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ORIGINAL PAPER

The acoustic properties of latex foam made from deproteinized natural rubber latex and epoxidized natural rubber latex

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Abstract

Acoustic foam materials are used to control noise pollution in a wide range of applications, including buildings and the transportation industry. This study explores the feasibility of replacing conventional acoustic foam made of synthetic material with natural rubber (NR) latex foam. The acoustic properties of two types of specialty NR latex foams, deproteinized natural rubber (DPNR) latex foam and epoxidized natural rubber (ENR) latex foam, were investigated using an impedance tube according to ISO 10534-2. It was found that the sound transmission loss (STL) performance is directly proportional to the thickness and density of the latex foam samples. A comparison between ENR, DPNR, and LATZ latex foams showed that the ENR foam exhibits the highest STL curve at all thickness and density levels. The sound absorption coefficient (SAC) performance was assessed at low and high frequencies. At low frequencies, the SAC was found to be affected by the density and thickness levels of the materials, whereas at higher frequencies, it was the morphological characteristics that influenced the SAC. The noise reduction coefficient (NRC) was used to evaluate the overall noise absorption performance of the foams. It was found that high-density DPNR latex foam exhibits a higher NRC value than high-density ENR latex foam. Overall, both ENR and DPNR latex foams meet the specifications for acoustic applications in buildings and the transportation industry, making them strong contenders for the next generation of environmentally friendly acoustic foams.

Keywords Specialty natural rubber latex foam · Sound absorption coefficient · Noise reduction coefficient · Sound transmission loss

Introduction

Noise pollution generated from many mechanical systems, including industrial machines, transportation, construction, home appliances, etc., has a negative effect on human health [1, 2]. Previous studies [2–4] have shown that long-term exposure to noise pollution can cause hearing loss, psychological stress, and mental fatigue. These adverse health effects can lead to workplace accidents and injuries. Noise, or sound, is a type of audible wave energy of different frequencies, usually divided into low frequency (< 1600 Hz) and high frequency (> 1600 Hz) [1, 2]. Whistling, for example, is classified as a high-frequency sound, whereas thunder growling is classified as a low-frequency sound. Acoustic foam materials have been widely used to address noise pollution, and their application field is broad and varies in scale from industrial machines to vehicles, recording studios, conference rooms, train stations, and others [3–5]. Through this technology, the energy carried by sound waves is dissipated by structural damping loss, viscous loss, and thermal loss [6, 7]. Furthermore, in the entertainment industry, acoustic foam material has been used to control undesirable noise, such as echoes, shadows, and resonances, to provide a premium acoustic environment [8, 9].

Acoustic foam materials can be made from different types of materials, but polymer foams have become the material of choice because of their simple manufacturing processes, economics, and the lightweight nature of the products. Polymer foams can be classified as closed-cell foam or open-cell

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foam structures [14]. Both closed-cell and open-cell foams have their advantages and disadvantages. Selecting the right foam structure for a particular application is crucial, because each has its own unique characteristics that enable it to perform its function [7, 15].

Closed-cell polymer foams have cells that are isolated from each other, and the cavities are surrounded by complete cell walls. When the wave energy reaches a reflective surface, it is forced to change direction. As a result, some of the noise is reflected, and some is transmitted through the closed-cell polymer foam. Technically, when sound waves strike the surface of a closed-cell polymer foam, the wave energy forces the cell walls to stretch, bend, and buckle [6, 7, 10], and these processes convert some of the sound energy into heat. Therefore, the main function of closed-cell polymer foams is to reduce the sound intensity to an acceptable level and minimize the propagation of noise from one room to another.

Open-cell polymer foams, on the other hand, provide better sound absorptive capacity compared to closed-cell polymer foams and are incredibly effective as noise absorbers for high frequency ranges [7, 16–18]. Open-cell polymer foams contain pores that are connected to each other through struts to form an interconnected network. The porous structures of open-cell polymer foams cause sound waves to enter the material through a number of pores and small cell openings and thus allow the sound wave energy to interact with these membranes [11, 12]. The energy is then trapped in the porous structures and forced to change direction several times. Each time the sound wave is reflected or redirected, part of its energy is absorbed by the membranes and converted to heat. Therefore, open-cell polymer foams are mainly used to control the level of sound reverberation inside a confined space, creating a pleasant acoustic environment.

Commercially available polymer foams are manufactured from petrochemicals, many of which are known to contribute to environmental and health problems [20–23]. Polyurethanes, for example, are prepared from isocyanates, a well-known cause of occupational asthma caused by high exposure at work during manufacturing. This has raised awareness among users of the possibility that, over time, toxic gases may be released that cause health hazards [13, 14]. Furthermore, with increasing awareness of the rise of global warming and fossil fuel depletion, as well as new legislation implemented by several countries to encourage the use of 'green materials' in the manufacture of new products, it is timely and desirable to develop acoustic foam materials from natural sources [26–28]. One possible solution is to substitute petrochemicals with specialty natural rubber (SpNR), of which there are two types: epoxidized NR (ENR) and deprotenized NR (DPNR).

ENR is a chemically modified NR prepared by in situ chemical reactions that convert part of the carbon–carbon double bonds of rubber chains into epoxy functional groups using performic acid [16, 17]. Products made of ENR possess high damping, excellent wet grip, low gas permeability, and high oil resistance compared to normal NR, but retain the intrinsic rubber elasticity [16, 18, 19]. Due to its high damping, it is worth exploring the possibility of diversification of the material into sound and vibration control applications. Mahmud Iskandar [15] studied the acoustic properties of rubber foam made from bulk ENR with non-uniform pore size and heterogeneous structures. The foam exhibited promising sound absorption capability at low frequencies but poor absorption capability at high frequencies as a result of the limited porosity and dead-end pores. The foam also had a higher density compared to commercial acoustic foams, which limits the potential applications of the foam in the transportation industry. The study suggested considering alternate types of ENR, such as developing acoustic foam using ENR latex, since latex foam can be produced at lower densities than rubber foam [20].

Compared to ENR latex, DPNR latex is a purified form of NR latex from which most of the components of the ash and protein components have been removed via enzymatic hydrolysis reactions [21, 22]. Products made from DPNR exhibit good dynamic properties, low stress relaxation, low creep, and lower extractable protein content compared to normal NR [31–33]. However, to the authors' knowledge, no study has been made on DPNR for acoustic foam applications, possibly due to the high cost of the material.

In our previous work [23], a new generation of SpNR latex was developed. The SpNR latex was prepared directly from freshly tapped NR latex to reduce the cost of the material. The SpNR latex was concentrated at 60% total solid content (TSC), allowing SpNR latex to be used to produce latex foam material. Previous studies [24, 25] observed that SpNR latex foam is an open-cell foam. This property is beneficial for noise control applications, which leads to the possibility of diversification of latex foam from its traditional bedding products into acoustic foam materials for buildings and transportation industry. Therefore, the focus of this study is to investigate the performance and factors that influence the acoustic properties of SpNR latex foams. A commercial grade of memory foam (CMF) was used as a benchmark. Successful development of acoustic foam from SpNR latex foam could provide a new generation of environmentally friendly acoustic foams, and a greener alternative to conventional acoustic foams made from petrochemicals.

Experimental

Materials and latex foam fabrication process

In this study, a CMF with density of 0.08 g/cm^3 was supplied by Goodfoam Sdn. Bhd., Malaysia. Both ENR latex and DPNR latex of 60% TSC were prepared from freshly tapped NR latex collected from MRB Plantation, Johor, Malaysia. ENR latex was prepared according to the Malaysian Rubber Board (MRB) standard process and formulation patented in PI2012004868 [26]and PI2017700457 [27], respectively. DPNR latex was prepared according to MRB standard process and formulation patented in PI2020004246 [28]. Physiochemical properties of both ENR latex and DPNR latex such as the size, viscosity, mechanical stability time, dry rubber content, total solid content, nitrogen content and epoxidation level, as well as the type of stabilizer used, are described in detail in previous work [23]. As a control, a commercial grade low ammonia NR latex (LATZ) was purchased from Getahindus (M) Sdn. Bhd. All chemicals were purchased from Alpha Nanotech (M) Sdn. Bhd., Selangor, Malaysia, and used as received. In a recent publication [24], the manufacturing process of SpNR latex foam was described in detail, and only a brief overview is given here. The process involves compounding, foaming, gelling, molding, vulcanizing, washing and drying processes, as shown in Fig. 1. The SpNR latex foam fabrication process is similar to that of the conventional Dunlop batch foaming process [20, 26], but the compounding and gelling formulations are novel, and are shown in Tables 1 and 2, respectively. In this study, two variables, density and thickness, were investigated to evaluate factors that influence the acoustic properties of SpNR latex foam. For density, three wet density levels of latex foam were prepared: high-density (0.16 g/cm^3, HD), medium-density (0.12 g/cm^3, MD), and low-density (0.09 g/cm^3, LD), by controlling the weight of the latex and volume expansion of the latex foam throughout the foaming process in accordance to MRB standard procedure [27].

