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Characterisation of Deproteinised Natural Rubber Latex Foam for Enhanced Acoustic and Vibration Isolation

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ABSTRACT

Natural acoustic foams used in recording studios, auditoriums, cinemas, etc., are largely of petrochemical origin and cause environmental and health problems. The current research explores the application of natural rubber (NR) latex foam as a substitute material. Three types of NR latex foams low ammonia (LATZ), deproteinized (DPNR), and epoxidized (ENR)were developed and characterized for their acoustic and mechanical performance. Sound performance was tested in an impedance tube to ISO 10534-2, for sound absorption coefficient (SAC), noise reduction coefficient (NRC), and sound transmission loss (STL). Results indicate that STL is a rising function of foam density, while SAC in the low-frequency range is a function of density but in high frequencies of morphological structure. Among the foams, high-density DPNR latex foam possessed the highest his paper investigates nonlinear dynamic behaviour in a bolted beam. Force-Controlled Technique (FCT), NRC, surpassing ENR and LATZ foams and commercial memory foam. Further mechanical evaluation of the DPNR foam revealed increased resilience, as evidenced by a maximum ball rebound and minimum hysteresis loss compared to polyurethane (PU) and memory (PM) foams. DPNR latex foam was also successfully manufactured in the configuration of seat cushions through the Dunlop batch process. Pressure-relief performance, as measured by a CONFORMatTM sensor system and mannequin, showed that DPNR cushions were lower in peak pressure than PU foam and were comparable with PM foam. Vibration transmissibility tests, as conducted in accordance with ASTM D3580-95, showed that the lowest attenuation frequency for DPNR latex foam resulted from low stiffness and high resilience. These findings identify DPNR latex foam as a highly potential, eco-friendly acoustic insulation and ergonomic cushioning material particularly for electric vehicle (EV) seat applications.

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INTRODUCTION

Noise pollution generated from several mechanical devices, such as industrial machinery, vehicles, construction equipment, and domestic appliances has been extensively known to pose a significant risk to human health [1-2]. A few research works [2-5] have indicated that longer exposure to high levels of noise pollution can contribute to the development of serious health problems like noise-induced hearing loss, sleep deprivation, elevated blood pressure, mental tension, and mental exhaustion. The acoustic foam items can be made from many other materials, but the polymer foams are the most sought after today because they are light, inexpensive, easy to manufacture, and can be designed in many ways. Of polymer foams, the foam structures are typically divided into two broad categories: closed-cell and open-cell foams [6]. Each type has its advantages and disadvantages, but the right foam structure needs to be chosen to give best performance in a specific application, for example, noise reduction for industrial applications, soundproofing for architectural applications, or vibration damping for automotive applications.

Most commercially produced polymer foams, such as polyurethane, are made from petrochemical sources linked to health and environmental risks. Their production involves isocyanates, known to cause occupational asthma, while the foams themselves may release harmful gases like VOCs throughout their use, raising significant health and safety concerns [7-8]. As awareness of climate change and the depletion of fossil fuel reserves grows, many nations have implemented policy initiatives to encourage the use of 'green materials' in the production of new products. In this context, the development of acoustic foam materials from organic sources is both timely and welcome [9-11]. In our earlier work [12], a new generation of SpNR latex was developed. SpNR latex was developed directly from recently tapped NR latex to minimize the material cost. The SpNR latex was concentrated to 60% total solid content (TSC), allowing SpNR latex to be used to produce latex foam material. Previous work [7-8] has observed that SpNR latex foam is an open-cell foam. This property is beneficial for noise-control applications, which leads to the potential for diversification of latex foam beyond its conventional applications. Bedding materials are being transformed into sound-absorbing foam, which is useful for the transport and construction industries. Thus, this research aims to investigate the effectiveness and factors influencing the acoustic behavior of SpNR latex foams. A commercial-grade version of memory foam (CMF) was utilized as a benchmark. Acoustic foam successfully developed from SpNR latex provides a new generation of environmentally friendly acoustic solutions, serving as a greener alternative to traditional acoustic foams made from petrochemical substances. The research work is also to determine the compressive stress-strain and rebound resilience properties of DPNR latex foam compared to those of commercially available foams, such as polyurethane (PU) foam and polyurethane memory (PM) foam for a comparative study. The insights gained from this study help to better understand the factors impacting the compressive stress-strain and rebound resilience properties of DPNR latex foam. As a result, specific applications can be effectively identified.

This paper assesses deproteinized natural rubber (DPNR) latex foam as a seat cushion alternative, with specific focus given to its pressure relief properties and vibration transmissibility, which are central to comfort and safety [13-14]. Conventional seat cushions are made from polyurethane, specifically a mix of polyol and isocyanate [15]. Health problems related to isocyanate in polyurethane foams have compelled research in the transport industry, prompting safer alternatives [14,16-17]. The building of seat cushions from DPNR latex foam may be a greener and safer option since it occurs naturally.

EXPERIMENTAL SETUP

Materials and latex foam fabrication process

In this study, CMF (0.08 g/cm^3) was supplied by Goodfoam Sdn. Bhd., and ENR and DPNR latex with 60% TSC were prepared from fresh NR latex from MRB Plantation, Johor, using MRB’s patented processes. The properties of ENR and DPNR latex are detailed in previous research [18-20]. Commercial low ammonia NR latex (LATZ) was used as a control. The SpNR latex foam was produced using a process similar to the Dunlop batch foaming method, involving compounding, foaming, gelling, molding, vulcanizing, washing, and drying as shown in Figure 1. Novel formulations for compounding and gelling were applied. This study focused on how density and thickness affect the foam's acoustic.

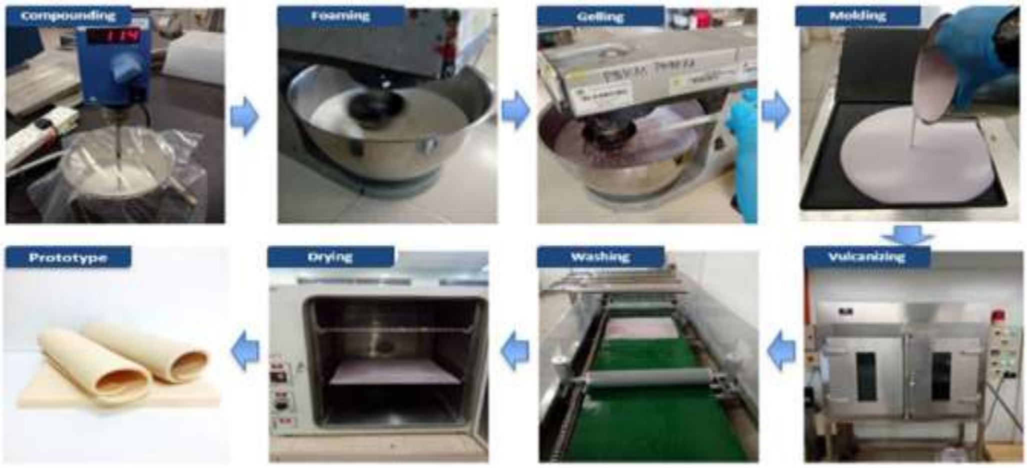


Figure 1. The different stages involved in the fabrication of DPNR, ENR, and LATZ latex foam. Prototype shown is 20 mm thick ENR latex foam.

