UTILIZATION OF SOLID WASTES FOR THE DEVELOPMENT OF VIBRATION-DAMPING MATERIALS

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Utilization of Solid Wastes for the Development of Vibration Damping Materials

by

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Dedicated to My Beloved Parents

CERTIFICATE

This is to certify that the thesis entitled **"Utilization of Solid Wastes for the Development of Vibration Damping Materials,"** submitted by **Ms. Sunali** to the Indian Institute of Technology Delhi for the award of "Doctor of Philosophy" is a record of the original, bonafide research work carried out by her under my supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma, to the best of my knowledge.

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ABSTRACT

The present study commences with a comprehensive exploration of two pressing contemporary challenges: solid waste management and vibration control. The vast amounts of solid waste generated by agriculture, industry, mining, and municipal activities lead to growing environmental challenges. Inefficient waste management practices result in significant air, soil, and groundwater contamination, adversely impacting urban ecosystems and posing considerable health hazards. Beyond localized pollution, they also play a substantial role in exacerbating climate change. Nevertheless, the process of pyrolysis offers a promising solution by transforming these waste streams into valuable carbonaceous materials.

Concurrently, unwanted vibrations can cause damage and reduce performance, making vibration control crucial in engineering. The four main techniques for controlling vibrations are active, semi-active, passive, and hybrid. The passive control method, valued for its stability, ease of use, and affordability, has been a common approach since the 1960s. This method employs viscoelastic damping materials (VDMs) to enhance the damping of structural vibrations. VDMs can absorb mechanical energy from a vibrating system and transform it into heat due to their intrinsic elastic and viscous properties. The demand for effective vibration control continues to grow, and the global market for VDMs is also rising. This market is expected to expand from USD 0.94 billion in 2023 to USD 1.34 billion by 2030, achieving a compound annual growth rate (CAGR) of 5.12%. This growth underscores the increasing need for advanced vibration management solutions across industries. Among various VDMs, rubber-based VDMs are the most popular choice due to their exceptional ability to absorb vibration energy and their versatility in various applications. However, in rubber-based VDMs, rubber alone often lacks essential properties like strength, toughness, and tear resistance, so

particulate fillers are typically added to enhance their mechanical performance. Fillers are widely incorporated into rubber composites to improve their hardness, modulus, skid resistance, tear strength, and wear resistance. However, widely used commercial fillers like carbon black (CB) require large quantities of non-renewable, petroleum-based resources, and their production is highly energy-intensive, contributing significantly to global CO_2 emissions. Furthermore, their non-renewable and non-biodegradable nature presents significant risks to the environment and humankind. Therefore, looking into the potential of the vibration-damping material market in the upcoming future and the abundant amount of various solid waste available, the present work aims to utilize solid wastes originating from various sources, including agricultural, industrial, and electronic waste, to develop vibration-damping materials.

State-of-the-art techniques seek the utilization of sustainable carbonaceous materials as reinforcing fillers obtained from different solid wastes, such as agricultural, industrial, and electronic wastes, to develop vibration-damping composites. The composites were formulated according to ASTM D3182-21a standards, utilizing two distinct rubber matrices: natural rubber and butyl rubber. A comprehensive evaluation of their physical, rheological, morphological, mechanical, thermal, and vibration-damping properties was conducted to assess their performance. Moreover, from an application standpoint, the hyperelastic model was identified for fabricated composites. Further, the vibration-damping properties were tested in different configurations, and radiated sound power levels of mild steel bare beams with and without a damping layer were evaluated. Additionally, the performance of the developed vibration-damping composites is benchmarked with commercial vibration-damping material. The waste-derived fillers present a sustainable and effective alternative to petroleum-based fillers for developing vibration-damping composites by minimizing greenhouse gas emissions and prioritizing sustainability.

सारांश

वर्तमान अध्ययन दो गंभीर समकालीन चुनौतियों की व्यापक खोज के साथ शुरू होता है: ठोस अपशिष्ट प्रबंधन और कंपन नियंत्रण। कृषि, उद्योग, खनन और नगरपालिका गतिविधियों से उत्पन्न होने वाले ठोस अपशिष्ट की भारी मात्रा पर्यावरणीय चुनौतियों को बढ़ाती है। अकुशल अपशिष्ट प्रबंधन प्रथाओं के परिणामस्वरूप हवा, मिट्टी और भूजल का महत्वपूर्ण प्रदूषण होता है, जो शहरी पारिस्थितिकी तंत्र पर प्रतिकूल प्रभाव डालता है और महत्वपूर्ण स्वास्थ्य खतरे पैदा करता है। स्थानीय प्रदूषण के अलावा, वे जलवायु परिवर्तन को बढ़ाने में भी महत्वपूर्ण भूमिका निभाते हैं। फिर भी, पायरोलिसिस की प्रक्रिया इन अपशिष्ट धाराओं को मूल्यवान कार्बनयुक्त सामग्रियों में परिवर्तित करके एक आशाजनक समाधान प्रदान करती है।