Generally, to produce HD, MD, and LD foams, approximately 800 g, 600 g, and 450 g of compounded NR latex were whipped until it reached the desired volume marked on the bowl, fixed at 5 L. Then, the latex foam was poured into square molds with different thickness: 10 mm, 20 mm, and 40 mm. Subsequently, the mold lid was closed and the latex foam was subjected to the vulcanization process in a hot air oven at 100 °C for 60 min. After the vulcanization process, the latex foam was peeled out of the mold, followed by a washing and drying process. All samples were kept dry at room temperature before testing.

Dry density measurements

During the foaming process, approximately 250 ml of latex foam was poured into a 250 ml square container. The latex foam sample was then subjected to a similar fabrication

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

Table 1 Compounding formulation used in this study

Ingredients	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

phr parts per hundred rubber

[a]LATZ latex

[b]DPNR latex

[c]ENR latex

process. The density was calculated as $\rho = m/V$ where m is the mass of the sample and V is the volume.

Indentation hardness measurements

The indentation hardness of the latex foam samples was determined using an Instron machine in accordance with Malaysian Standards MS679 [28]. The indentor foot was brought into contact with the top surface of the test specimen. The test sample was then indented to 40% of its 40 mm initial thickness. The corresponding force in Newtons was recorded as the indentation hardness index.

Visualization of morphological structure

Hitachi SU1510 low-vacuum scanning electron microscopy (SEM) was used to visualize the morphological structures of the foam samples. A test portion of 5 mm × 5 mm × 5 mm was cut from the samples using a razor blade and attached to a sample stub using carbon double-sided tape. The specimen was visualized using back-scattered electrons (BSE) operated at an accelerating voltage of 5 kV. The SEM images were captured at × 70 magnification. No metallic coating was required. The images obtained from SEM were then analyzed using ImageJ software to quantify the pore size distribution of the latex foams.

Acoustic properties measurements

The acoustic properties of the DPNR, ENR and LATZ latex foam samples were evaluated by measuring sound transmission loss (STL), sound absorption coefficient (SAC), and noise reduction coefficient (NRC) using an impedance tube model, Kundt tube type SCS9020B. The impedance tube is made up of two combination tubes, two microphones (type GRAS-40BP, ¼ in, for pressure and type GRAS-26AC, ¼ in, for the preamplifier), a two-channel data acquisition system with 0.1 dB resolution, and SCS-90 software, as illustrated in Fig. 2.

The calibrator used was a Larson-Davis CAL 200. The impedance tube system used in the experiment includes a large tube with an inner diameter of 100 mm and a small tube with an inner diameter of 28 mm to measure the absorption coefficients at the low frequencies (160–1600 Hz) and high frequencies (1600–6300 Hz), respectively. The full frequency range for the sound absorption coefficients presented in this report is a combination of the values measured in the large tube and the small tube, which gives the measured frequency range of 160–6300 Hz. Three thicknesses of test samples were used: 10 mm, 20 mm and 40 mm. A circular die cutter was used to cut the samples into cylindrical shapes that matched the size of the impedance tubes. Additionally, a comparison was made between 20 mm single layer foams and 10 mm double-layer foam sandwiches. To make a 20 mm double-layer foam sandwich, needle pins were used to join two 10 mm foams. Acoustic properties were measured according to ISO 10534-2 [29]. STL is a measure of the loss of energy from sound waves experienced as the wave passes through the material, as shown schematically in Fig. 3, and is calculated using the ratio of the power of

Table 2 Gelling formulation used in this study

Ingredients	TSC (%)	Dry weight (phr)		
		HD	MD	LD
NR latex[a,b,c]	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]

phr parts per hundred rubber

[a]LATZ latex

[b]DPNR latex

[c]ENR latex

the incident wave energy, W_i, to the power of the transmitted wave energy, W_t, and expressed in decibels (dB) [30]. According to previous studies [31, 32], noise reduction of at least 10 dB is essential for sound insulation. A material that has an STL of 33 dB or greater would be adequate for a noise barrier in any application.

$$\text{Soundtransmissionloss(SLT)} = 10\log_{10}\left(\frac{W_i}{W_t}\right). \quad (1)$$

SAC is a measure of the sound energy that is absorbed after incidence on a material surface, as shown schematically in Fig. 4, and is defined as

$$\text{Soundabsorptioncoefficient(SAC)} = 1 - \left(\frac{I_r}{I_i}\right), \quad (2)$$

where I_r is the reflected sound intensity and I_i is the incident sound intensity. The SAC of materials varies in the range of 0 to 1. An SAC of 0 means that the sound is completely reflected by the material, whereas an SAC of 1 means that the sound is completely absorbed by the material. Therefore, a higher SAC represents better sound absorption.

NRC is defined as the arithmetic mean of the SAC at frequencies 250, 500, 1000, 2000 and 4000 Hz [34], and represents a measure of the ability of a material to absorb broad-spectrum sound.

Results and discussion

Physical properties

Three target density levels, HD, MD, and LD foams of DPNR and LATZ latex, were successfully fabricated, but only HD and MD foams could be fabricated for ENR latex, because the LD foam collapsed during the gelling process. As shown in Table 3, there was no significant difference in the dry density values between the DPNR and LATZ latex

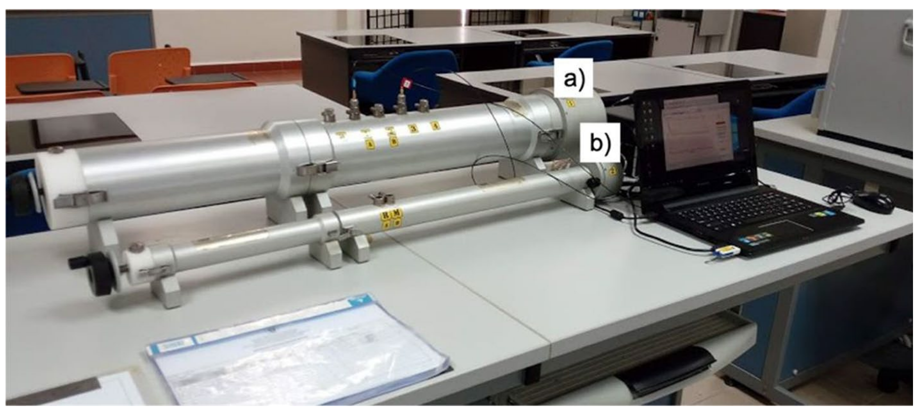

Fig. 2 Impedance tube model Kundt tube type SCS9020B. **a** a 100 mm diameter test tube; **b** a 28 mm diameter test tube

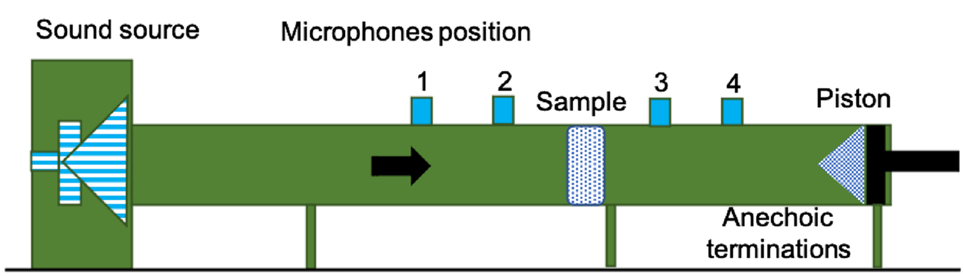

Fig. 3 Schematic diagram of the impedance tube set up for STL test. Adapted from [33]

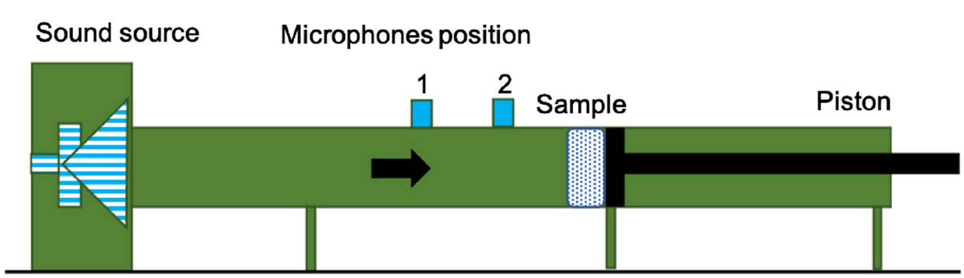

Fig. 4 Schematic diagram of the impedance tube setup for the SAC test. Adapted from [35]

Table 3 Density of latex foams 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)	–

Average of three replicates. Values in brackets represent the standard deviation

Table 4 Indentation hardness of latex foams fabricated in this study

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)	–

Average of three replicates. Values in brackets represent the standard deviation

foams. The ENR latex foam exhibits slightly higher density values than the DPNR and LATZ latex foams at MD and HD.