Three types of wet densities of latex foam were prepared for this study: high-density (HD) with 0.16 g/cm^3, medium-density (MD) with 0.12 g/cm^3, and low-density (LD) with 0.09 g/cm^3. These were achieved by varying the latex weight and controlling the volume expansion of the foam during foaming process, following the MRB standard procedure[17]. For HD, MD, and LD foam production, an amount of about 800 g, 600 g, and 450 g of compounded NR latex was whipped to the required volume stated at 5 L on the mixing bowl. The whipped latex foam was subsequently filled into square molds measuring 20 mm in thickness. Next, the molds were sealed and the latex foam vulcanized using a hot air oven at 100 °C for 60 minutes. The vulcanized latex foam was then removed from the mold and went through washing and drying processes. All the foam samples were conditioned in dry air at room temperature before testing. For comparison, two types of polyurethane foams—flexible polyurethane (PU) and memory foam (PM) were used. They were both provided by Goodfoam Sdn. Bhd., Malaysia.

Table 1. Compounding formulation used in this study

Ingredient	TSC (%)	Dry weight (phr)
NR latex [a, b, c]	60	100
Potassium oleate	20	1.50
Sulphur dispersion	60	2.50
Zinc oxide (ZnO) dispersion	60	0.15
Zinc diethyl dithiocarbamate (ZDEC) dispersion	50	0.75
Zinc dibutyl dithiocarbamate (ZDBC) dispersion	50	0.25
Zinc 2-mercaptobenzothiazole (ZMBT) dispersion	50	1.0
Antioxidant dispersion (Wing stay-L)	50	1.0

[a] LATZ latex; [b] DPNR latex; [c] ENR latex; phr = parts per hundred rubber

Table 2. Gelling formulation used in this study.

Ingredient	TSC (%)	Dry weight (phr)		
		HD	MD	LD
NR Latex	60	100	100	100
Diphenyl guanidine (DPG) dispersion	40	0.3	0.3	0.3
Zinc oxide (ZnO) dispersion	60	5	5	5
Sodium silicofluoride (SSF) dispersion	50	0.5[a],0.8[b],0.9[c]	0.7[a],1.0[b],1.0[c]	0.8[a],1.2[b],1.2[c]

[a] LATZ latex; [b] DPNR latex; [c] ENR latex; phr = parts per hundred rubber

Dry density measurements

Approximately 250 ml of foam latex was loaded into a 250 ml square mould during foaming. The sample was fabricated under the same fabrication process, and its density (ρ) was calculated from the relation $\rho = m/V$, where m is the sample mass and V is its volume.

Indentation hardness measurements

Indentation hardness of the latex foam samples was measured using an Instron machine in conformity with Malaysian Standard MS679 [21]. The indentor foot was set on the top surface of the sample, which was then compressed to 40% of its original 40 mm thickness. The load in Newtons recorded as indentation hardness index.

Visualisation of morphological structure

The morphological structure of the foam samples was examined using a Hitachi SU1510 low-vacuum scanning electron microscope (SEM). A test specimen measuring 5 mm × 5 mm × 5 mm was cut from the samples using a razor blade and mounted onto a sample stub with carbon double-sided tape. SEM images were analysed using ImageJ to quantify pore size distribution in the latex foams.

Acoustic properties measurements

Transmissibility of vibration of samples of foam was analyzed on a UCON VT-9008 vibration machine based on ASTM D3580-95 standards. Pieces of foam measuring 40 mm × 40 mm × 40 mm were placed between a base plate and a free top plate, with two cylindrical weights placed on top of it. A vibration of 1 mm amplitude with frequencies from 2 to 20 Hz was imposed. Accelerometers were employed to sense input and output vibrations, and transmissibility (amplitude of output/input) was sensed and analyzed using VSC software.

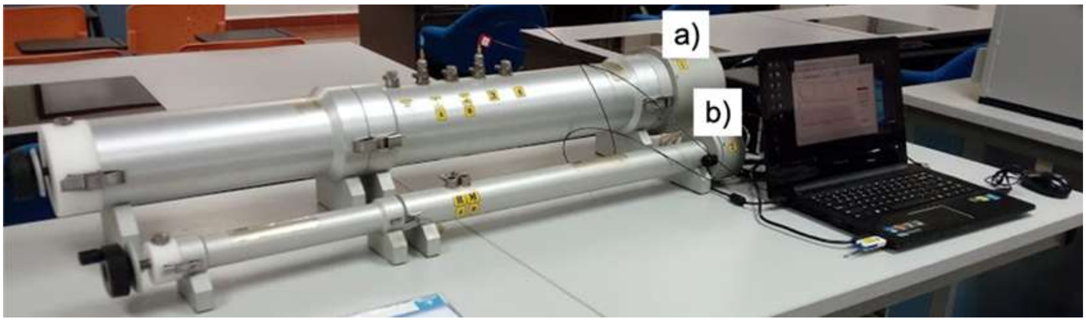


Figure 2. Impedance tube model Kundt tube type SCS9020B. a) A 100 mm diameter test tube; b) A 28 mm diameter test tube.

Compression Test

Compression test was performed to examine the compressive stress–strain behavior of DPNR latex foam, PU foam, and PM foam. The foam samples were trimmed to 200 mm × 200 mm × 40 mm (length × width × thickness). Tests were conducted at room temperature (~27 °C) using a servo-hydraulic MTS Multi-Axis testing machine with a 25 kN load cell. Five successive loading and unloading were used on each sample at a frequency of 0.2 Hz. Loading was induced by applying compression in the shape of a square platen, lowering the sample height to 50% of original thickness. It was anticipated that no separation will occur between the platen and the foam samples during loading and unloading. Load and displacement were digitally recorded during testing.

Ball Rebound Resilience Test

The rebound resilience properties of DPNR latex foam, polyurethane (PU) foam, and PM foam were evaluated using a ball-rebound test device by ASTM D3574 [22]. A magnetic steel ball with a diameter of 16 ± 0.2 mm and a mass of 16.3 ± 0.2 g was dropped vertically from a height of 500 mm onto foam samples measuring 200 mm × 200 mm × 40 mm (length × width × thickness). The rebound resilience was calculated as a percentage using the formula:

$$\text{Rebound resilience (\%)} = (\text{hfinal} / \text{hmax}) \times 100 \quad (1)$$

where hfinal is the maximum rebound height of the ball, determined from recorded video footage, and hmax is the initial drop height. A video camera was used to capture and analyze the rebound height accurately.

Evaluation on Pressure-relief Performance

The study used pressure mapping technology with a mannequin and a CONFORMat™ sensor system to evaluate how well seat cushion materials relieve pressure. The sensor mat was placed on the foam sample, and the mannequin simulated a human sitting posture. After calibration, the system generated color-coded maps showing pressure distribution, with red indicating high pressure and dark blue showing low pressure.

