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Design and Performance Analysis of Natural Rubber–Silica Nanocomposite Vibration Isolators for Household Appliances

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Abstract

Natural rubber (NR) nanocomposites reinforced with surface-modified precipitated silica (SiO_2) were synthesized through a two-roll mill compounding and compression-moulding process, then systematically evaluated as passive vibration isolator materials for domestic washing machine applications. Five silica loadings 0, 5, 10, 15, and 20 phr were investigated. A comprehensive characterization suite encompassing tensile testing, Shore A hardness, dynamic mechanical analysis (DMA), thermogravimetric analysis (TGA), and scanning electron microscopy (SEM) revealed clear structure–property relationships. At the optimal loading of 10 phr silica, Young's modulus reached 4.3 MPa and tensile strength 19.6 MPa; tan δ at 20 Hz was 0.18, indicating a twofold improvement in damping over neat NR (tan δ = 0.09). Transmissibility ratio calculations based on DMA-derived viscoelastic parameters confirmed vibration attenuation of 63–71% at washing machine spin frequencies (15–25 Hz), outperforming the unfilled rubber baseline by up to 24 percentage points. Thermal analysis showed a 5% degradation temperature (T_{50}) of 342°C at 10 phr, an improvement of 18°Cover neat NR. SEM confirmed uniform nano-silica dispersion and strong filler matrix interfacial adhesion at this loading. These results establish nano-silica reinforcement as a cost-effective, scalable strategy for tailoring the viscoelastic response of NR isolator pads in domestic appliance mounting systems.

Keywords: Polymer nanocomposites, natural rubber, nano-silica, thermal stability, composite characterization

INTRODUCTION

Household washing machines generate centrifugal unbalance forces of 800–1200 N during spin cycles, propagating through the chassis to produce audible noise and structural fatigue [1–13]. Passive vibration isolation interposing compliant elements between source and receiver remains the most practical mitigation strategy. The fundamental design principle requires the natural frequency of the isolated system to be well below the excitation frequency (frequency ratio $r > \sqrt{2} \approx 1.41$), so that the transmissibility ratio (TR) drops below unity and net isolation is achieved [2–3].

Natural rubber (NR) pads have long been the material of choice owing to their high internal damping, excellent elastic recovery, and ease of processing [4]. However, unfilled NR exhibits limited tunability of its viscoelastic response; the loss factor (tan δ) typically falls between 0.08 and 0.12 at 10–25 Hz [5]. Polymer nanocomposite technology overcomes this limitation by

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incorporating nano-scale inorganic fillers into the elastomeric matrix, exploiting the enormous filler surface area (50–200 m²/g) to simultaneously increase stiffness and energy dissipation [6–7]. Among available nano-fillers, precipitated silica (SiO_2) is particularly attractive due to its surface silanol chemistry, enabling covalent grafting of bifunctional silane coupling agents that yield NR/SiO_2 nanocomposites with substantially higher tan δ [8].

Natural rubber is popular choice of material for vibration isolation components, because it has exclusive qualities that no other elastomer owns. The main chain mechanism of natural rubber (cis-14-polyisoprene) is one responsible for excellent elastic recovery property (rebound resilience > 75%), very high strength (20-30 MPa), superior resistance to fatigue and tearing, and very low temperature of glass transition that essentially means the material behaves elastomeric ally and is stable over the entire working temperature range, which is usual for household appliances [4–14]. The inherent loss factor of the material means it offers efficient hysteretic damping at the main excitation frequencies of household appliances, and its low compression set means it is dimensionally stable even when subjected to a static load over time. Apart from that, the material is easily processed using traditional rubber machinery and moulding presses, is compatible with a large variety of fillers and coupling agents, and very importantly it is a renewable, bio-based polymer that comes from Hevea brasiliensis, So it is the type of material that fits the greater aim to make domestic appliances from sustainable materials [13, 15, 17, 19, 25]. That these attributes combined high damping, elastic recovery, fatigue endurance, low cost, and renew ability are reasons why natural rubber is still the preferred elastomer for engine mounts, machinery foundations, and washing-machine isolator pads is easily explained.