The density of latex foams has a significant impact on the indentation hardness value. Table 4 shows that the indentation hardness value of latex foams decreases in tandem with density levels. ENR is the hardest foam material, followed by LATZ and DPNR latex foams. This could be due to the presence of the epoxy group in the rubber chains, which may be responsible for increasing the rigidity of the material. On the other hand, the lower indentation hardness value of DPNR latex foam compared to LATZ could be related to the elimination of proteins from the latex system, which have previously been indicated to act as fillers that increase the stiffness of latex foam [21, 35, 36].

Figure 5 shows SEMs of the morphological structures of the foam materials investigated in this study. Two regions were visualized under SEM, the top and bottom of the samples. Minor morphological differences can be observed between the top and bottom regions of the samples. CMF foam exhibits a distinct foam cell structure compared to LATZ, DPNR, and ENR latex foam. The pores in CMF foam appear to be elongated, while the pores in LATZ, DPNR, and ENR latex foam are more circular. The different morphological properties between CMF and NR (LATZ, DPNR, ENR) are likely due to the different interplay between the rheology and surface tension during the foaming process. CMF is produced through chemical reactions of two reactants; reactant A (polyols, chain extenders, blowing agents, gelling and blowing catalysts, surfactants, etc.) and reactant B (isocyanates), as raw materials [37]. On the other hand, NR latex foam is produced through mechanical agitation, where the compounded NR latex is whipped in a Hobart mixer where the stirrer rotates in a planetary motion at high speed to entrap air into the NR latex compound [24, 25]. The different morphological structures of the foam materials, in particular between the NR foams and the CMF foams, are expected to show different acoustic performance. Previous studies have explored how morphological characteristics such as pore size and the percentage of pores (porosity) have their own significant absorbing impact at low and high frequencies [15, 38, 39]. In this study, ImageJ software was used to measure the pore size, pore area and porosity.

Figure 6 shows the average pore size of the foam materials examined in this study. It can be seen that LD foam has a larger average pore size compared to MD foam, followed by HD foam. This is expected, because the lower the density, the higher the air phase to solid phase ratio of the material. The DPNR (LD) foam has the largest pore size, while the ENR (HD) foam has the smallest pore size. As mentioned above, CMF foam has a density of 0.08 g/cm^3, which is similar to that of DPNR (MD) foam and LATZ (MD) foam. In comparison with similar density levels, CMF foam has the largest pore size, followed by DPNR (MD) foam and LATZ (MD) foam.

Figure 7 reports the mean pore area and porosity of the latex foams. To calculate porosity, the total pore area is divided by the total area of the SEM image. As expected, the mean pore area increases as the density of the latex is reduced. The ENR (HD) latex foam had the smallest mean pore area, whereas the DPNR (LD) latex foam had the largest mean pore area. CMF foam, on the other hand, has the largest mean pore area among medium-density foams. Figure 7 also shows that low-density foams exhibit higher porosity compared to medium-density foams and high-density foams. The most porous material is DPNR (LD), which has a porosity of more than 50%. The least porosity is seen in ENR (HD) latex foam.

Effect of density levels on acoustic properties

STL measurements as a function of frequency in latex foam samples with a thickness of 20 mm are shown in Fig. 8 for the different foam densities. In general, the STL curves increase with increasing frequency. In all cases, the HD foams show a higher STL value than the MD foams, followed by the LD foams. The structure of the voids and pores of the latex foams, which acts as the medium of transmission of the sound wave energy, is an aspect that may cause the STL value of HD foam to be higher than that of MD and LD foam. HD foam was observed to have a lower mean pore area than MD and LD foams. This could result in the material having a stronger resistance to sound-wave transmissibility, resulting in a higher STL value. This is in line with previous

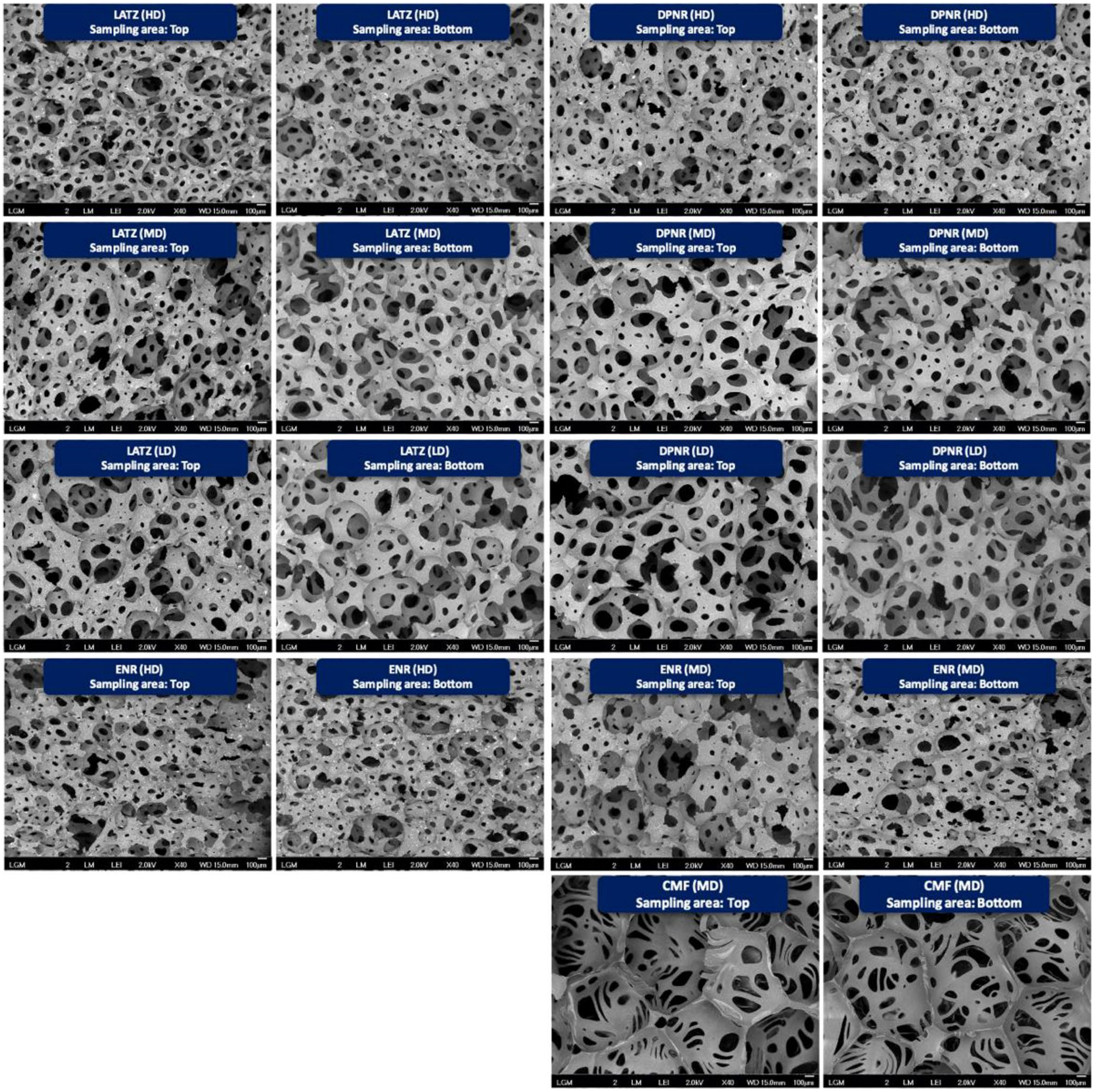

Fig. 5 Morphological structures of the foam materials examined in this study

research [40], which found that having a larger surface area per unit volume causes more energy loss due to friction. On the other hand, a previous study [41] found that the STL value is governed by the stiffness of the materials. Although the stiffness was not measured directly here, the indentation hardness of HD foam was found to be higher than that of MD and LD foams, suggesting agreement with observations in the literature. A comparison between ENR, DPNR, and LATZ latex foams shows that ENR foam exhibits the highest STL curve at every density level. This could be a unique property of ENR, possibly due to the inclusion of the epoxy group in the rubber chains that increases both the stiffness and the damping characteristics of the material [16, 18, 19]. CMF foam is a viscoelastic polyurethane foam designed by NASA in the 1960s to serve as an impact absorber for their astronauts [42–44]. CMF foam is now used in a wide variety of products, including sound insulators [37, 45]. This study found that, at a similar density level (MD), CMF foam exhibits a higher STL at all frequencies than LATZ and DPNR foams, but a comparable STL to ENR foam. Unfortunately,