Vibration Transmissibility Test

Transmissibility of vibration of samples of foam was analyzed on a UCON VT-9008 vibration machine based on ASTM D3580-95 standards. Pieces of foam measuring 40 mm × 40 mm × 40 mm were placed between a base plate and a free top plate, with two cylindrical weights placed on top of it. A vibration of 1 mm amplitude with frequencies from 2 to 20 Hz was imposed. Accelerometers were employed to sense input and output vibrations, and transmissibility (amplitude of output/input) was sensed and analyzed using VSC software.

RESULTS AND DISCUSSION

Physical Properties

Three target densities, HD, MD and LD foams of DPNR and LATZ latex were successfully prepared, while HD and MD foams alone could be prepared for ENR latex because the LD foam collapsed during gelling. From Table 3, it is evident that there is no difference in actual density values between DPNR and LATZ latex foams. The ENR latex foam has higher density values than the DPNR and LATZ latex foams at MD and HD, by a slight margin.

Table 3. Density of latex foam fabricated in this study.

Parameters	Dry density (g/cm^3)		
	LATZ	DPNR	ENR
High-density (HD)	0.102 (0.003)	0.103 (0.006)	0.111 (0.009)
Medium-density (MD)	0.084 (0.004)	0.084 (0.002)	0.090 (0.001)
Low-density (LD)	0.063 (0.006)	0.064 (0.006)	-

Data represent the average of three measurements; standard deviations are shown in brackets.

The indentation hardness value depends largely on the latex foams' density. The indentation hardness value of the latex foams reduces with the increase in the level of density, as seen from Table 4. ENR is the hardest foam material, then LATZ and DPNR latex foams. This could be explained by the fact that the rubber chains contain the epoxy group, which could be responsible for increasing the material's rigidity. Or else, the decrease in the indentation hardness of DPNR latex foam compared to LATZ could be due to the stripping of proteins from the latex system that was earlier found to act as fillers that increase the stiffness of the latex foam.

Table 4. Hardness under indentation of latex foams developed in this research

Parameters	Indentation hardness (N)		
	LATZ	DPNR	ENR
High-density (HD)	203 (5)	186 (7)	220 (1)
Medium-density (MD)	105 (9)	91 (7)	121 (8)
Low-density (LD)	89 (7)	70 (2)	-

Data represent the average of three measurements; standard deviations are shown in brackets.

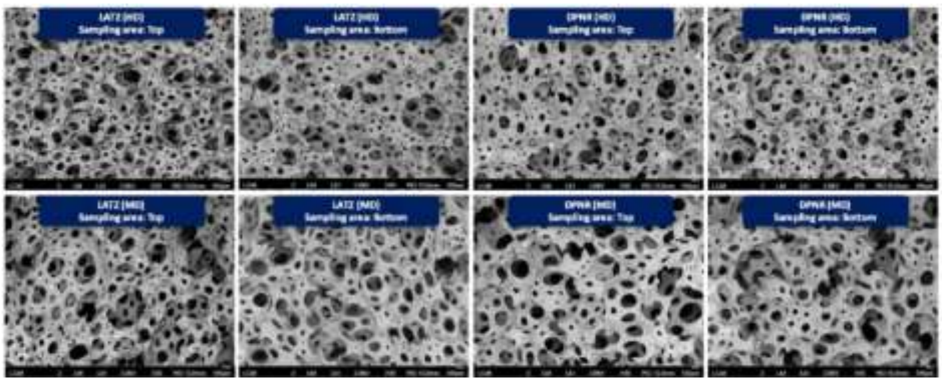
Table 5 presents the density and Shore F hardness of DPNR latex foam, PU foam, and PM foam. PM foam shows the highest density, followed by DPNR latex foam and PU foam. As polymer foams are composites of solid and air phases, density is mainly influenced by the solid phase.

Table 5. Density and Shore F hardness of PU foam, PM foam and DPNR latex foam.

Parameter	DPNR	PU	PM
Dry density (g/cm^3)	0.064 (0.006)	0.040 (0.004)	0.080 (0.004)
Shore F hardness	25.7 (0.96)	34.2 (0.85)	17.1 (0.32)

Data represent the average of three measurements; standard deviations are shown in brackets.

Figure 3 shows SEM images of the foam materials' morphology, focusing on both the top and bottom regions. Slight differences in structure were observed between these two areas. The CMF foam has a unique elongated pore structure, unlike the more circular pores in LATZ, DPNR, and ENR latex foams. SEM analysis showed that pore area decreases with increasing foam density as shown in Figure 3. Using Image software, mean pore area and porosity were measured, revealing that lower-density foams have larger pores and higher porosity. DPNR (LD) had the largest pores and highest porosity (over 50%), while ENR (HD) had the smallest pores and lowest porosity. Among medium-density foams, CMF had the largest pore size.



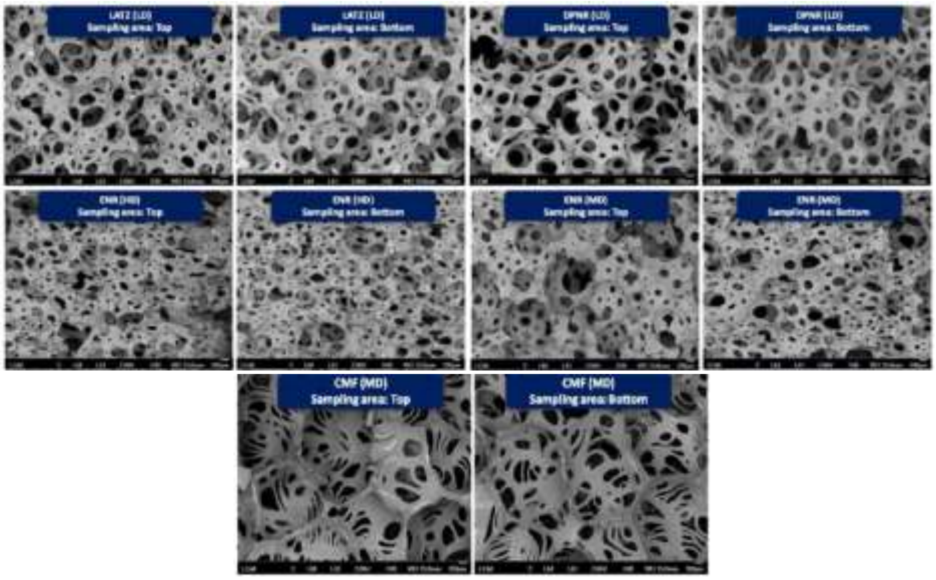


Figure 3. Microstructural analysis of the foam materials conducted in this study

Figure 4 presents the average pore size of the foam materials analyzed in this study. The results show that LD foam exhibits the largest average pore size, followed by MD foam, and then HD foam. This trend is expected, as lower-density foams have a higher air-to-solid phase ratio. Among all samples, DPNR (LD) foam has the largest pore size, whereas ENR (HD) foam has the smallest. As noted earlier, CMF foam has a density of 0.08 g/cm³, which is comparable to that of DPNR (MD) and LATZ (MD) foams. When comparing materials with similar densities, CMF foam demonstrates the largest pore size, followed by DPNR (MD) and LATZ (MD) foams.

