition, corroborating earlier reports[18–20].

3.2 Analysis of Tear Strength, Compression Set, and Water Absorption

3.2.1 Tear Strength

A mild increase in tear strength was observed with increasing fibre loading up to 2 phr, followed by a decline at 4 phr. This enhancement in tear strength is attributed to the reinforcing effect of short fibre filling, consistent with findings reported by others also[18,24] as shown in Table 2 and Fig. 3(a).

3.2.2 Compression Set

The compression set percentage decreased with increasing fibre content up to 2 phr and then slightly increased at 4 phr, as shown in Table 2. The use of peroxide-based cure systems, known for producing low compression set properties, proved essential for anti-vibration mounts, as evident from the results. The reduction in compression set is attributed to enhanced interaction between fibres and the matrix in compositions containing 0.5–4 phr fibre. Similar trends were reported elsewhere[18].

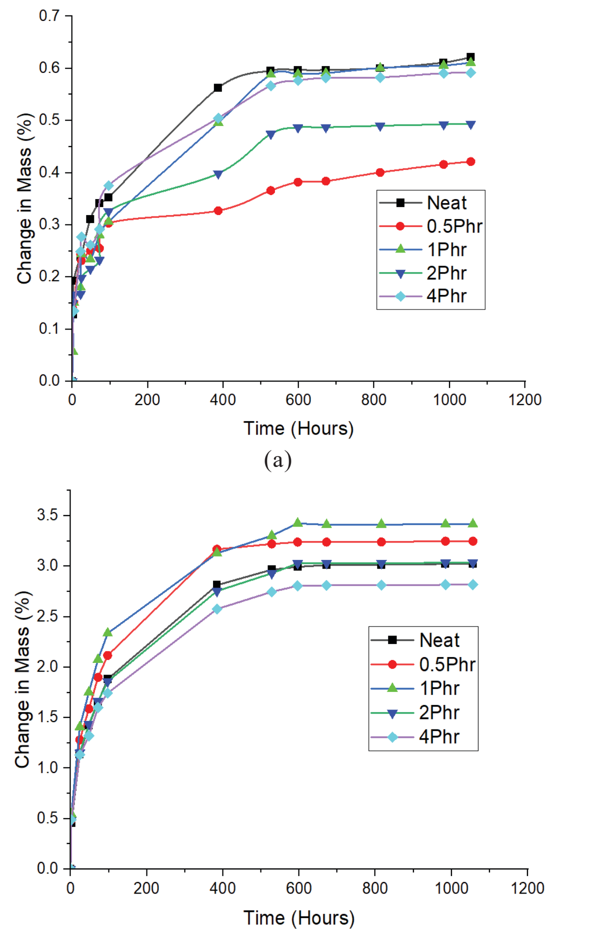


Figure 3. Resistance to liquid, (a) Water absorption; and (b) Diesel absorption.

Table 2. Mechanical and resistance to liquids compounds

Property	Unit	Standard	1	2	3	4	5
Hardness	Shore A	ASTM D2240	72.38	73.5	73.81	75.68	80.15
Density	g/cc	ASTM D4052	1.226	1.233	1.257	1.274	1.288
Tensile strength	MPa	ASTM D412	12.80	12.54	13.03	13.53	12.25
M100	MPa	ASTM D412	3.26	3.46	3.75	4.03	4.68
M200	MPa	ASTM D412	6.47	6.77	7.28	7.42	8.33
M300	MPa	ASTM D412	9.74	10.06	10.48	10.64	10.76
EB %	%	ASTM D412	444	432	418	411	391
Tear strength	N/mm	ASTM D624	54.74	55.52	57.49	57.88	54.84
Compression set	%	ASTM D395B	15.58	15.12	14.16	11.28	13.76
Water absorption	%	ASTMD471	0.2398	0.2156	0.2439	0.1984	0.2773
Diesel absorption	%	ASTMD471	1.1376	1.2810	1.4093	1.1524	1.1327

Table 3 Glass transition and Tan δ of compounds

Property	Unit	Standard	1	2	3	4	5
DSC Tg, °C	-	ASTM D3418	- 27.27	-27.95	-27.42	-27.04	-27.57
DMA Tg, °C	-	ASTM D4065	-30.01	-27.90	-11.47	-11.57	-10.58
DMA Tan δ	-	ASTM D4065	1.13	0.7519	0.8326	1.2736	1.0783