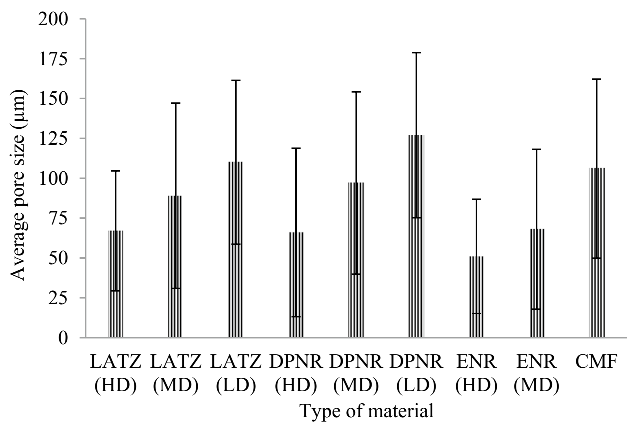

Fig. 6 Average pore size of foam materials examined in this study. Standard deviation is shown as error bars

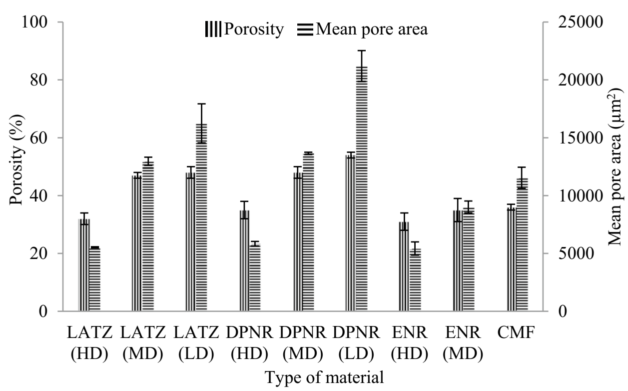

Fig. 7 Mean pore area and porosity of foam materials examined in this study. Standard deviation is shown as error bars

it was not possible to obtain HD CMF foam in this study to compare with ENR (HD) foam. As mentioned above, for sound insulation applications, the material should be able to reduce noise by at least 10 dB. For building acoustic applications, a frequency range of 160 Hz to 3150 Hz is generally investigated, because it covers the range from speech tones to traffic noise [46]. Figure 8 shows that the STL value of 20 mm ENR (HD) foam is higher than 10 dB throughout the frequency range, indicating that it meets the specifications for acoustic applications in buildings.

Figure 9 shows the SAC measurements as a function of frequency in latex foam samples with a thickness of 20 mm for the different foam densities. It reveals that, in the low frequency range (160–1800 Hz), both the LATZ (HD) and DPNR (HD) samples have higher SAC values than the MD and LD samples. According to Chen et al. [39], acoustic resistance has a significant impact on the SAC value in the low-frequency range. Low-frequency sound waves have longer wavelengths than high-frequency sound waves, making them more difficult to absorb. Therefore, increasing the density levels of latex foams could increase the acoustic resistance of the material due to the increase in mass, which is helpful in the absorption of low-frequency sound waves [39]. The same study also suggested that the morphological structures of the foam materials influence the performance of SAC. The results obtained in Fig. 6 indicated that the mean pore size of HD foam is smaller than that of MD and LD foams, and the smaller the pore size, the higher the acoustic resistance. This is consistent with a previous study [34], which found that densely packed foam cell structures increased airflow resistivity, trapping and dissipating sound waves within the foam cell structures. In the high-frequency range (> 1600 Hz), the SAC curve of LATZ (HD) and DPNR (HD) decreased and then increased again. It is also noticeable that the SAC curve of the HD foam tended to fluctuate with increasing frequency. For MD foam, DPNR (MD) shows higher SAC values compared to LATZ (MD), ENR (MD), and CMF foams. Furthermore, the SAC value of DPNR (MD) was observed to be close to 1 in a frequency range of 3000–4000 Hz; this is a critical range that leads to unpleasant sound levels and could cause hearing loss in humans on daily exposure at high amplitudes [12].

The results also suggest that decreasing the density of the foams from HD foam to MD foam improved SAC performance at high frequencies. This is the reverse of what was observed in the STL measurements. According to a previous study [40], at high frequencies, the wavelengths are short and the diameter of the pores has a limited effect. Setaki et al. [5], however, claimed that the macroscale size of pores is generally effective at high frequencies, allowing sound waves to propagate into the foams to dissipate more sound energy. In this study, as indicated in Fig. 6, the lower the density, the larger the pore size. Although decreasing the density of the latex foam from HD to MD improved the SAC performance, further decreasing the density from MD foam to LD foam did not show further improvement, suggesting that this correlation may be limited to certain pore sizes and/or densities.

The noise reduction coefficient (NRC) measurements reported in Table 5 are used to evaluate the sound absorption efficiency of foam materials over a wide acoustic frequency range. An NRC of 0 represents perfect reflection, while an NRC of 1 shows perfect absorption [47]. The NRC value drops as the density of LATZ and DPNR latex foams is reduced from HD to MD to LD. However, no difference in NRC value was observed when the density of the ENR latex foam was decreased from HD to MD. At similar MD levels, ENR latex foam exhibits a higher NRC value, followed by DPNR, LATZ latex foams, and finally CMF foam. The NRCs of LD foams of both LATZ and DPNR latex foam are comparable to those of MD CMF foam.

It can be concluded that the density of latex foam plays a vital role in absorbing the propagation of sound waves. HD

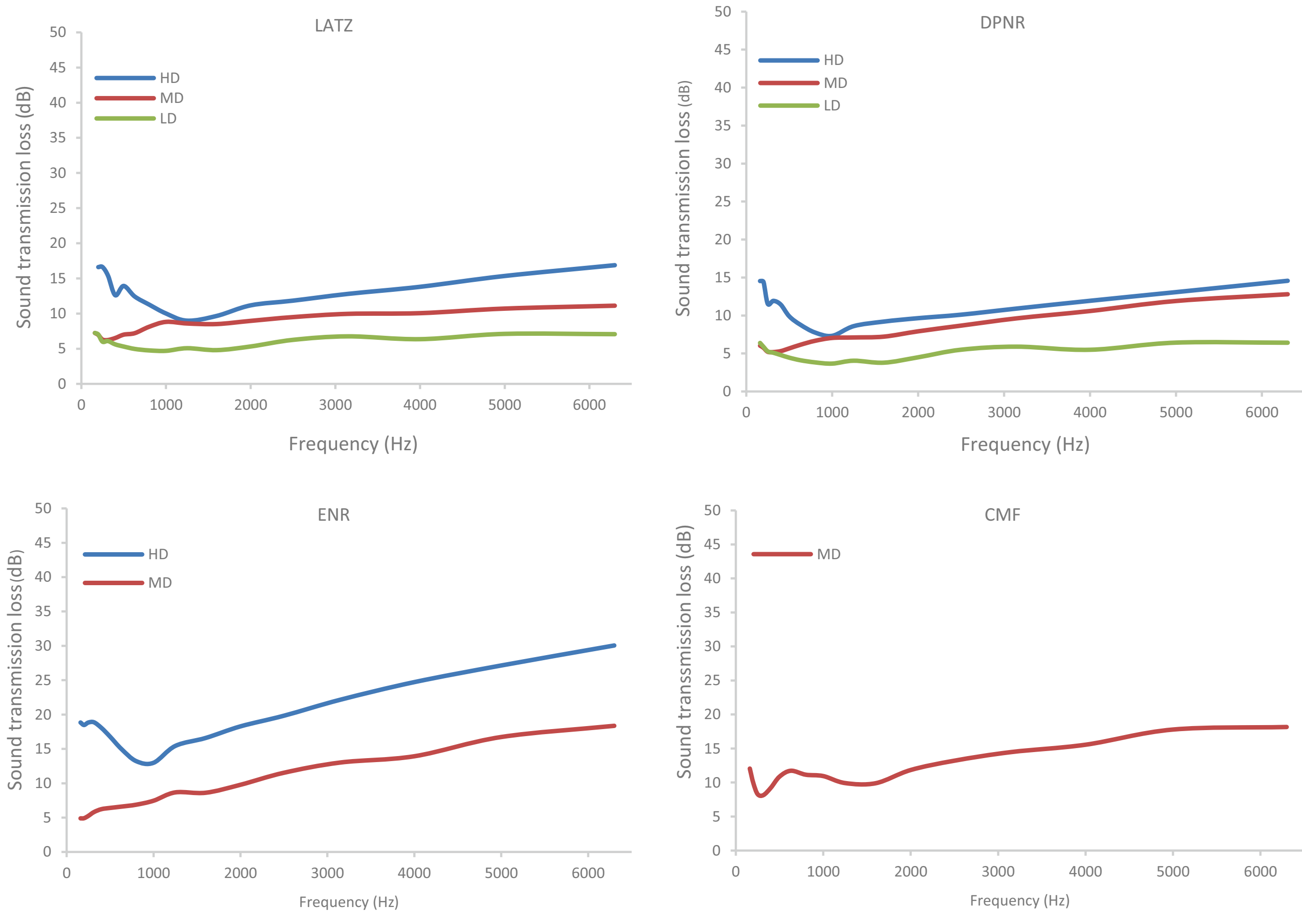

Fig. 8 STL measurements as a function of frequency in 20-mm thick latex foam samples