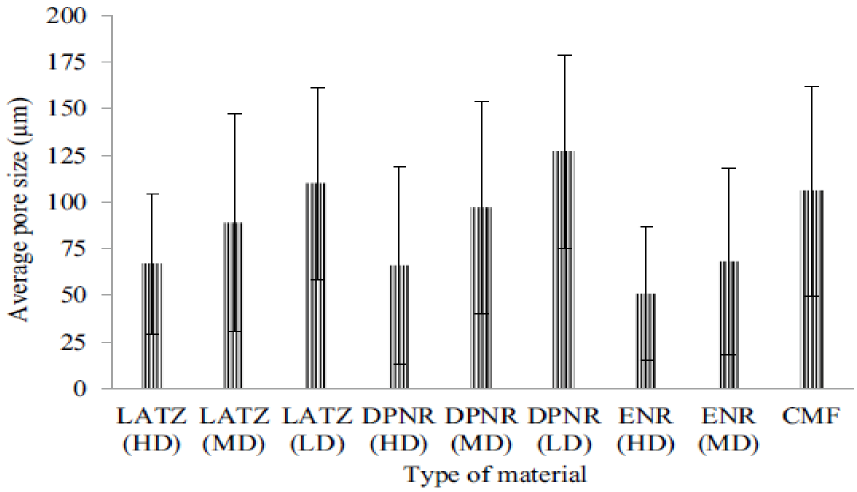


Figure 4. Average pore area and porosity of foam materials examined in this study. Standard deviation is shown as error bars

Figure 5 presents the mean pore area and porosity of the latex foams. Porosity was calculated by dividing the total pore area by the total area of the SEM image. As expected, the mean pore area increases as the latex density decreases. ENR (HD) latex foam exhibits the smallest mean pore area, while DPNR (LD) latex foam shows the largest. Among the medium-density foams, CMF foam records the largest mean pore area. Figure 5 further reveals that low-density foams have higher porosity compared to medium- and high-density foams. The most porous sample is DPNR (LD), with a porosity exceeding 50%, whereas ENR (HD) latex foam shows the lowest porosity.

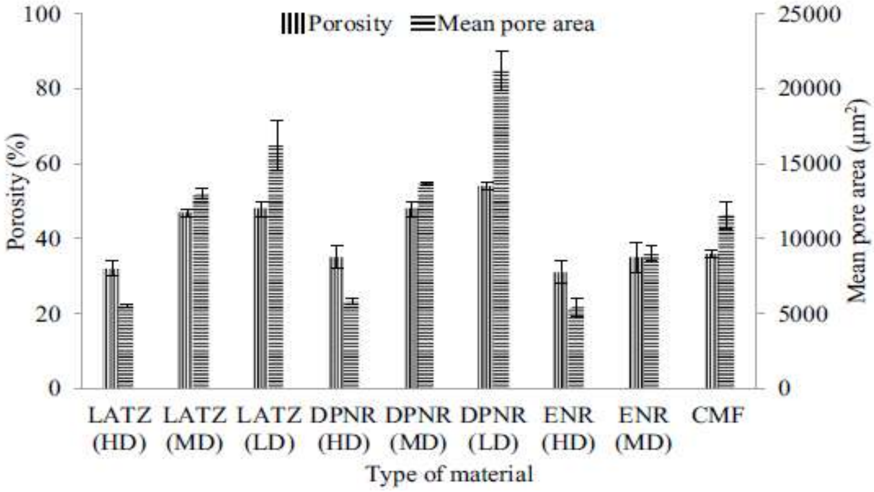


Figure 5. Mean pore area and porosity of foam materials examined in this study. Standard deviation is shown as error bars

In this study, the morphological structures of DPNR latex foam, PU foam, and PM foam were examined. As shown in Figure 6, all three are open-cell foams interconnected by struts but differ in their cell features. DPNR latex foam contains elliptical pores smaller than 300 microns, PM foam has elongated less circular pores, while PU foam exhibits a springy, coil-like structure. SEM images reveal that PM foam has the thickest cell walls, followed by DPNR latex foam and PU foam. This suggests that greater cell wall thickness contributes to higher foam density referred to Table 5.

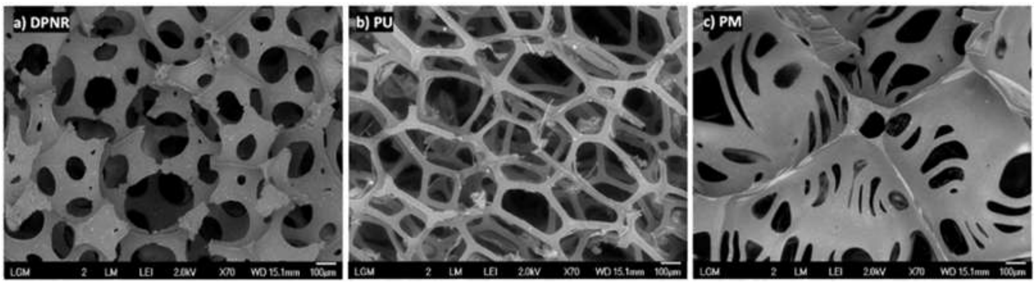


Figure 6. Morphological structures of DPNR latex foam, PU foam, and PM foam at ×70 magnification

Effect of density levels on acoustic properties

Figure 7 illustrates the STL measurements against frequency for latex foam samples with varying densities (thickness: 20 mm). In general, STL is an increasing function of frequency, with increasing values for the HD foams compared to MD foams, and then LD foams. This trend might be attributed to the pore and void structure of the foam, the medium where sound-wave energy is carried. HD foam, having a lower mean pore area than MD and LD foams, offers greater sound transmission resistance and hence greater STL values. This result accords with previous work [23] that increased surface area per unit volume increases energy dissipation by friction. Material stiffness was also highlighted as the controlling parameter for STL by another study [24]. Whereas stiffness was not directly quantified here, indentation hardness for HD foam was highest among MD and LD foams, consistent with literature conclusions.

Among ENR, DPNR, and LATZ latex foams, ENR consistently exhibited the largest STL at all densities, by virtue of the epoxy groups present in its rubber chains that are responsible for stiffness and damping [25-26]. CMF foam had superior STL values compared to LATZ and DPNR foams at all the frequencies and was comparable to ENR foam at the MD density level. HD CMF foam was not compared with ENR (HD) foam.

For effective sound attenuation, the materials should have a minimum of 10 dB STL. For building acoustics, it is typically aimed to be 160–3150 Hz, covering the speech tones and traffic noise [27]. From Figure 7, ENR (HD) foam 20 mm exceeded 10 dB STL throughout the range, justifying its application in building acoustics. Based on the obtained results, which indicate NLFRFs with softening behaviour and a reduction in NLFRFs amplitude, the developed nonlinear FE modelling and analysis using FCT has proven successful. Nonlinear functions, with the cubic stiffness of 2.261×10^9 N/m^3 are assigned to each bolted joint. The adoption of these functions has effectively predicted the nonlinear dynamic characteristics of the bolted beam.