समवर्ती रूप से, अवांछित कंपन नुकसान पहुंचा सकते हैं और प्रदर्शन को कम कर सकते हैं, जिससे इंजीनियरिंग में कंपन नियंत्रण महत्वपूर्ण हो जाता है। कंपन को नियंत्रित करने की चार मुख्य तकनीकें सक्रिय, अर्ध-सक्रिय, निष्क्रिय और संकर विधियाँ हैं। निष्क्रिय नियंत्रण विधि, जो अपनी स्थिरता, उपयोग में आसानी और सामर्थ्य के लिए मूल्यवान है, 1960 के दशक से एक आम दृष्टिकोण रही है। यह विधि संरचनात्मक कंपन की डंपिंग को बढ़ाने के लिए विस्कोइलास्टिक डंपिंग सामग्री (वीडीएम) का उपयोग करती है। वीडीएम एक कंपन प्रणाली से यांत्रिक ऊर्जा को अवशोषित कर सकते हैं और अपने आंतरिक लोचदार और चिपचिपे गुणों के कारण इसे गर्मी में बदल सकते हैं।

प्रभावी कंपन नियंत्रण की मांग लगातार बढ़ रही है, और वीडीएम के लिए वैश्विक बाजार भी बढ़ रहा है। इस बाजार के 2023 में 0.94 बिलियन अमेरिकी डॉलर से बढ़कर 2030 तक 1.34 बिलियन अमेरिकी डॉलर तक बढ़ने की उम्मीद है, जिससे 5.12% की चक्रवृद्धि वार्षिक वृद्धि दर (सीएजीआर) प्राप्त होगी। यह वृद्धि उद्योगों में उन्नत कंपन प्रबंधन समाधानों की बढ़ती आवश्यकता को रेखांकित करती है। विभिन्न

वीडीएम में, कंपन ऊर्जा को अवशोषित करने की असाधारण क्षमता और विभिन्न अनुप्रयोगों में उनकी बहुमुखी प्रतिभा के कारण रबर-आधारित वीडीएम सबसे लोकप्रिय विकल्प हैं। हालाँकि, रबर-आधारित वीडीएम में, अकेले रबर में अक्सर ताकत, क्रूरता और आंसू प्रतिरोध जैसे आवश्यक गुणों का अभाव होता है, इसलिए उनके यांत्रिक प्रदर्शन को बढ़ाने के लिए आमतौर पर पार्टिकुलेट फिलर्स जोड़े जाते हैं।

रबर कंपोजिट की कठोरता, मापांक, स्किड प्रतिरोध, आंसू ताकत और पहनने के प्रतिरोध को बेहतर बनाने के लिए फिलर्स को व्यापक रूप से रबर कंपोजिट में शामिल किया जाता है। हालाँकि, कार्बन ब्लैक (सीबी) जैसे व्यापक रूप से उपयोग किए जाने वाले वाणिज्यिक फिलर्स के लिए बड़ी मात्रा में गैर-नवीकरणीय, पेट्रोलियम-आधारित संसाधनों की आवश्यकता होती है, और उनका उत्पादन अत्यधिक ऊर्जा-गहन है, जो वैश्विक CO2 उत्सर्जन में महत्वपूर्ण योगदान देता है। इसके अलावा, उनकी गैर-नवीकरणीय और गैर-बायोडिग्रेडेबल प्रकृति पर्यावरण और मानव जाति के लिए महत्वपूर्ण जोखिम प्रस्तुत करती है। इसलिए, आगामी भविष्य में कंपन-डंपिंग सामग्री बाजार की क्षमता और उपलब्ध विभिन्न ठोस कचरे की प्रचुर मात्रा को देखते हुए, वर्तमान कार्य का उद्देश्य कंपन-डंपिंग सामग्री विकसित करने के लिए कृषि, औद्योगिक और इलेक्ट्रॉनिक कचरे सहित विभिन्न स्रोतों से उत्पन्न होने वाले ठोस कचरे का उपयोग करना है।

अत्याधुनिक तकनीकें कंपन-डैम्पिंग कंपोजिट विकसित करने के लिए कृषि, औद्योगिक और इलेक्ट्रॉनिक कचरे जैसे विभिन्न ठोस अपशिष्टों से प्राप्त मजबूत भराव के रूप में टिकाऊ कार्बनयुक्त सामग्रियों के उपयोग की तलाश करती हैं। कंपोजिट को एएसटीएम डी3182-21ए मानकों के अनुसार तैयार किया गया था, जिसमें दो अलग-अलग रबर मैट्रिसेस का उपयोग किया गया था: प्राकृतिक रबर और ब्यूटाइल रबर। उनके प्रदर्शन का आकलन करने के लिए उनके भौतिक, रियोलॉजिकल, रूपात्मक, यांत्रिक, थर्मल और कंपन-डैम्पिंग गुणों का व्यापक मूल्यांकन किया गया था। इसके अलावा, अनुप्रयोग के दृष्टिकोण से, फैब्रिकेटेड कंपोजिट के लिए हाइपरलास्टिक मॉडल की पहचान की गई थी। इसके अलावा, कंपन-