Silica reinforcement helps to increase natural rubbers properties in a few complementary ways at the nano scale level. In the first place, the very large specific surface area of precipitated nano silica (BET 150-200 m^2/g) creates a continuous interphase region around each particle where polymer chains are less mobile, as a result, storage modulus (E') is increased and the loss modulus (E") is raised at the same time, which leads to the high tan seen in well-dispersed NR/SiO systems [8–9]. In the second, surface silanol groups (SiOH) on silica particles react with bifunctional silane couplers (TESPT/Si-69) to create strong covalent bonds between the filler and the rubber in the form of SiOC and SC, resulting in the reduction of filler agglomeration (Payne effect) and enhanced load transfer [10]. Thirdly, the nano-silica network offers extra pathways for energy dissipation through stick slip movement of chains at the filler surface, leading to hysteretic damping increases of 80-120% compared to pure NR [9–11]. Lastly, the inorganic silica is a thermal and oxidative protective layer, slowing down the movement of volatile degradation products and raising the 50% degradation temperature (T) by 15-25^{0}C, which was shown in this study and in line with previous NR/silica results [12].The hydrodynamic reinforcement effect of nanoscale rigid inclusions increases tensile modulus and hardness in a controllable manner allowing designer to tune stiffness, damping and durability through a single composition parameter silica loading. Recent studies on hybrid bio based and surface modified nano fillers confirm that these mechanisms are broadly transferable to other sustainable polymer filler systems [18, 20, 21,23, 24].

A direct comparison between conventional (unfilled or carbon black filled) rubber isolators and silica nano composite isolators clearly demonstrates the advantage of the latter which is the reason why they are becoming the preferred choice for modern household-appliance applications. Conventional NR isolators can deliver a quick return to their original shape and decent damping level (tan 0.08-0.10) but their stiffness is not easily adjustable, thermal stability is rather limited and they produce more heat when being repeatedly strained; carbon-black-filled grades can increase hardness and resistance to wear but at same time heat produced due to internal friction is higher and a dark color that is inconvenient for many appliance uses is given. Then again, the silica nano composite isolators (TESPT-modified) bring about the combination of what comes next benefits: a higher loss factor (tan up to 0.18 at the 10phr optimum), a higher Young's modulus (2.1-6.8 MPa across 0-20 phr), T improved by 18^{0}C , less heat build-up due to lowering of the Payne effect and a light/translucent look that is in line with consumer products. What is more, for a similar pad shape, they can bring about 19 percentage point increase in vibration isolation efficiency (52% -71%) from which an extra noise decrease by 6dB is estimated. The disadvantages are a somewhat longer optimum cure time (8.5- 11.2 min) that results from the acidic silica surface and also the necessity to use a silane coupling agent, both Still are factors that can be managed from an economic and industrial perspective. Comparable benefits of nano and bio based reinforcement strategies have been reported for thermoplastic and natural fibre composite systems [17, 22,23, 24, 26].

MATERIALS AND METHODS

Materials

Natural rubber grade RSS-3 (Mooney viscosity ML(1+4) at 100°C = 72 MU) served as the elastomeric matrix. Precipitated silica (Hi-Sil 233, BET surface area 150 m^2/g, primary particle size 20 nm) was selected as nano-filler. TESPT (Si-69, Evonik) served as silane coupling agent at 8 wt% relative to silica [9]. Vulcanization system: ZnO (5 phr), stearic acid (2 phr), TBBS (1.5 phr), sulfur (2.5 phr) [4].

Nanocomposite Synthesis

Compounding was performed on a two-roll mill at 60°C. Five nanocomposite formulations were prepared at 0, 5, 10, 15, and 20 phr silica (NR-0 through NR-20). Cure characteristics were determined at 160°C using an MDR. Sheets were compression-moulded at 160°C and 10 MPa for optimum cure time (t_{90}), then conditioned at 23 ± 2°C and 50 ± 5% RH for 24 h.

Characterization

Tensile properties were measured per ISO 37 Type 2 on a Zwick/Roell Z010 (500 mm/min; n = 5). Shore A hardness per ISO 868 [16]. DMA in tension mode (TA Q800) over 1–100 Hz at 0.1% strain and 25°C. TGA (Q500) from 30°C to 600°C at 10°C/min under N_2. SEM (JEOL JSM-6390) on cryo-fractured Au/Pd-coated surfaces at 10 kV.