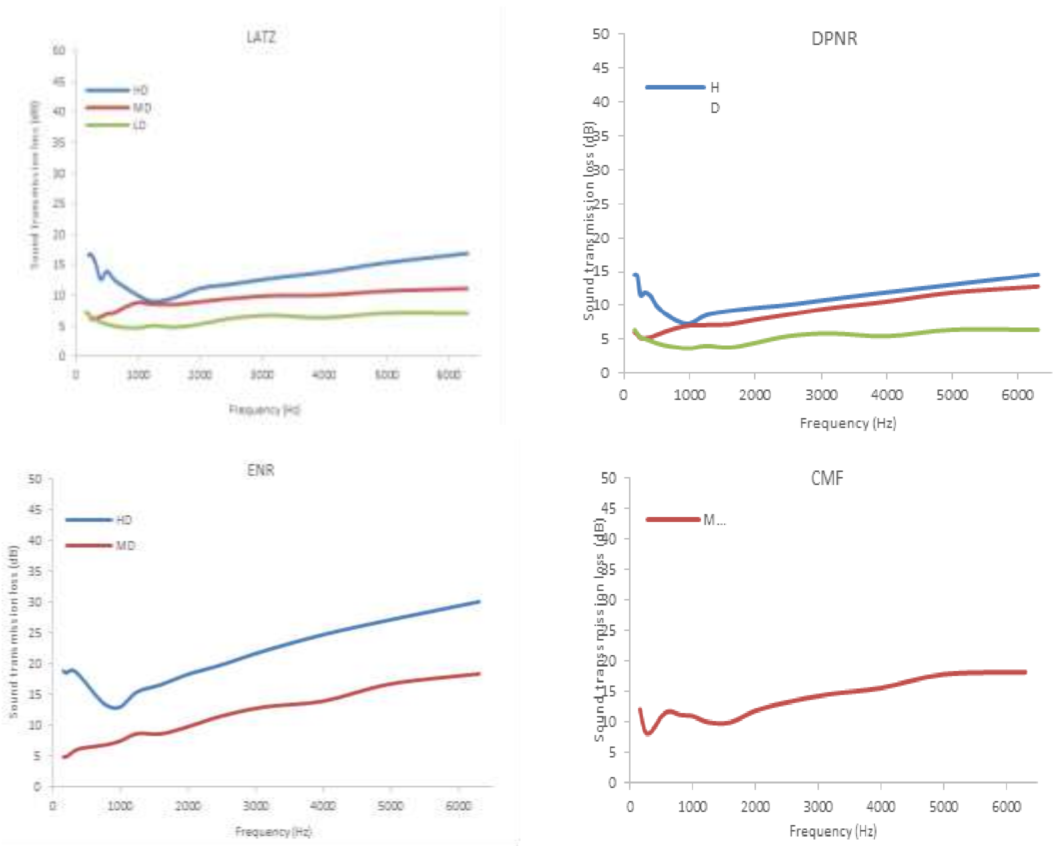


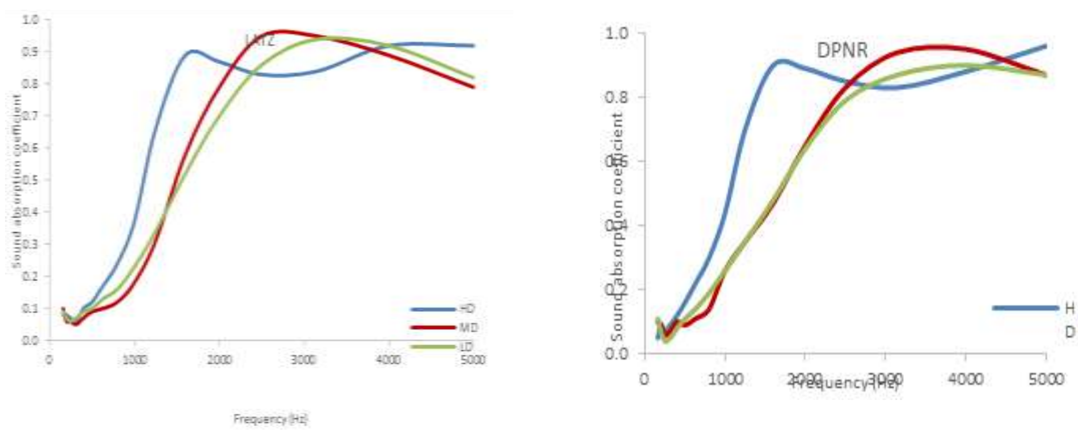
Figure 7. Measurements of STL as a function of frequency on 20 mm thick latex foam specimens

Figure 8 shows the SAC measurements as a function of frequency for 20 mm latex foam samples of different densities. In the low-frequency range (160–1800 Hz), LATZ (HD) and DPNR (HD) exhibit higher SAC values than their MD and LD counterparts. Acoustic resistance strongly influences SAC at low frequencies because low-frequency waves have longer wavelengths and are harder to absorb. Increasing foam density raises its mass and acoustic resistance, improving low-frequency absorption. Morphological structure also plays a role: as shown in Figure 4, HD foams have smaller mean pore sizes than MD and LD foams, and smaller pores increase acoustic resistance.

At high frequencies (>1600 Hz), the SAC curves of LATZ (HD) and DPNR (HD) first decrease and then rise again, with noticeable fluctuations. For MD foams, DPNR (MD) achieves the highest SAC values compared to LATZ (MD), ENR (MD), and CMF, approaching a value of 1 between 3000–4000 Hz, a range associated with unpleasant noise levels and potential hearing damage under prolonged high-amplitude exposure [28]. Unlike STL, SAC performance at high frequencies improves when density decreases from HD to MD, likely because shorter wavelengths are less influenced by pore diameter or, as argued by Setaki et al. [29], because larger macropores allow greater wave penetration and energy dissipation. However, further reducing density from MD to LD does not enhance SAC, suggesting an optimal pore size/density range.

Noise reduction coefficient (NRC) values, summarised in Table 6, assess average absorption over a broad frequency spectrum, where NRC = 0 indicates total reflection and NRC = 1 indicates perfect absorption. For LATZ and DPNR foams, NRC decreases progressively from HD to MD to LD. In ENR foams, however, NRC remains unchanged between HD and MD. At the MD level, ENR exhibits the highest NRC, followed by DPNR, LATZ, and CMF. LD LATZ and LD DPNR foams have NRC values similar to MD CMF foam.

In summary, foam density significantly influences sound absorption. HD foams excel in low-frequency SAC and have higher STL and NRC values overall, while MD foams perform better in high-frequency SAC. This behaviour reflects the relationship between foam structure, pore size, and the wavelength of incident sound waves.