foam has a higher STL value than MD and LD foams. HD foam shows a higher SAC value compared to MD and LD latex foams in the low frequency range. However, when it comes to the high-frequency range, MD and LD foams show higher SAC values compared to HD foam. This relates to the wavelength of sound waves passing through the material [48]. HD foam shows a higher NRC value than MD foam and LD foam, in a wider acoustic frequency range.

Effect of thickness levels on acoustic properties

In this section, the effects of foam thickness on STL and SAC curves and NRC values were evaluated. Figures 10, 11, 12 show the effect of thickness on the STL curves of HD, MD, and LD foams, respectively. The results indicated that all types of foam material showed an increase in STL when the sample thickness increased from 10 to 20 mm and finally to 40 mm. This is in line with a previous study [51] that found that STL is related to material thickness and provides more absorption or damping of the bass sound. The reason for this is that the low-frequency wavelengths are long, which means that thicker materials have greater opportunities for sound absorption [49, 50]. Figure 10 shows that, for HD foam, the highest STL value was observed in ENR HD latex foam with a thickness of 40 mm, where the sample exhibits a loss of 44 dB at a frequency of 6300 Hz. However, Fig. 11 shows that, for MD foam, CMF exhibits the highest STL value. The increase in STL of CMF when the thickness of the material increases from 20 to 40 mm is quite pronounced and thus could be a reason why many acoustic CMF panels employed in the building and infrastructure industries are 40 mm thick. However, it should be noted that the use of thick material for noise control in some applications, such as automotive vehicle cabins, is not recommended, because it will reduce the capacity of the cabin. There could yet be advantages in selecting ENR (HD) latex foam over CMF foam, since this type of material has a comparable STL but lower thickness. On the other hand, for LATZ and DPNR latex foam, it was quite surprising to see that both MD and LD foams demonstrated only moderate increases in STL curves with increasing thickness.

Figures 13, 14, 15 show the effect of foam thickness levels on the SAC curves of HD, MD, and LD foams, respectively. It is apparent that increasing the thickness of the

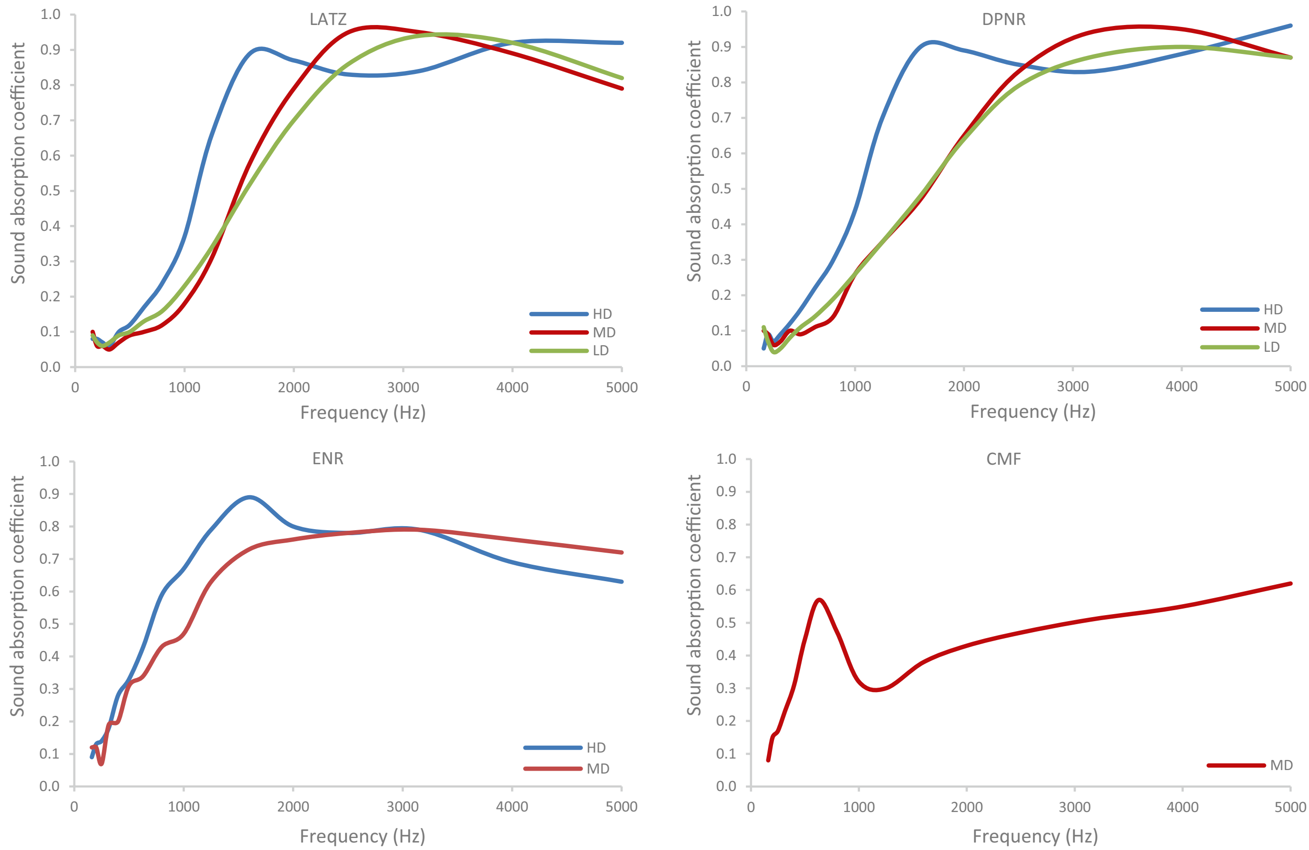

Fig. 9 Measurements of SAC as a function of frequency in 20-mm thick latex foam samples

foam material from 10 to 20 mm to 40 mm broadens the frequency range with a high SAC value, starting at much lower frequencies. It can be observed that for HD and MD foams fabricated at 40 mm, the SAC curves fluctuate as the frequency increased.

The SAC curves initially show a gradual increase until they reach a maximum value, then decrease, before again increasing. This behavior has been explained by Rienstra and Hirschberg [51] in terms of the closer match between the acoustic wavelengths and the thickness of the material. The study suggests that the SAC value has only a direct relationship with the thickness of foam at low frequencies, but is less affected at high frequencies. In the low-frequency range, the higher the thickness, the higher the SAC value. In the LD foam, there was a steady increase in the SAC curve from a low- to high-frequency range at each level of thickness. This could be due to the specific morphological characteristics of the material itself in absorbing and reflecting the energy of sound waves. This is in agreement with previous studies [48–50] that found that the absorption coefficient of a material is influenced not only by the thickness, but also by the configuration of the morphological structure and the frequency of the sound wave that strikes the surface structure of the material. For HD foam, the SAC curve reached a maximum value (the 'peak absorption coefficient') at frequencies of ~ 1200 Hz, ~ 1600 Hz and ~ 1800 Hz for LATZ, DPNR, and ENR latex foam, respectively. Similarly, to HD foam, 40 mm of MD foam shows excellent absorbing capacity in the low frequency range, but then fluctuates somewhat as the frequency increases. At a frequency between 160 and 1250 Hz, the SAC curves of both LATZ (MD) and DPNR (MD) 40 mm thick latex foams steadily increased. However, beyond 1250 Hz, the SAC curves fluctuate between ~ 0.8 and 1 and foam material with an SAC value of 0.8 or higher is classified as a Class A sound absorber [55]. On the other hand, the SAC curves of 10 mm samples of HD and MD foams are mostly increasing steadily and do not show this same fluctuation. In CMF foam, although the SAC curve