3.2.3 Water Absorption

Water absorption values over 24 hrs (Table 2) decreased linearly with increasing fibre loading up to 2 phr, followed by a slight increase at 4 phr. These findings align with the results reported by Anuar[19], *et al.*

Long-term water absorption data, plotted in Fig. 3(a), reveal that water absorption for all compositions reached an equilibrium of approximately 0.48 % after 600 hrs and increased slightly to 0.49 % at 1056 hrs. Notably, this was the lowest water absorption value observed in the series, except for the composition with 0.5 phr fibres loading.

3.2.4 Diesel Absorption Behaviour

The diesel absorption values for 24 hours are presented in Table 2. Diesel absorption increased linearly up to 1 phr fibre loading, followed by a decline for compositions with 2–4 phr fibre. Despite these changes, the post-immersion hardness of the samples remained within the acceptable limit, with variations not exceeding 2 Shore A[15].

The long-term diesel absorption behaviour is illustrated in Fig. 3(b). Diesel absorption for all compositions stabilized after 600 hrs. Notably, the neat and 2 phr fibre-filled compositions exhibited stabilization at approximately 3.028 % after 600 hrs, maintaining this value up to 1056 hrs. These absorption levels were significantly lower compared to the 4 phr fibre-filled composition.

The stability of the 2 phr fibre-filled composition highlights its suitability for onboard machinery applications in diesel exposure environments.

3.3 Thermal Analysis and Dynamic Properties

The thermal and dynamic properties of the composites were analysed to assess their performance under varying conditions is shown in Fig. 4.

3.3.1 Glass Transition Temperature and Tan δ

The glass transition temperatures (Tg) of all compositions are presented in Table 3. The tanδ values of the compounds are shown in Fig. 4(a), with the maximum tan δ of 1.2736 observed for the 2 phr fibre-loaded composition. This composition was selected for the final moulding of the mount. It appears that the critical fibre loading for increased tan δ is surpassed beyond 2 phr, consistent with the stick-slip phenomena reported in short fibre composites elsewhere also[20,24].

The values of tanδ increased with fibre incorporation, indicating reduced heat dissipation in the matrix, as reported by Geethamma[21], *et al.*. The tan δ versus temperature curve of these composites exhibited two prominent peaks, attributed to the dynamic mechanical behaviour of the matrix and fibre interface, as also noted by Geethamma[21], *et al.*