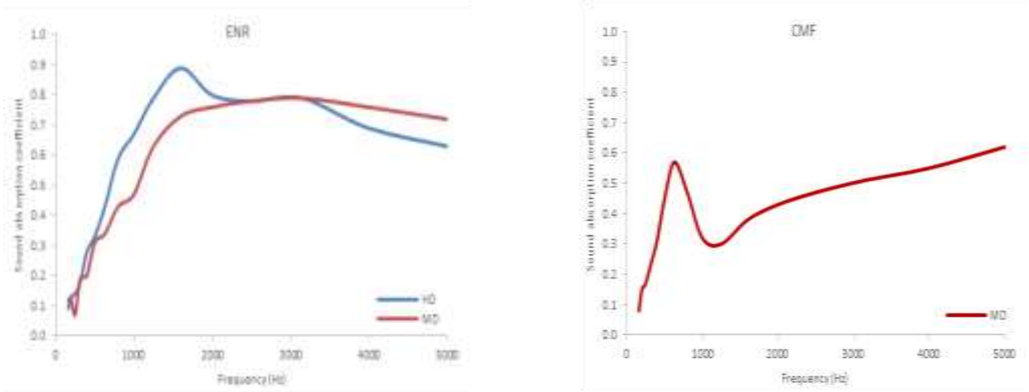


Figure 8. Measurements of SAC as a function of frequency on 20 mm thick latex foam specimens

Table 6. Noise reduction coefficient of 20 mm latex foams

Type of material	LATZ	DPNR	ENR	CMF
HD	0.47	0.49	0.49	NA
MD	0.43	0.44	0.49	0.40
LD	0.40	0.39	NA	NA

Compressive stress-strain behaviour

The cyclic compressive stress–strain responses of the DPNR latex, PU, and PM foams are presented in Figure 9. For comparison of their stress–strain behaviour, both the first and third loading–unloading cycles were plotted. The difference between the two curves, also known as the hysteresis loop, is a measure of the recovery of the foam upon unloading [30]. In this case, the third cycle has been considered because it is widely assumed to be the most stable hysteresis behaviour [31]. The results indicate that loading–unloading response of each foam has a strong reliance on its intrinsic mechanical properties under compressive stress. Among samples, PM foam has the largest hysteresis loop, indicating a more slower recovery compared to PU and DPNR latex foams. As recorded in earlier studies [30,32-33], the deformation mechanism comprises foam cell wall bending, frictional contact, and expulsion of pores upon loading, followed by air reabsorption upon unloading. The recovery rate is therefore a function of the porous network breathability and the relaxation properties of the material. Previous reports [34=35] had suggested that PM foam has a glass transition temperature (Tg) of between –10 and 20 °C, considerably higher than for PU (–46 °C) and for DPNR latex (–70 °C). The relatively high Tg of PM foam suppresses chain mobility, resulting in slow air uptake and re-expansion at unloading—hence its slow-recovery or "memory" effect. Thus, both PM and PU foams possess larger hysteresis loops and larger stress loss between the third and first cycles. DPNR latex foam, however, possesses the smallest hysteresis loop and smallest stress loss, a feature which can be attributed to its high resilience and low stiffness.

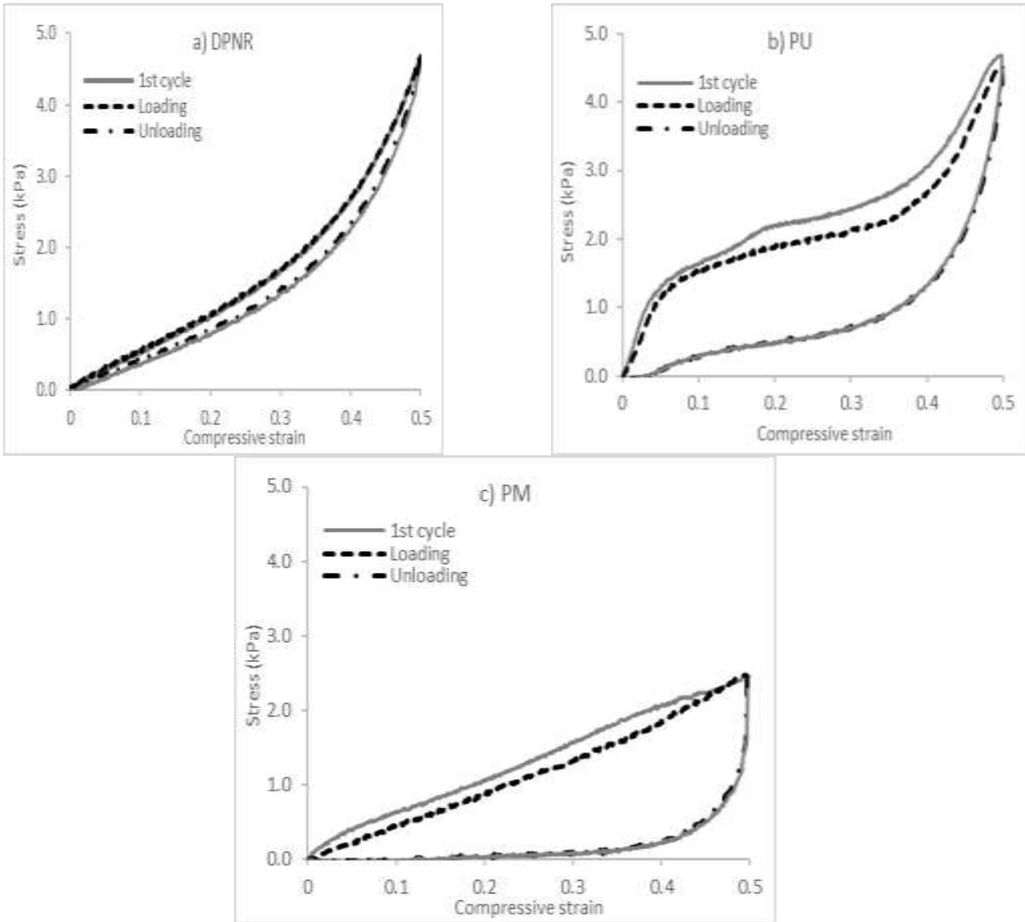


Figure 9. Loading-unloading curve of a) DPNR latex foam, b) PU foam, and c) PM foam. The solid line represents the first cycle, the dash line represents the third cycle.

Previous studies [36-38] have reported that a small hysteresis loop may also be associated with the dimensional stability of a material, reflecting its resistance to sagging or bottoming out during use. This suggests that DPNR latex foam is capable of withstanding high pressures and heavy loads, a desirable property for cushioning applications. Moreover, similar studies [36-38] have indicated that the deformation characteristics of foam under compression are linked to durability, where lower deformation corresponds to a longer service life. Although durability and dimensional stability tests were not conducted in the present work, the results of the compression test, together with supporting literature, suggest that DPNR latex foam is well-suited for heavy-duty industrial applications, such as seat cushions in the transportation sector.