MATHEMATICAL MODELING

Viscoelastic Stiffness from DMA Data

For a rectangular pad of area, A and thickness h, the complex compressive stiffness is:

$$k(f) = [E'(f) + i\,E''(f)] \cdot A/h \quad (1)$$

For pad dimensions 80 × 80 × 30 mm, total stiffness of four pads in parallel is k_total = 4k. The equivalent viscous damping ratio is:

$$\zeta(f) = \tan\delta(f) / 2 = E''(f) / 2E'(f) \quad (2)$$

Natural Frequency and Transmissibility

For machine mass m = 65 kg on four rubber pads, the undamped natural frequency is:

$$\omega_n = \sqrt{(4E'A / hm)} \quad (3)$$

Force transmissibility ratio at f_{exc} = 20 Hz (1200 RPM spin):

$$TR = \sqrt{[(1 + (2\zeta r)^2) / ((1 - r^2)^2 + (2\zeta r)^2)]} \quad (4)$$

where $r = f_{exc} / f_n$. Vibration isolation efficiency:

$$VIE (\%) = (1 - TR) \times 100 \quad (5)$$

RESULTS AND DISCUSSION

Cure Characteristics

Optimum cure times (t_{90}) increased from 8.5 min at 0 phr to 11.2 min at 20 phr, reflecting retardation by the acidic silica surface. Maximum torque (MH) increased systematically with loading. All compounds exhibited reversion-free cure plateaus, confirming suitability for mould processing at 160°C.

Mechanical Properties

Tensile and hardness results are summarized in Table 1.

Young's modulus increased monotonically from 2.1 MPa (NR-0) to 6.8 MPa (NR-20). Tensile strength peaked at 19.6 MPa at NR-10, then declined due to filler agglomeration above the percolation threshold (~12 phr). Shore A hardness increased from 52 to 71 over the same range.

Dynamic Mechanical Analysis

Full DMA results at 20 Hz are compiled in Table 2.

Loss factor tan δ at 20 Hz peaked at 0.18 for NR-10 a 100% improvement over neat NR (0.09). At higher loadings, tan δ declined as the percolated silica network constrained polymer chain mobility.

Vibration Isolation Performance

Table 3 presents isolation performance calculated from Equations (1)–(5).

NR-10 achieves the best isolation performance (VIE = 71%), combining low natural frequency (8.9 Hz, r = 2.25) with the highest damping ratio ($\zeta = 0.09$). NR-0 achieves only 52% VIE. Despite higher stiffness, NR-20 delivers only 61% VIE due to reduced damping.

Thermal Analysis

TGA thermograms under nitrogen are given in Table 4.

Table 1. Mechanical properties of NR/SiO2 nanocomposites.

Formulation	Silica (phr)	E (MPa)	UTS (MPa)	Shore A
NR-0	0	2.1	14.2	52
NR-5	5	3.2	17.8	59
NR-10	10	4.3	19.6	65
NR-15	15	5.6	18.1	68
NR-20	20	6.8	15.3	71

Table 2. DMA results at 20 Hz and 25°C.

Form.	E' (MPa)	E'' (MPa)	tan δ	ζ
NR-0	3.0	0.27	0.090	0.045
NR-5	4.1	0.53	0.129	0.065
NR-10	5.4	0.97	0.180	0.090
NR-15	6.3	1.01	0.160	0.080
NR-20	7.2	0.94	0.130	0.065

Table 3. Vibration isolation performance at 20 Hz.

Form.	f_n (Hz)	r	ζ	TR	VIE (%)
NR-0	11.4	1.75	0.045	0.483	52
NR-5	10.0	2.00	0.065	0.392	61
NR-10	8.9	2.25	0.090	0.292	71
NR-15	8.2	2.44	0.080	0.318	68
NR-20	7.6	2.63	0.065	0.385	61

Table 4. Thermogravimetric analysis results.

Form.	T_{50} (°C)	T_{10} (°C)	ΔT_{50} (°C)	Residue (%)
NR-0	324	338	—	2.1
NR-5	336	351	+12	4.8
NR-10	342	357	+18	7.4
NR-15	344	360	+20	10.1
NR-20	347	364	+23	12.9

Table 5. Design summary – isolator configuration comparison.