Table 5 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

NA not available

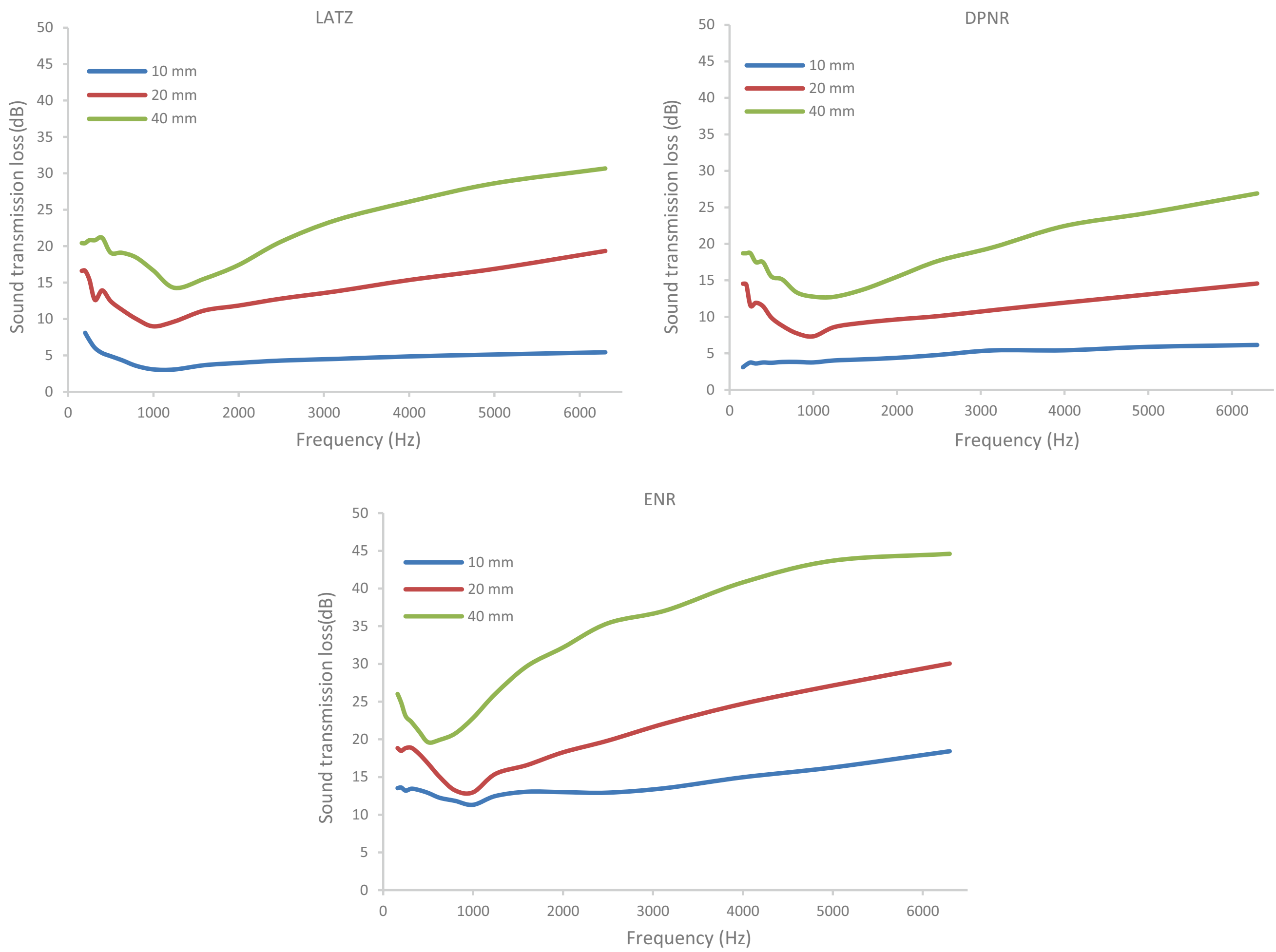

Fig. 10 Effect of thickness levels on STL curve of HD foam

fluctuates slightly, an overall increase in the SAC curve was observed with increasing frequency at each level of thickness. For ENR latex foam, the effect of the thickness of the SAC curve is similar to that observed in LATZ and DPNR latex foams.

To evaluate the acoustic performance of the foam materials, the NRC value was also determined for a range of thicknesses, as shown in Table 6. Increasing the thickness of the foam material from 10 to 20 mm to 40 mm increases the NRC value for all foams and all densities. This is expected, because a higher thickness provides better absorption of the incident wave and reflects less energy [39, 40]. The highest NRC was observed in 40 mm thick DPNR (HD). Table 6 also indicates that, at 40 mm thickness, the NRC value of HD latex foams is consistently higher than that of MD latex foams. A significant effect of thickness could also be observed in MD CMF foam, the standard acoustic foam material. Increasing the thickness of the CMF foam from 10 to 20 mm to 40 mm increases the NRC value by 41% and 130%, respectively. A comparison between CMF foam and latex foams fabricated in this study shows that the performance of all materials developed in this study is comparable to, if not better than, CMF foam. Since latex foams are obtained from natural materials, this could offer environmental advantages in the relevant industries.

Effect of double-layer foam on acoustic properties

A comparison of STL, SAC and NRC values was carried out between single layers of 20 mm foams and double layers of 10 mm foams, to better understand whether the acoustic properties of foams could be further improved by sandwiching together multiple layers of foam, as shown in Figs. 16 and 17. Double-layer foams exhibit higher STL values compared to single-layer foams of the same total thickness. This could be due to the additional presence of skin layers on each foam, which are likely to increase resistance to sound wave transmissibility. A similar pattern was observed in terms of SAC values, particularly in the low frequency range. The presence of a skin layer

