

GREEN VIBRATIONS: DYNAMIC STIFFNESS AND CONSTITUTIVE MODELLING OF RECYCLED NONWOVEN MATERIALS FOR SUSTAINABLE VIBRATION DAMPING IN FLOORING

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ABSTRACT

The increasing concern over environmental sustainability has driven the exploration of waste-based materials as innovative engineering applications. Dynamic compressive mechanical tests were performed at varying frequencies to evaluate energy dissipation and stiffness. The results show that compressed samples exhibit higher Young's modulus, tensile strength, and dynamic stiffness compared to their uncompressed counterparts, particularly at higher frequencies. However, these compressed structures also display greater heterogeneity due to uneven fiber distribution and bonding during the compression process. Uncompressed structures, while more flexible and capable of larger deformations, dissipate energy more effectively at lower frequencies due to their looser fiber arrangement. Furthermore, the presence of small fiber black polyester and footwear waste in the samples negatively impacts mechanical performance in uncompressed structures, with shorter fibers hindering effective entanglement in the matrix. Compressed samples with low amounts of black polyester show improved homogeneity and mechanical properties. Overall, the study demonstrates that compression significantly enhances stiffness and energy dissipation at higher frequencies, while fiber composition and distribution play critical roles in determining the mechanical performance of these materials. A constitutive model based on the Kelvin-Voigt viscoelastic model was proposed to capture the complex mechanical behavior of the nonwoven and compressed nonwoven structures under dynamic loading, accounting for the elastic and viscous properties of the materials. By incorporating this model, we can facilitate further numerical studies that simulate real-world conditions, analyze stress distribution, and predict material performance under varying frequencies and loads.

Keywords

Dynamic Stiffness; Viscoelasticity; Nonwoven; Compressed Nonwoven; Dynamic Compression Analysis; Mechanical Properties; Constitutive model

1 INTRODUCTION

Urban ground vibrations caused by trains and vehicles pose risks to buildings, sensitive equipment, and human health. These vibrations propagate through the soil, potentially damaging structures and causing psychological effects such as sleep disorders [1]. Factors such as traffic volume, vehicle type, and road conditions significantly influence vibration intensity. As a response, many countries have implemented regulations to control such disturbances [2].

Floating floor systems are widely used to mitigate these vibrations, especially high-frequency components [1]. However, they can inadvertently amplify low-frequency vibrations due to interactions between the floating layer, the resilient interlayer, and the underlying slab [3]. This amplification is influenced by the material's damping properties and trapped air, altering the system's natural frequency. Various solutions have been developed to improve vibration isolation under floating floors. Constrained layer damping effectively reduces structural energy transfer by limiting internal motion between rigid layers. Spring-supported concrete slabs offer high isolation for high frequencies but are less effective at low frequencies. Recent innovations include composite isolation pads with carbon nano coils and styrene-butadiene, reducing amplification by over 8% and offering up to 75% noise reduction. Other

effective systems include dry-type double floors for timber constructions, decoupled CLT slabs with elastic interlayers, and optimized air cavities that enhance acoustic isolation by tuning resonance frequency [4], [5].

Despite their effectiveness, conventional damping materials present environmental challenges due to emissions, waste, and poor recyclability. Materials such as asphalt contribute significantly to CO₂ and phosphorus pollution. Moreover, many existing strategies are costly or impractical for widespread implementation and often exclude maintenance and end-of-life impacts from sustainability analyses[6], [7].

These concerns have driven interest in eco-friendly construction materials derived from renewable, biodegradable, or recycled sources. Textile and footwear waste are particularly promising, offering low-cost, fast-production materials with strong acoustic and thermal insulation potential. Numerous studies have successfully integrated these wastes into nonwoven composites for use in construction, automotive, and agricultural applications[8], [9].

This study aims to evaluate the dynamic mechanical behavior of nonwoven structures made from recycled footwear waste. Using the manufacturing process developed by Alves et al.[10], and applying the Kelvin-Voigt viscoelastic model, we quantify the dissipated energy and propose a constitutive model. These results are intended to inform structural design and support finite element simulations of recycled damping materials in practical engineering contexts.

2 MATERIALS AND METHODS

2.1 Waste Grinding

Three types of waste were used: post-industrial white and black polyester from footwear production, and post-consumer footwear waste. White polyester was sourced from AMF Safety Shoes (Portugal), and the remaining waste from CTCP. All materials were milled using a cutting mill with 10×10 mm and 4×4 mm sieves, resulting in fiber lengths between 1–16 mm, measured via stereo microscopy.