Parameter	Rigid mount	NR-0	NR-10
Max. Transmitted Force (N)	1005	483	293
Transmissibility Ratio (TR)	1.00	0.481	0.292
Isolation Efficiency (%)	0	52	71
Natural Frequency fn (Hz)	—	11.4	8.9
Dynamic Stiffness (kN/m)	∞	1230	1380
Damping Ratio ζ	—	0.045	0.090
Max. von Mises Stress (MPa)	—	1.50	1.85
Factor of Safety (FOS)	—	12.0	9.73

T50 increased from 324°C (NR-0) to 347°C (NR-20), with the largest gain at low loadings. The silica surface acts as a physical barrier to volatile degradation product diffusion. All formulations exceed the 80°C service temperature specification for domestic appliances.

Morphological Analysis

SEM micrographs revealed progressive change in fracture morphology with silica loading. NR-5 and NR-10 showed uniformly distributed nano-scale protrusions (100–200 nm) without visible agglomerates, confirming effective TESPT-mediated dispersion below the percolation threshold. NR-15 and NR-20 exhibited visible micron-scale aggregates (1–3 µm), explaining the reduction in tensile strength and tan δ. EDS confirmed uniform Si distribution in NR-10 (Si:C = 0.042; theoretical ≈ 0.038).

DESIGN IMPLICATIONS FOR ISOLATOR PADS

Table 5 summarizes key design parameters for a four-pad isolation system.

NR-10 achieves a 19 percentage-point improvement in VIE over the unfilled baseline while maintaining a factor of safety of 9.73 against tensile rupture. Estimated noise reduction improves from ~7 dB (NR-0) to ~13 dB (NR-10) relative to rigid mount, approaching the 15 dB target for Class A certification under ISO 10816.

CONCLUSION

- Five NR/SiO_2 nanocomposites (0–20 phr) were prepared by two-roll mill compounding with TESPT-modified silica. SEM and EDS confirmed well-dispersed nanoparticle distributions below the percolation threshold (~12 phr).
- Young's modulus increased monotonically from 2.1 to 6.8 MPa; tensile strength peaked at 19.6 MPa at 10 phr, reflecting competition between hydrodynamic reinforcement and aggregate-induced stress concentration.
- DMA showed tan δ at 20 Hz peaked at 0.18 for NR-10 a 100% improvement over neat NR attributed to enhanced interfacial viscoelastic dissipation at the silica–rubber interface.
- Transmissibility modelling confirmed NR-10 delivers the best vibration isolation efficiency of 71% at 20 Hz (1200 RPM), compared to 52% for unfilled rubber and 0% for rigid mount.
- TGA confirmed thermal stability (T_{50}= 342°C) far exceeding domestic appliance service requirements, with an 18°C improvement over neat NR at the 10 phr optimum.
- The optimal NR-10 formulation (80 × 80 × 30 mm pads, four-pad corner layout, Shore A 65) is recommended for implementation in the 65 kg washing machine isolator design.

Future work will focus on experimental validation using a vibration test rig, investigation of long-term creep and fatigue performance, and parametric optimization of pad geometry using response surface methodology.