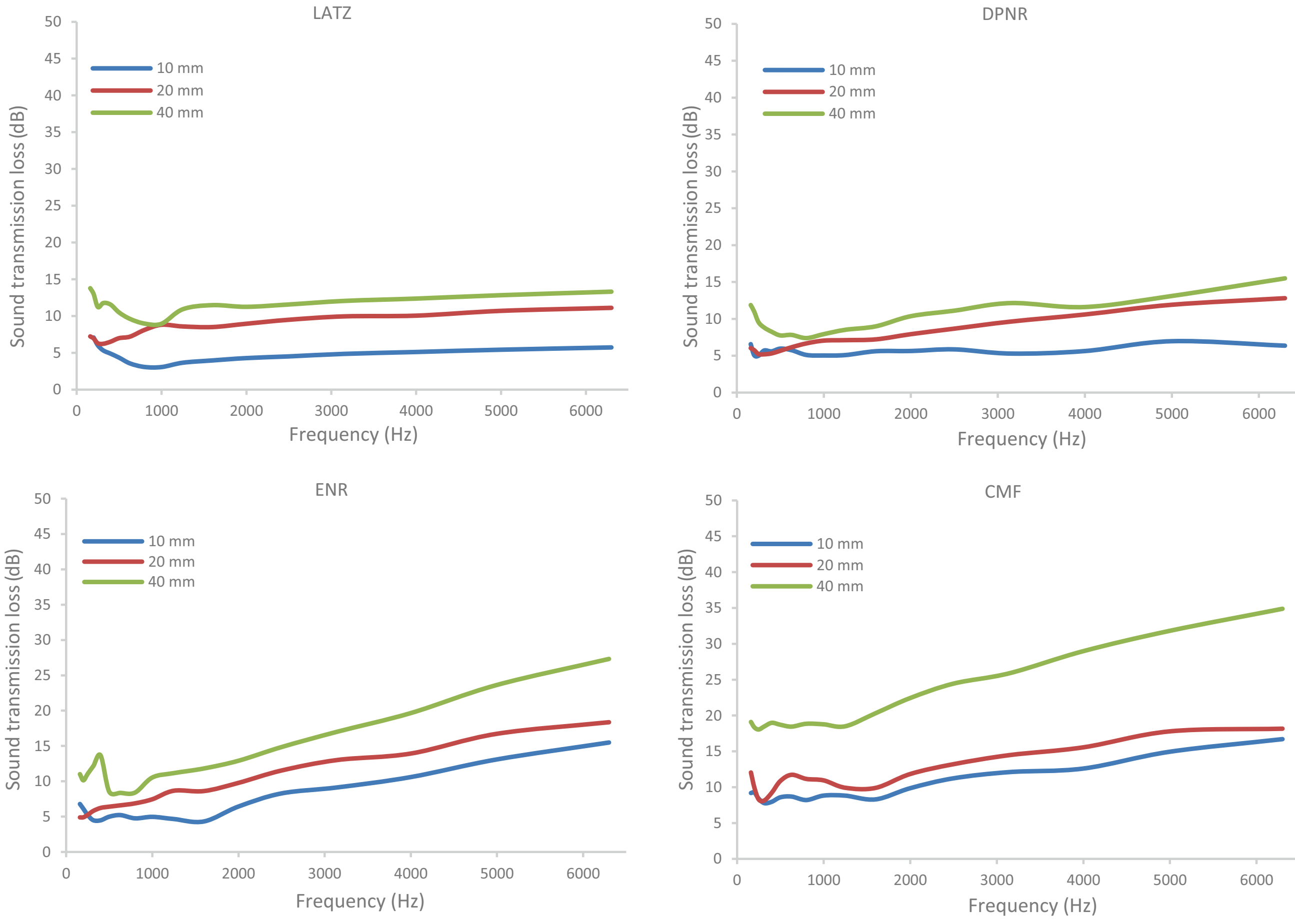

Fig. 11 Effect of thickness levels on STL curve of MD foam

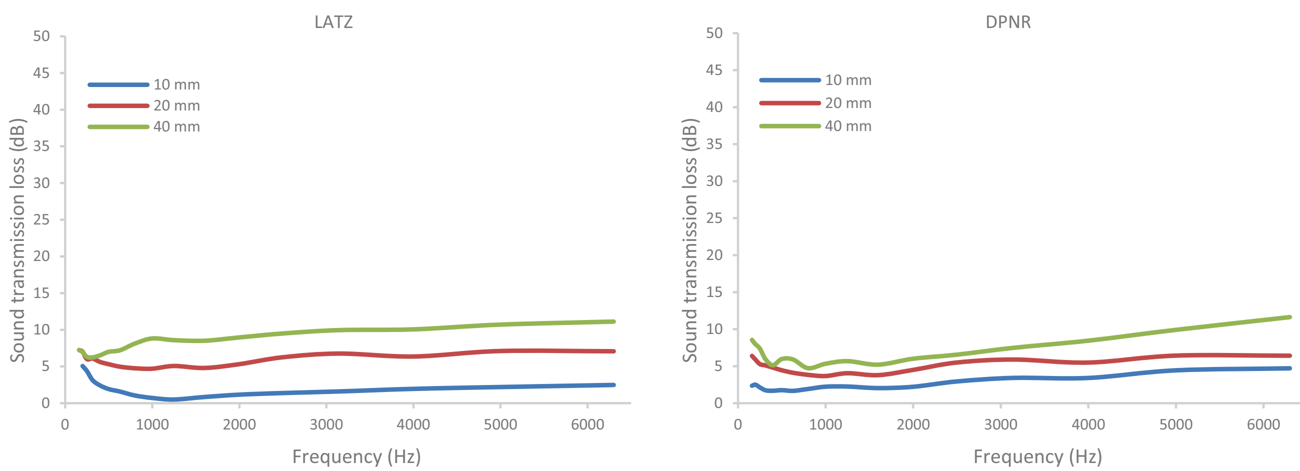

Fig. 12 Effect of thickness levels on the STL curve of LD foam

in the middle of the double layer latex foams is likely to affect the propagation of sound waves, which influences the SAC value at a low frequency range. However, in the high frequency range, the single-layer foams exhibit higher SAC values than the double-layer foams. Table 7 shows that there were no significant differences in NRC values between single-layer and double-layer latex foams of the same total thickness.

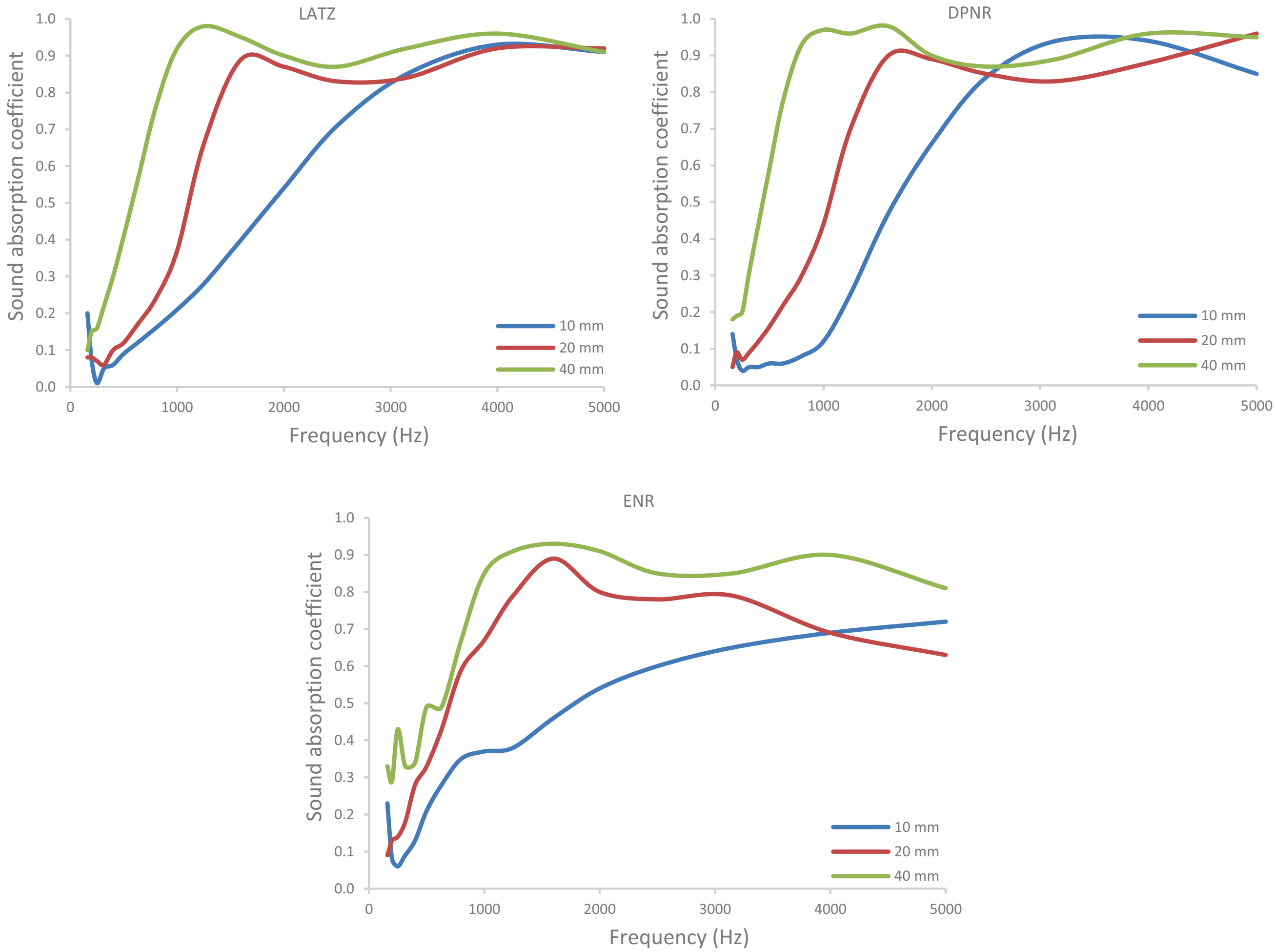

Fig. 13 Effect of thickness levels on the SAC curve of HD foam

Conclusion

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), where the STL reached 44 dB at 6300 Hz with a foam layer 40 mm thick. 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. The NRC measurements revealed that increasing the foam material thickness from 10 to 20 mm to 40 mm increased the NRC for all foams and DPNR (HD) produced the highest NRC value.