डैम्पिंग गुणों का विभिन्न विन्यासों में परीक्षण किया गया था, और डम्पिंग परत के साथ और बिना हल्के स्टील के नंगे बीम के विकिरणित ध्वनि शक्ति स्तरों का मूल्यांकन किया गया था। इसके अतिरिक्त, विकसित कंपन-डैम्पिंग कंपोजिट के प्रदर्शन को वाणिज्यिक कंपन-डंपिंग सामग्री के साथ बेंचमार्क किया गया है। अपशिष्ट-व्युत्पन्न फिलर्स ग्रीनहाउस गैस उत्सर्जन को कम करके और स्थिरता को प्राथमिकता देकर कंपन-डैम्पिंग कंपोजिट विकसित करने के लिए पेट्रोलियम-आधारित फिलर्स का एक टिकाऊ और प्रभावी विकल्प प्रस्तुत करते हैं।

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

GHG	Green House Gases	MSW	Municipal Solid Waste
CO_2	Carbon Dioxide	VDM	Viscoelastic Damping Materials
EEE	Electrical And Electronic Equipment	RVDM	Rubber-Based Viscoelastic Damping Materials
LED	Light Emitting Diode	WVDM	Water-Based Viscoelastic Damping Materials
E-waste	Electronic Waste	BVDM	Bitumen-Based Viscoelastic Damping Materials
LIB	Lithium-Ion Battery	PIVDM	Piezoelectric-Based Viscoelastic Damping Materials
PVDMs	Particle-Based Viscoelastic Damping Materials	USD	United State Dollar
NR	Natural Rubber	CAGR	Compound Annual Growth Rate
BR	Butyl Rubber	PHR	Parts Per Hundred Rubbers
CB	Carbon Black	BB	Bamboo Biochar
ZnO	Zinc Oxide	PCB	Pyrolytic Carbon Black
TiO_2	Titanium dioxide	SG	Spent Graphite
Al_2O_3	Aluminum oxide	SWL	Sound Power Level
CNTs	Carbon Nanotubes	SONAH	Statistically Optimized Near-Field Acoustic Holography
SBR	Styrene Butadiene Rubber	mPCB	Modified PCB
NBR	Nitrile Butadiene Rubber	LICs	Lithium-Ion Capacitors
MBTS	Benzothiazole Disulfide	EVA	Ethylene-Vinyl Acetate
DMA	Dynamic mechanical analysis	EPDM	Ethylene Propylene Diene Monomer
Tan δ	Loss Tangent	PIB	Polyisobutylene
E′	Storage Modulus	HDCPD	Hydrogenated dicyclopentadiene
E″	Loss Modulus	USD	United State Dollar

FRF	Frequency Response Function	EBA	Ethylene co-butyl Acrylate
WTR	Waste Tire Rubber	UCLD	Unconstrained Layer Damping
RRAC	Rubberized Recycled Aggregate Concrete	CLD	Constrained Layer Damping
PU	Polyurethane Powder	FLD	Free Layer Damping
FES	Foundry Exhaust Sand	TC	Thermal Conductivity
SCLD	Smart Constrained Layer Damping	TS	Tensile Strength
PCLD	Partially Constrained Layer Damping	% EB	Percentage Elongation at Break
RSS	Ribbed Smoke Sheets	M_{100}, M_{200}, and M_{300}	Modulus at 100%, 200%, and 300% Elongations
6-PPD	1,3-Dimethyl butyl)-N-phenyl-P-Phenylenediamine	T_s	Tear Strength
TBBS	N-tert-butyl-2-benzothiazole sulfenamide	RI	Reinforcing Index
TGA	Thermal Degradation Analysis	B & K	Bruel and Kjaer
FESEM	Field Emission Scanning Electron Microscopy	DI Water	Deionized Water
CHNS	Carbon, Hydrogen, Nitrogen, Sulphur Elemental Analysis	CA	Contact Angle
BET	Brunauer-Emmett-Teller	STL	Sound Transmission Loss
FTIR	Fourier Transform Infrared Spectroscopy	MSBB	Mild Steel Bare Beam
XRD	X-Ray Diffraction	H_2SO_4	Sulfuric Acid
SCLD	Smart Constrained Layer Damping	DPG	Diphenyl guanidine
RMSE	Root Mean Square Error	MSE	Mean Square Error

LIST OF SYMBOLS

ξ	Damping Ratio/Structural Damping Ratio	I	Strain Invariant
T_g	Glass Transition Temperature	λ	Stretch Ratio
µm	Micrometre	W	Strain Energy Function
°	Degree	W_{Dev}	Deviatoric Hyperelasticity
C	Celsius	W_{Dil}	Dilatational Hyperelasticity
MPa	Mega Pascal	$\overline{I_1}$	First Invariants of the Left Cauchy-Green Deformation Tensor
Hz	Hertz	$\overline{I_2}$	Second Invariants of the Left Cauchy-Green Deformation Tensor
ω_n	Natural Frequency/ Resonant Frequency	θ	Theta
N	Newton	g	Gram
mm	millimetre	kg	Kilogram
min	minute	mg	Milligram
cm	Centimetre	ml	Milli-litre
m	Meter	keV	Kilo-electron-volt
W	Watts	dB	Decibel
K	Kelvin	%	Percentage