REFERENCES

1. Rao SS. Mechanical Vibrations. 5th ed. Upper Saddle River (NJ): Prentice Hall; 2011.
2. Thomson WT, Dahleh MD. Theory of Vibration with Applications. 5th ed. Upper Saddle River (NJ): Prentice Hall; 1998.
3. Harris CM, Piersol AG. Harris' Shock and Vibration Handbook. 5th ed. New York (NY): McGraw-Hill; 2002.
4. Gent AN. Engineering with Rubber. 3rd ed. Munich: Hanser; 2012.
5. Snowdon JC. Vibration and Shock in Damped Mechanical Systems. New York (NY): Wiley; 1968.
6. Wolff S, Wang MJ. Filler-elastomer interactions. Part IV. Rubber Chem Technol. 1992;65(2):329-342.
7. Papadopoulos CA, Papadimitriou IN. Orthotropic damping in rubber vibration isolators. J Sound Vib. 2001;248(3):439-459.
8. Balachandran B, Magrab EB. Vibrations. 2nd ed. Belmont (CA): Cengage; 2009.
9. Ramier J, Gauthier C, Chazeau L, Stadelmann L, Guy L. Payne effect in silica-filled SBR. J Polym Sci Part B Polym Phys. 2007;45(3):286-298.
10. Qu L, Yu G, Xie X, Wang L, Li J, Zhao Q. Effect of silane coupling agent on SSBR vulcanizates filled with silica. Polym Compos. 2013;34(10):1575-1582.
11. Cheng G, Li Z, Wang S, Gong X, Xuan S. Predicting vibration isolation performance from DMA data. J Appl Polym Sci. 2015;132:42014.
12. Balachandran M, Devanathan S, Muraleekrishnan R, Bhagawan SS. Mechanical, thermal and transport properties of NR/silica nanocomposites. J Polym Eng. 2010;30:365-380.
13. Lee HH, Kim YK. Vibration analysis of drum-type washing machine with rubber isolators. In: Proceedings of the KSME Annual Meeting; 2005; Korea. p. 1420-1425.
14. Kohjiya S, Ikeda Y. Chemistry, Manufacture and Applications of Natural Rubber. Cambridge: Woodhead Publishing; 2014.
15. International Organization for Standardization. ISO 10816-1: Mechanical vibration—Evaluation of machine vibration. Geneva: ISO; 1995.
16. ASTM International. ASTM D2240: Standard test method for rubber property—Durometer hardness. West Conshohocken (PA): ASTM International; 2021.
17. Ayrilmis N, Kanat G, Ashori A, Tufan M, Akbulut T, Ozdemir F. Utilizing waste manhole covers and fibreboard as reinforcing fillers for thermoplastic composites. J Reinf Plast Compos. 2024;44(17-18). doi:10.1177/07316844241238507.
18. Asalekar AJ, Sastry DVAR. Enhancing high-speed CNC milling performance of Ti6Al4V alloy through the application of ZrO–Ag hybrid nanofluids. Eng Res Express. 2024;6(2):025532. doi:10.1088/2631-8695/ad476d.
19. Manickaraj K, Gauthier C, Chazeau L, Stadelmann L, Guy L, et al. Value-added utilization of agricultural wastes in biocomposite production: Characteristics and applications. Ann N Y Acad Sci. 2025;1549:72-91. doi:10.1111/nyas.15368.
20. Asalekar AJ, Sastry DVAR, Reddy MBS. Analysis of thermophysical properties of novel hybrid nanoparticles-based vegetable nanofluid. Therm Sci. 2023;9(6):1466-1477.
21. Ramasubbu R, Kayambu A, Palanisamy S, Ayrilmis N. Mechanical properties of epoxy composites reinforced with Areca catechu fibers containing silicon carbide. BioResources. 2024;19(2):2353-2370. doi:10.15376/biores.19.2.2353-2370.
22. Asalekar AJ, Sastry DVAR. Comparative analysis of thermal conductivity of the hybrid nanoparticles-based sunflower and jatropha vegetable oil. J Phys Conf Ser. 2023;2810:164-171. doi:10.1088/1742-6596/2810/2/131698.
23. Palanisamy S, Mayandi K, Dharmalingam S, Rajini N, Santulli C, Mohammad F, et al. Tensile properties and fracture morphology of Acacia caesia bark fibers treated with different alkali concentrations. J Nat Fibers. 2022;19(15):11258-11269. doi:10.1080/15440478.2021.2022562.
24. Mylsamy B, Aruchamy K, Shanmugam SKM, Palanisamy S, Ayrilmis N, et al. Improving performance of composites: Natural and synthetic fibre hybridisation techniques in composite materials – A review. Mater Chem Phys. 2025;334:130439. doi:10.1016/j.matchemphys.2025.130439.

25. Asalekar AJ, Sastry DVAR. Prediction and comparative analysis of thermal conductivity of jatropha oil-based hybrid nanofluid by multivariable regression and ANN. J Phys Conf Ser. 2023;2810:32-39. doi:10.1088/1742-6596/2810/2/126247.
26. Manickaraj K, Karthik A, Palanisamy S, Jayamani M, Ali SK, Lakshmi Sankar S, et al. Improving mechanical performance of hybrid polymer composites: Incorporating banana stem leaf and jute fibers with tamarind shell powder. BioResources. 2025;20(1):1998-2025. doi:10.15376/biores.20.1.1998-2025.