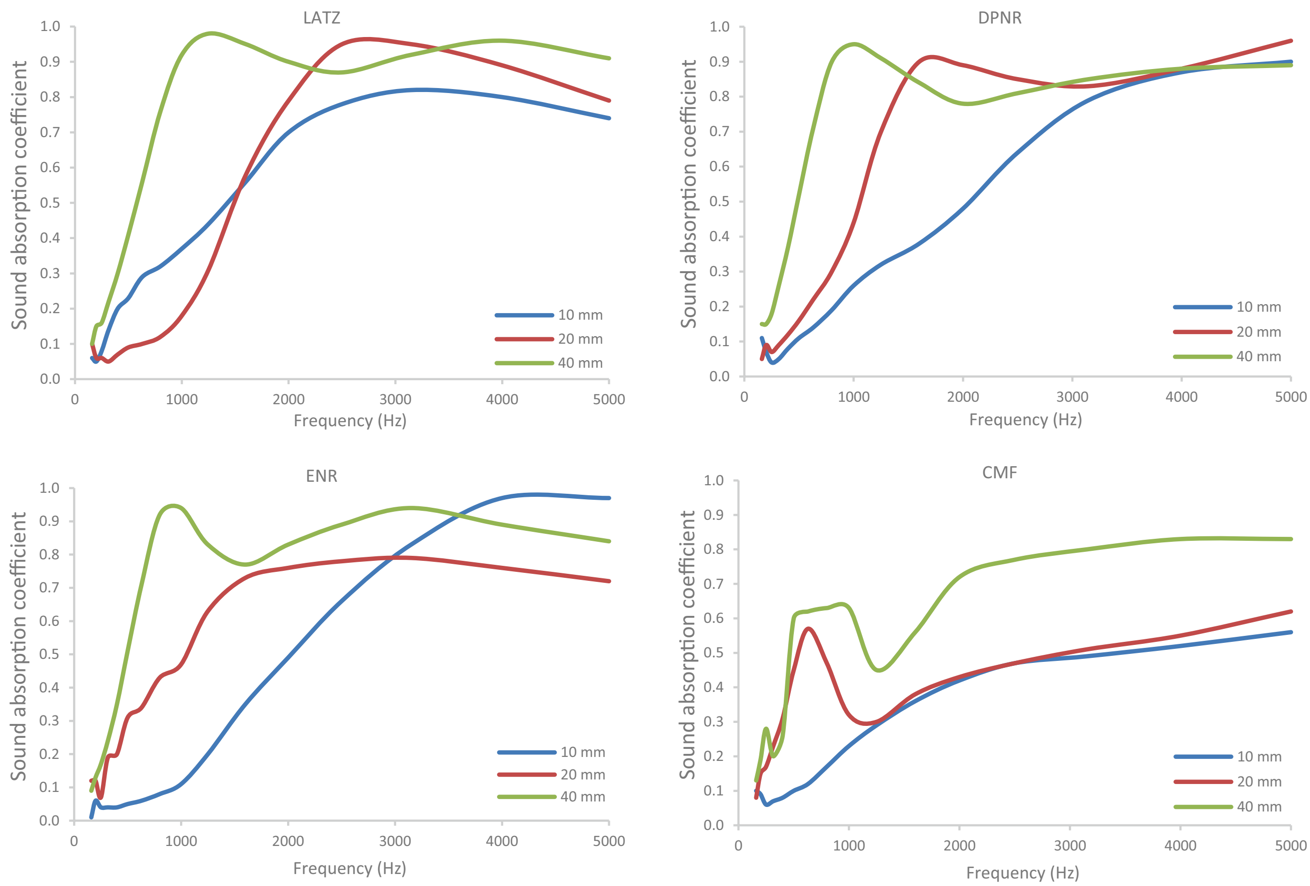

Fig. 14 Effect of thickness levels on the SAC curve of MD foam

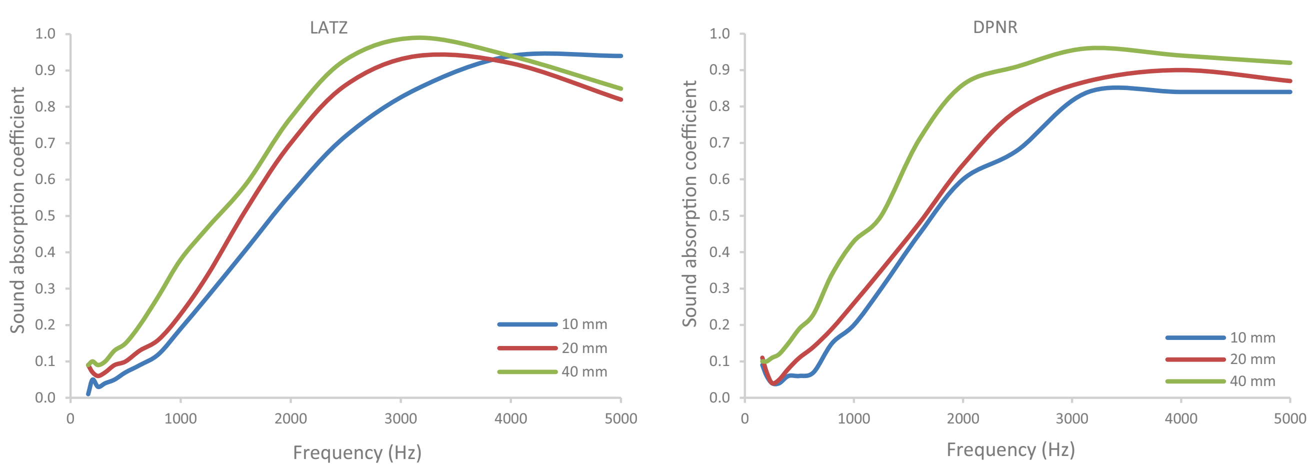

Fig. 15 Effect of thickness levels on the SAC curve of LD foam

Table 6 Effect of foam thickness on the NRC value of latex foams

Thickness (mm)	LATZ			DPNR			ENR		CMF
	HD	MD	LD	HD	MD	LD	HD	MD	MD
10	0.36	0.40	0.35	0.36	0.35	0.34	0.37	0.30	0.27
20	0.47	0.43	0.40	0.49	0.49	0.39	0.49	0.37	0.38
40	0.70	0.65	0.47	0.72	0.66	0.52	0.70	0.64	0.62

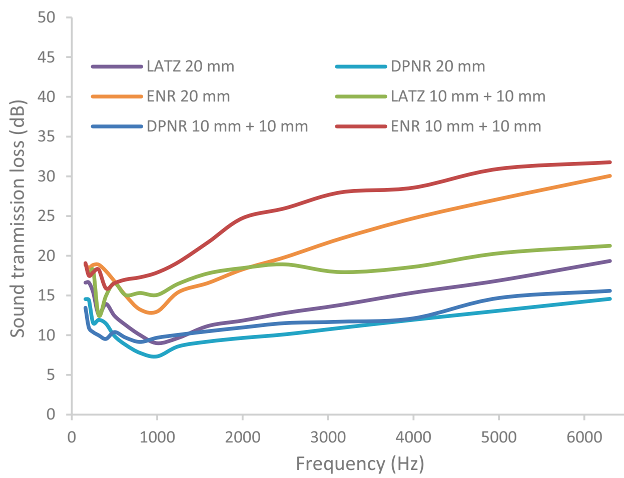

Fig. 16 The effect of sandwiching two layers of foam relative to a single layer of foam of the same total thickness on the STL curve

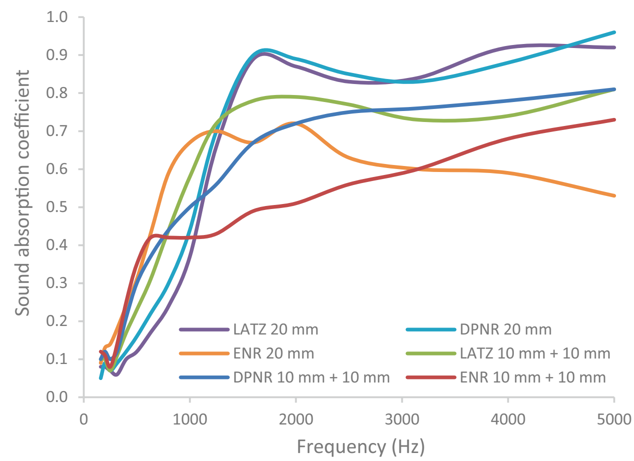

Fig. 17 The effect of sandwiching two layers of foam relative to a single layer of foam of the same total thickness on the SAC curve

Table 7 Effect of the latex foam sandwich layer on the NRC value

	LATZ 10 mm + 10 mm	DPNR 10 mm + 10 mm	ENR 10 mm + 10 mm	LATZ 20 mm	DPNR 20 mm	ENR 20 mm
NRC	0.48	0.48	0.41	0.47	0.49	0.49

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Authors' contribution Conceptualization; [RR, ABC, SK, JHH, FRMR, DDF]; methodology: [RR, ABC, SK, FRMR] formal analysis and investigation: [RR, ABC, SK, JHH, FRMR, DDF]; writing—original draft preparation: [RR, ABC]; writing—review and editing: [RR, ABC, SK, JHH, DDF]; funding acquisition: [RR, ABC, JHH]; resources: [RR, FRMR]; supervision: [ABC, SK, JHH, DDF]. All authors reviewed the results and approved the final version of the manuscript.

Declarations

Conflict of interest The authors declare that there is no conflict of interest with respect to the publication of this article.

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