2.2 Nonwoven structures production

Ten nonwoven structures were produced using needle-punching of white polyester, black polyester, and footwear waste, with a recycled polyester matrix added to improve fiber entanglement (Samples A, C, E, G, I). Some samples were further compressed at 10 kN and 250 °C for 4 minutes to create denser structures (Samples B, D, F, H, J), as observed in Figure 1.

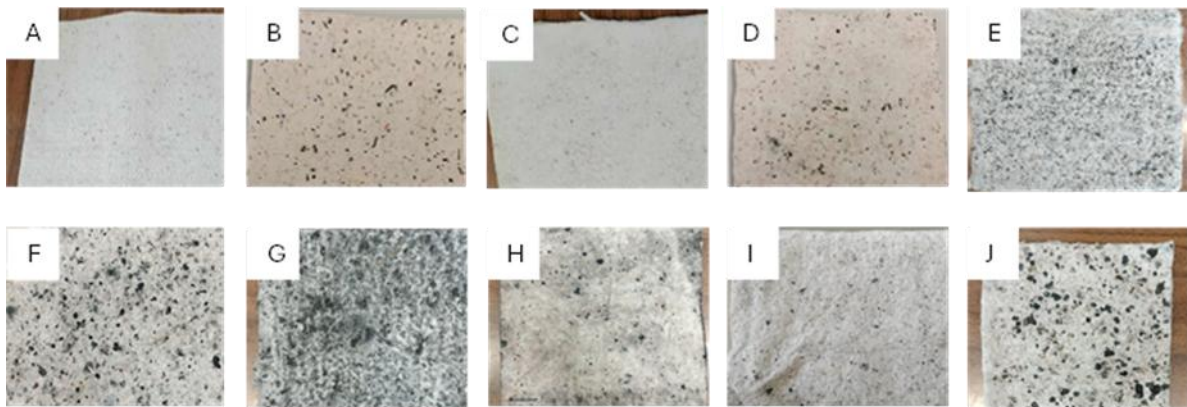


Figure 1 Samples of nonwoven structures.

2.3 Physical properties

The physical properties assessed were thickness, area weight, and bulk density. Thickness was measured per ISO 9073-4 using ten random points per sample; area weight was determined from three samples using an electronic balance. Bulk density was calculated from thickness and area weight.

2.4 Tensile mechanical properties

Tensile tests were performed using a 10 kN load cell following ISO 9073-3 for uncompressed samples (A, C, E, G, I) and ASTM D3039 for compressed ones (B, D, F, H, J). Five specimens per sample were

tested, and average strain and tensile strength were calculated. Young's modulus was obtained using Python's RANSAC regression to exclude outliers and fit a linear model up to the failure point.

2.5 Compressive dynamic characterization

This study evaluated the compressive dynamic properties of recycled polyester nonwoven materials for use as vibration dampers in flooring. Samples (20×20 mm) were grouped by composition and processing and tested in triplicate under cyclic sinusoidal loading using a shaker setup with triaxial accelerometers and a load cell. Tests followed a modified ISO 9052-1:1989 protocol, with a static preload of 25 N. After initial cycles to stabilize the material, samples were tested across frequencies from 5 to 30 Hz (higher frequencies were excluded due to overlapping hysteresis curves). Data was processed in Python to calculate strain, stress, dissipated energy, and dynamic stiffness based on standardized equations.

3 Theory and calculations

3.1 Polyester nonwoven constitutive model

To model energy dissipation, the Kelvin-Voigt viscoelastic model was selected, as it effectively captures the time-dependent behavior of nonwoven materials under cyclic loading. This model, consisting of a spring and dashpot in parallel, represents both elastic and viscous responses, making it well-suited for characterizing recycled polyester nonwovens used in vibration damping (Figure 2).

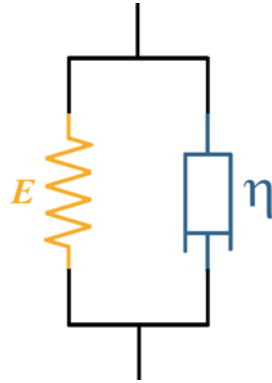


Figure 2 Kelvin-Voigt Model, representing two parallel elements: the spring on the left (the elastic component) and the dashpot on the right (the viscous component).

In the Kelvin-Voigt model, total stress is the sum of elastic and viscous components: the spring stores energy, while the dashpot dissipates it. Together, they describe the material's ability to resist and dampen deformation, with higher viscosity (η) indicating greater energy dissipation (equation 1).

$$\sigma = E\epsilon + \eta \frac{d\epsilon}{dt} \quad (1)$$

3.2 Dissipated energy and hysteretic behavior

Viscoelastic materials exhibit hysteresis under cyclic loading, forming a stress-strain loop whose enclosed area represents the dissipated energy. Unlike elastic materials, energy input is not fully recovered due to internal friction (Figure 3).