It is well established that in a hysteresis loop, the area under the loading curve represents the total mechanical energy input, while the area under the unloading curve corresponds to the energy returned. The area enclosed between the two curves indicates the dissipated energy, which is primarily converted into heat [38]. Thus, hysteresis analysis provides valuable insight into the energy absorption capacity and pressure-relief potential of foam materials. The hysteresis loss ratio can be expressed by the following equation:

$$\text{Hysteresis loss ratio} = H/E \quad (2)$$

Here, H represents the hysteresis, or dissipated energy, defined as the difference between the areas under the loading and unloading curves, while E is the supplied energy, represented by the area under the loading curve. Figure 10 presents the hysteresis loss ratio of the foams studied. Among them, PM foam shows the highest hysteresis loss ratio, followed by PU foam and then DPNR latex foam. The lower ratio in DPNR latex foam reflects its predominantly elastic nature, allowing it to store a greater amount of energy during deformation.

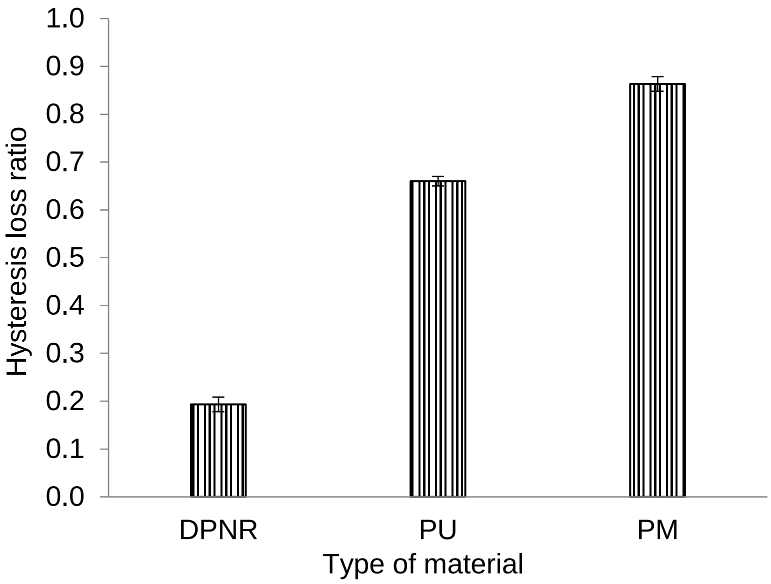


Figure 10. Hysteresis loss ratio of DPNR latex foam, PU foam, and PM foam

PM foam is a classic viscoelastic material that dissipates most of the input energy as heat rather than storing it when deformed [39]. This explains why DPNR latex foam possesses a lower proportion of hysteresis loss compared to PM and PU foams. Hysteresis loss is usually attributed to energy-dissipating processes like collapse of foam cells and friction between structural elements of collapsing cells [17]. Previous studies [32,34] have also reported that, when subjected to compression, the network of foam cells generates a resisting force owing to three major effects: relaxation, pneumatic, and adhesive. The relaxation effect is linked to chain mobility, which depends upon the glass transition temperature (Tg) and the intrinsic elasticity of the material. The pneumatic effect relies on the morphological structure of the foam, in particular porosity, while the adhesive effect is a result of frictional contact between cell walls and struts. Combined, these factors suggest that the ratio of hysteresis loss in foams is dominated by viscoelastic properties.

Ball-rebound resilience

Figure 11 shows the percentage rebound height following dropping the ball on to the foam surfaces. DPNR latex foam rebounded highest, followed by PU foam and then PM foam. This indicates that DPNR latex foam is the most elastic, being able to return the energy of the dropped ball to a large extent. In contrast, PM foam, a viscoelastic foam first developed by NASA in the 1960s as a shock absorber [37], has the lowest rebound. Its slow recovery inhibits pressure upward, and the majority of impact energy is stored and lost as heat rather than being transferred back as bounce [37].

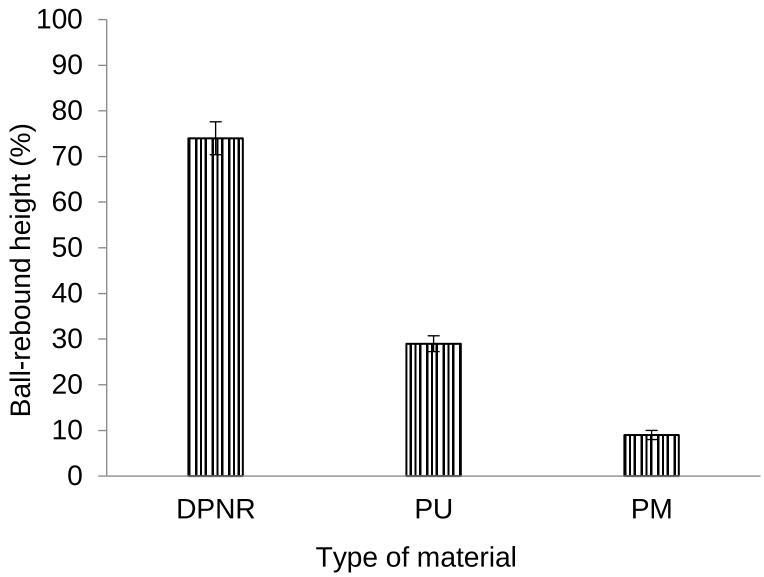


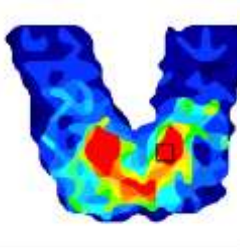
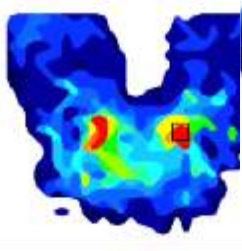
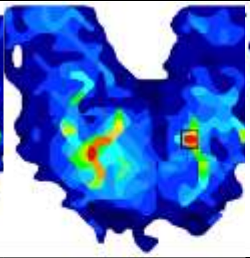
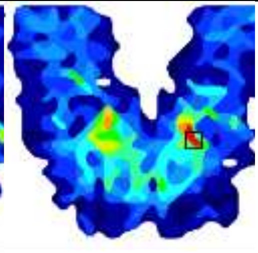
Figure 11. Percentage of rebound height of DPNR latex foam, PU foam and PM foam.

PU, being a conventional polyurethane foam, would be expected to have more rebound than PM foam, yet the test shows that its rebound height is still lower than that of DPNR latex foam. Lower rebound height means more energy absorption and pressure relief, which is why PM foam leads in this area, followed by PU and then by DPNR latex foam. On the other hand, rebound height also reflects material resilience. Since resilience is related to durability and dimensional stability [39], DPNR latex foam's higher rebound shows it is more resistant compared to PU and PM foams. This makes DPNR latex foam a good candidate for heavy-duty cushioning applications such as automotive seats and shoe insoles.