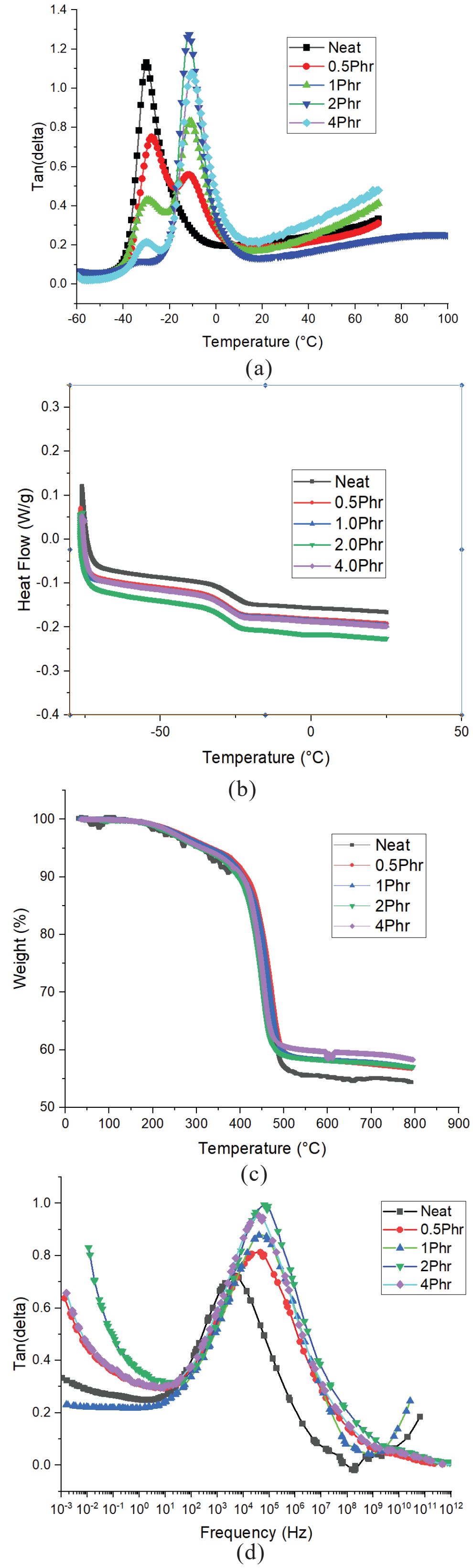


Figure 4. Properties of compounds, (a) DMA; (b) DSC; (c) TGA; and (d) Tanδ vs. frequency.

3.3.2 DSC Analysis

Differential scanning calorimeter (DSC) studies revealed a Tg ranging from -27.27 °C to -27.57 °C (Table 3). As shown in Fig. 4(b), the glass transition temperature remained largely unchanged with increasing fibre loading, while the heat flow decreased. These findings align with earlier studies[22-24].

3.3.3 TGA Analysis

Thermo gravimetric analysis (TGA) results are presented in Fig. 4(c). The thermal stability and percentage weight retained were consistent with standard values, confirming the suitability of the composites for high-temperature applications also studied by Nafees[25], *et al.*.

3.3.4 Dynamic Mechanical Analysis-TTS

The DMA-TTS curve of tan δ over frequency is shown in Fig. 4(d). The data reveals that tan δ values are highest and the curve broadens significantly for the 2 phr fibre composition, while a slight reduction in tan δ is observed for the 4 phr fibre composition. The observed trend may be attributed to the critical fibre loading for the stick-slip phenomenon, as noted in earlier studies[20–21,24,26]. These results indicate that the 2 phr fibre composition offers superior damping properties for low-frequency applications.

3.4 Static and Dynamic Properties of the Mount

The moulded mounts were evaluated through static and dynamic tests. The static deflection at a 220 kg load and the hysteresis loop area for the series are provided in Table 4.

Static deflection values decreased from 1.1 mm to 0.56 mm with increasing fibre loading, indicating an increase in stiffness. As shown in Fig. 5(a), hysteresis loss increased linearly with fibre loading up to 2 phr and then decreased at 4 phr.

Based on these findings, the 2 phr fibre-filled composition was selected for further evaluation due to its superior vibration isolation properties and optimal balance of stiffness and damping.

4. CONCLUSIONS

A short carbon fibre-filled NBR composite with 2 phr fibre loading was developed for anti-vibration mounts. The composition exhibited optimal mechanical and dynamic properties, achieving low-frequency vibration isolation under a

Table 4. Load-deflection and hysteresis properties of moulded mounts

Property	Unit	Standard	1	2	3	4	5
Mount feflection @ 220 kg	mm	Custom	1.1	0.98	0.85	0.77	0.56
Mount hysteresis	Nm	Custom	0.2629	0.3130	0.3835	0.3848	0.2012
Mount resonance @152 kg	Hz	Custom	24	23	22	18	27