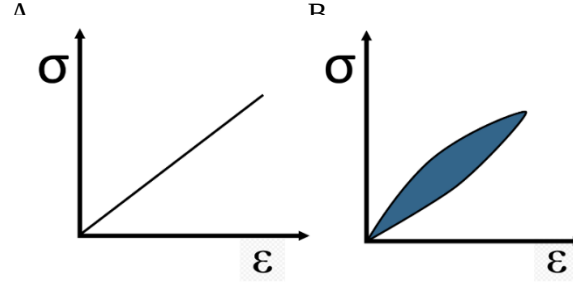


Figure 3 Illustration of the linear elastic Stress-Strain relationship (A) and the nonlinear hysteretic behavior of a viscoelastic material (B), highlighting energy dissipation and the lag between stress and strain during cyclic loading, represented by the blue loop in the stress-strain curve."

When a sinusoidal strain is applied, the dissipated energy per cycle can be derived analytically and is proportional to the square of strain amplitude, viscosity, and frequency. This relationship, given by Equation 2 is used to quantify energy loss in the studied nonwoven materials.

$$W_{dissipated} = 2\epsilon_0^2\pi^2\eta f \quad (2)$$

4 Results and discussion

4.1 Physical properties

Physical properties of the samples are shown in Table 1.

Table 1 Static mechanical properties of the structures

Sample	Thickness (mm)	Area Weight (g/cm ²)	Bulk Density (g/cm ³)
A	10	0.16	0.16
B	5	0.24	0.47
C	10	0.14	0.14
D	6	0.25	0.42
E	8	0.16	0.19
F	4	0.18	0.45
G	8	0.22	0.27
H	4	0.17	0.43
I	6	0.048	0.081
J	5	0.24	0.48

Area weight and bulk density increased in all the compressed nonwoven structures in Samples B, D, H, J compared to the uncompressed Samples A, C, G, I due to manufacturing compression. The exceptions were Samples E and F, where the compressed Sample F showed decreased thickness and increased bulk density without a significant change in area weight. For the other compressed samples, the same weight was distributed over a smaller volume, resulting in higher area weight and bulk density, as reflected by the reduced thickness.

4.2 Tensile Mechanical Characterization

The static mechanical properties of the nonwoven structures, including tensile strain, tensile strength, Young's modulus and the coefficient of determination of the linear regression used to calculate young modulus are observed in Figure 4.

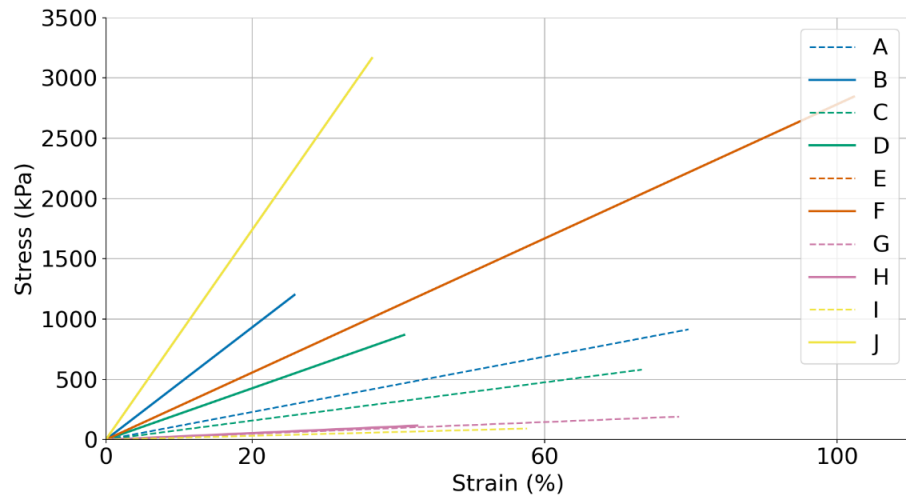
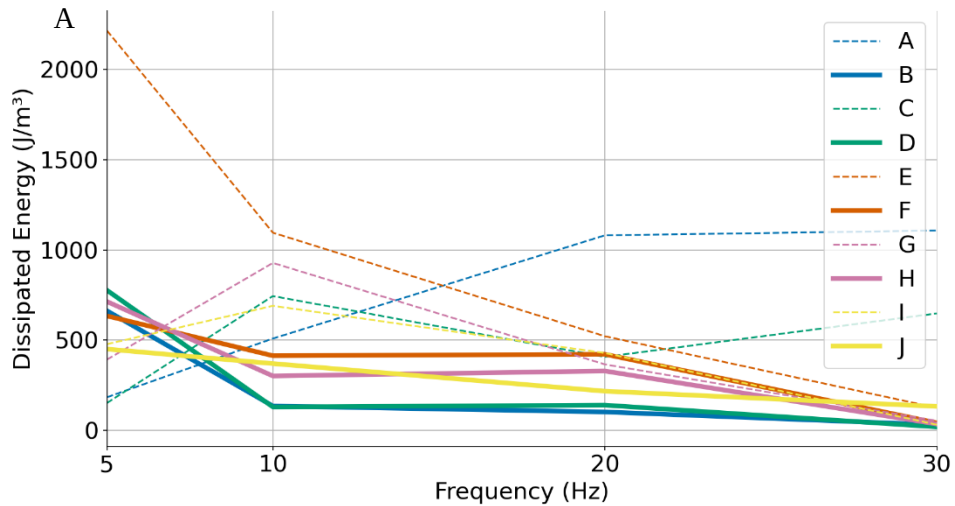