Pressure-relief Performance

Table 6 displays snapshots of real-time measurements of pressure distribution and surface contact area of PU foam, PM foam, and DPNR latex foam and without foam when a mannequin was seated on the top of the seat cushions. Unusual colour intensities and contours of the mannequin's posterior were detected in all forms of seat cushion. That is various physical responses of seat cushions to mannequin loading. Surface contact area of PU foam, PM foam, and DPNR latex foam and foam-free were 106563 mm^2, 114376 mm^2, 114159 mm^2 and 86596 mm^2, respectively. In this study, it was discovered that foam utilization as seat cushions tends to increase the interface (surface contact area) between seat and mannequin. Contact area with the surface of DPNR latex foam is equivalent to PM foam. But a peak pressure area was determined in the mid-posterior region of the mannequin. The average peak pressure value of PU foam, PM foam, and DPNR latex foam and foamless were computed as 96 kPa, 66 kPa, 68 kPa and 238 kPa, respectively. According to previous research [40-42] the point of stress (peak pressure) is the area where humans feel pain while seated, especially due to long-distance travel. It must be relieved from stress at the point of stress in the posterior area to prevent development of pressure ulcers. Therefore, with the objective of maximizing the pressure distributions at the interface area between the posterior area and the seat system by means of seat cushions, it is prevalent in the transport industry. The current research ascertained that with PU foam as the seat cushion, the average peak value of pressure is reduced by over half of the average peak value of pressure without foam. By contrast, if DPNR latex foam or PM foam is used, the mean peak pressure value is reduced by more than two-thirds of the mean peak pressure value without foam. DPNR latex foam showed good pressure-relief capability could be an outcome of the materials' softness, which allow the foam to mold itself to the posterior curvature and offer a larger interface (surface contact area) between the seat and the posterior area, hence decreasing the peak pressure at the stress points [43-44].

Table 7. Snapshots of the pressure distribution mapping of the foam materials examined in this study

Without foam	PU foam	PM foam	DPNR latex foam	Pressure scale
				

Vibration Transmissibility Study

Figure 12 shows the vibration transmissibility of DPNR latex foam, PU foam, and PM foam as a function of frequency. The comparison was made using resonance peak, resonance frequency, and attenuation frequency. Two regions were identified: the amplification region, where transmissibility is greater than one, and the isolation region, where it is less than one [45]. The corresponding values for each foam are summarized in Table 7.

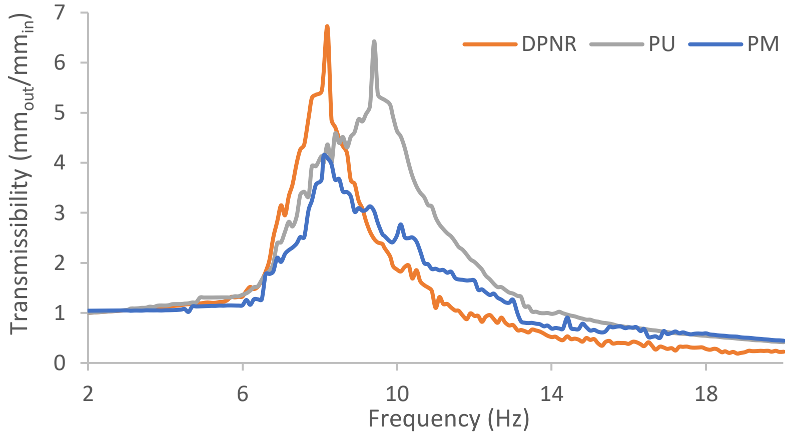


Figure 12. Vibration transmissibility of DPNR latex foam, PU foam, and PM foam

According to Chan et al. [46] a lower resonance peak indicates better vibration damping. Table 7 shows that PM foam has the lowest resonance peak, meaning it provides better damping than PU and DPNR latex foams. PU foam has the highest resonance frequency, which agrees with earlier studies [46-47] showing that harder materials have higher resonance frequencies. This matches the Shore F hardness values in Table 5, where PU foam is the hardest. PM foam's good damping is linked to its viscoelastic nature and higher density. Designed by NASA in the 1960s as an impact absorber [37], it is now widely used in products like luxury car seats. Comparing PM and PU foams is straightforward since both are polyurethane-based, but adding DPNR latex foam makes the comparison more complex because it is rubber-based. Rubber's high elasticity gives a different vibration response, and even though DPNR latex foam is denser than PU foam, it still shows a higher resonance peak.

Table 8. Vibration transmissibility characteristics of foam materials examined in this study

Type of material	Resonance peak	Resonance frequency (Hz)	Attenuation frequency (Hz)
DPNR latex foam	6.71	8.20	11.70
PU foam	6.42	9.30	13.70
PM foam	4.14	8.05	13.10

As shown in Table 8, DPNR latex foam is harder than PM foam, so its resonance frequency would be expected to be higher. However, the results indicate only small differences between the two. Table 8 also shows that DPNR latex foam has the lowest attenuation frequency, likely due to its low stiffness and high resilience. Beginning at 9.50 Hz, DPNR latex foam shows lower resonance than the other foams and reaches vibration isolation at 11.70 Hz, earlier than PM foam. Previous studies [48-49] reported that vibrations above 12 Hz can negatively affect parts of the human body such as the legs, arms, shoulders, and head. The present findings suggest that DPNR latex foam offers better damping than PU and PM foams in the isolation region, making it a suitable material for seat cushions designed to block high-frequency vibrations. Since vehicles such as motorcycles, high-speed crafts, trains, and trucks are often exposed to such vibrations [37], DPNR latex foam could serve as an effective alternative for cushioning in these applications.

CONCLUSIONS

This study has explored the morphology and acoustic properties of novel latex foams made from natural materials. Images obtained from SEM showed no significant differences in morphological structures between the top and bottom areas of the foam samples. Image analysis confirmed that the pore sizes of the high-density DPNR and ENR latex foams were found to be smaller than those of the medium and low density. As a result, decreasing the density of the latex foams improved their porosity.

In terms of acoustic properties, the highest STL value was exhibited by ENR latex foam (HD). The SAC value in the low frequency range is governed by the density and thickness levels of the material, and increasing the density and thickness led to an increase in the SAC value, likely because of the increased mass, which aids in the absorption of low frequency sound waves. However, in the high-frequency range, morphological characteristics, such as pore size, play an important role in determining the SAC value as a result of the shorter wavelengths concerned. As a result, the SAC levels fluctuate as the sound frequency increases.

DPNR latex foam an elasticity material thus has excellent bounce-back and load-distribution features. DPNR latex foam has the lowest hysteresis loss ratio, followed by PU foam and PM foam. The advantage of DPNR latex foam over PU and PM is that DPNR latex foam is softer than PU but has a better return-to-form than PM, which is beneficial for seat cushions in the transportation industry. The ball-rebound test indicates that DPNR latex foam has a higher resilience property compared to PU foam and PM foam, thus DPNR latex foam is suitable for padding applications such as shoe insoles.

A novel deproteinized natural rubber (DPNR) latex foam seat cushion was successfully developed. The DPNR latex foam showed a high surface contact area and low peak pressure value. This is due to the softness of the materials, which results in a high interface between the seat and the posterior area of the mannequin. This study also found that DPNR latex foam has the lowest attenuation frequency, resulting in greater vibration isolation compared to PU foam and PM foam. It can be concluded that DPNR latex foam has both excellent pressure-relief and vibration-isolation performance, suitable for seat cushions intended for the transportation industry.

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