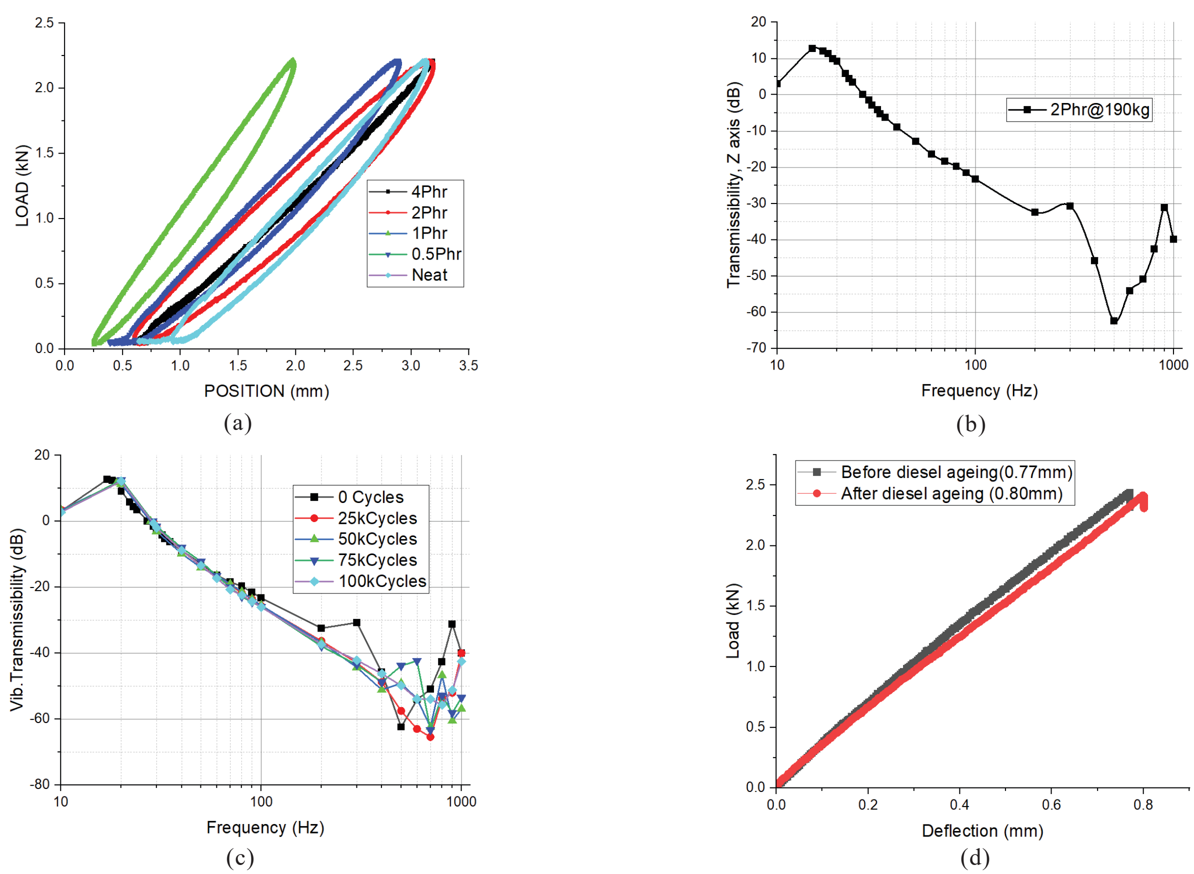


Figure 5. Properties of mounts, (a) Hysteresis; (b) Transmissibility of mount-4 with 2 Phr fibre in the z-axis; (c) Mount-4 transmissibility after fatigue; and (d) Load vs deflection after diesel ageing.

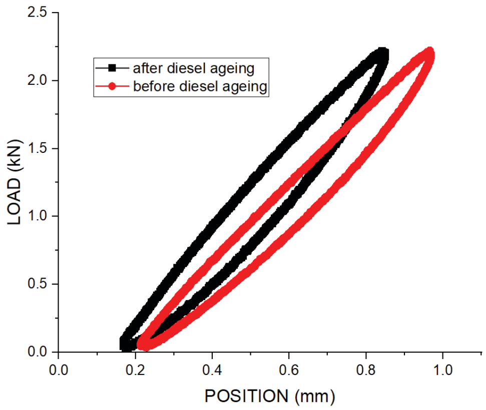


Figure 6. Hysteresis loop after diesel ageing.

220 kg load. The mounts maintained stability and performance after fatigue and environmental exposure tests, making them suitable for onboard machinery applications.

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CONTRIBUTORS

Mr Shajahan K. obtained MTech from the Cochin University of Science and Technology (CUSAT), Kochi, India and working at NPOL, Kochi.
His contribution in the current study: Design of rubber composition, mount configuration, characterization and realizing the prototypes, evolution of the idea behind the paper, compilation of results and authoring of the paper.

Mr Arun Sundar R.S. obtained MSc in Chemistry from Manonmaniam Sundaranar University, Tirunelveli, Tamilnadu. His contribution in the current study: Mechanical property evaluation and characterisation using instruments.

Dr Ramesh Kumar A.V. obtained PhD from CSM Kanpur University, Kanpur, India.
His contribution in the current study: Research supervision, input for characterization and editing of papers.

Dr Reji John obtained his PhD from IIT, Chennai, India.
His contribution in the current study: Supervisory contributions, editing of the paper and its structural modifications, discussions and ideas to evolve the work as a paper.