Figure 4 Linear regression of the tensile mechanical behavior of the samples.

In general, Tensile Strength and Young Modulus increased when the samples were compressed, while their Tensile Strain and coefficient of determination decreased when compressed (Samples B, D, H, J), when compared with their uncompressed counterparts (Samples A, C, G, I). This, however, was not observed in Samples E and F, in which the compressed structure in Sample F had the highest Tensile Strain (102.3%) of all the samples and a high Tensile Strength (3099 kPa), Young Modulus (2782 kPa), while the uncompressed Sample E had the lowest Tensile Strain (102.3%), lowest Tensile Strength (26 kPa), a low Young Modulus (224 kPa).

4.3 Compressive dynamic loading

The dynamic mechanical properties of the nonwoven structures, namely dissipated energy and viscous coefficient are observed in Figure 5 and Table 2.



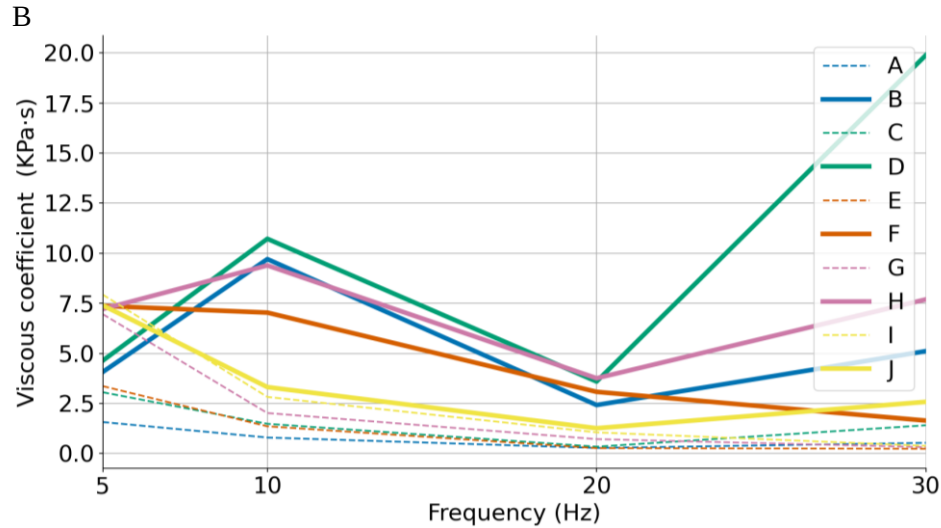


Figure 5 Evolution of (A) Dissipated energy and (B) Viscous coefficient over dynamic compression frequency.

Overall, the analysis highlights how material composition and compression influence the damped energy and viscous coefficients across different frequencies, with specific samples like F and B demonstrating significant energy dissipation through high viscous coefficients despite lower damped energy.

The results reveal distinct variations in damped energy and viscous coefficient across the different nonwoven samples (A to J) when subjected to frequencies of 5, 10, 20, and 30 Hz. Notably, Sample A exhibits high damped energy and viscous coefficient at lower frequencies (5 and 10 Hz), with a significant drop at 20 Hz and zero values at 30 Hz. Upon compression, Sample B shows a decrease in damped energy across all frequencies but maintains high viscous coefficients, especially at 10 Hz and 30 Hz. Sample C displays moderate damped energy with a noticeable peak at 10 Hz, while Sample D shows reduced energy but significantly higher viscous coefficients at 10 and 30 Hz.

Sample E, composed of 60% matrix and 40% black waste polyester, stands out with the highest damped energy at 5 Hz, which decreases with increasing frequency, but maintains relatively low viscous coefficients across all frequencies. Conversely, Sample F demonstrates lower damped energy but high viscous coefficients, particularly at 5 and 10 Hz, indicating effective damping with a focus on energy dissipation through viscous mechanisms.

Sample G shows a more consistent pattern, with moderate damped energy and viscous coefficients that peak at lower frequencies and diminish as frequency increases. Sample H, which is the compressed version of Sample G, retains similar energy dissipation behavior but with slightly elevated viscous coefficients at all frequencies, particularly at 10 and 30 Hz. Finally, Sample I and its compressed counterpart Sample J exhibit moderate to low damped energy and viscous coefficients, with Sample I peaking at 5 Hz and Sample J showing a similar behavior but peaking at 10 Hz. These results highlight the significant impact of compression and material composition on the damping behavior of the nonwoven structures.

Table 2 Dynamic stiffness of the obtained samples of nonwoven structures

Sample	Dynamic stiffness (MN/m ³)			
	5 Hz	10 Hz	20 Hz	30 Hz
A	54.34	20.08	10.12	13.80
B	80.53	208.34	138.77	1064.55
C	68.17	26.89	20.67	21.18
D	60.81	164.78	135.34	981.22
E	25.36	28.91	20.89	31.13
F	136.82	157.95	99.12	264.69

G	58.17	33.73	35.45	54.88
H	125.34	221.78	144.99	622.70
I	94.54	112.63	61.09	107.04
J	100.27	125.34	82.24	135.15

In general, compressed samples B, D, F, H, J exhibit higher dynamic stiffness, particularly at higher frequencies (20 Hz and 30 Hz). Sample B shows a notable increase in stiffness at 30 Hz (1064.55 MN/m³), while uncompressed samples A, C, E, G, I display lower and more consistent values across all frequencies. Sample E stands out with relatively low stiffness at all frequencies, while sample F maintains a balanced increase across all frequency ranges.

4.4 Suggestive constitutive modelling

The suggested constitutive model parameters for the obtained samples are demonstrated in Table 3.

Table 3 Dynamic stiffness of the obtained samples of nonwoven structures

Sample	Young Modulus (kPa)	Dynamic stiffness (MN/m ³)			
		5 Hz	10 Hz	20 Hz	30 Hz
A	1148	1.57	0.79	0.28	0.53
B	4656	4.07	9.70	2.42	5.11
C	793	3.06	1.48	0.34	1.41
D	2131	4.64	10.72	3.59	19.89
E	224	3.37	1.36	0.27	0.24
F	2782	7.37	7.04	3.08	1.65
G	244	6.96	2.02	0.72	0.32
H	274	7.21	9.39	3.76	7.69
I	161	7.93	2.83	1.06	0.38
J	8696	7.40	3.32	1.26	2.58

The suggested Kelvin-Voigt constitutive model effectively characterizes the viscoelastic behavior of the nonwoven samples by combining their elastic and viscous properties. The model utilizes Young's modulus and viscous coefficients at varying frequencies (5, 10, 20, and 30 Hz) to describe how each sample responds to deformation under cyclical loading.

5 CONCLUSIONS

Compression of nonwoven structures significantly affected their physical and mechanical properties. Generally, compression increased area weight and bulk density by reducing thickness, as seen in samples B, D, H, and J. A notable exception was sample F, which maintained similar area weight despite increased density, due to its unique composition of short black polyester fibers and high matrix content. Tensile tests showed that compressed samples (B, D, F, H) had higher Young's modulus and tensile strength but greater heterogeneity, likely due to uneven fiber distribution. Uncompressed samples (A, C, G, I) showed higher strain due to increased flexibility. Samples with high content of black polyester or footwear waste performed worse mechanically, though sample F benefited from compression, showing improved uniformity and strength.

Under dynamic compression, compressed samples dissipated more energy at low frequencies (5 Hz), while uncompressed ones performed better at 10 Hz due to greater flexibility. At higher frequencies (20–30 Hz), all samples saw reduced damping efficiency, but compressed structures retained some damping through microstructural deformations.

Dynamic stiffness tests confirmed the superior performance of compressed structures, especially at high frequencies, far exceeding values of commercial materials like polyurethane foams. The Kelvin-Voigt model effectively captured the viscoelastic behavior of the materials, supporting its use for predicting performance and optimizing vibration-damping designs.

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