
The Acoustical Performance of Foamed Material in Reducing Impact Noise and Vibration through Upper Floors during Temperature Rise

Tawfeeq W. MOHAMMED *

*College of Engineering, Mustansiriyah University, Iraq,
tawfeeqwasmi@uomustansiriyah.edu.iq*

Ibrahim A. ATIYAH

*College of Engineering, Mustansiriyah University, Iraq,
ibrahim1980@uomustansiriyah.edu.iq*

* Author to whom correspondence should be addressed

Abstract: - This study aims to express the acoustic performance of the foaming material (polyurethane) as a function of temperature. The aim is to investigate the role of the foam in damping the impact of vibration on the upper floor in a building that occurs in conjunction with the increase in the temperature of an enclosed space. A range of temperatures in a hot arid region is suggested to be 25- 75 °C for an enclosed space. The study analyses the main effective parameters that are involved in determining the noise reduction, such as stiffness and resonance frequency. It has been noticed that there is a significant decrease in the value of the material's stiffness. A decrease of up to 25% at 75 °C can be reached compared to that at room temperature. The decrease in stiffness decreases the corresponding value of the resonance frequency up to 10%. Therefore, the value of noise reduction increases. This increase can reach 3 dB or 7% at a frequency of 500 Hz.

Keywords: - temperature, noise, impact, damping, foam.

1. INTRODUCTION

An impact source, such as those created by footsteps or the moving of an object, sets up vibrations directly on the floor that spread out to the lower parts through construction elements. Hence, floors should be insulated acoustically to reduce impact transmission. There are two principal ways of providing an acceptable finished floor surface or topping by using resilient layers or floating floors. In resilient layers, the concrete floors are layered with vinyl or other rubbery materials. The floating floor is usually wooden tiles or made of some composite materials, and it consists of a slab of rigid material supported by a polymeric pad [1, 2].

The vibrational damping of polymers can be affected by two important parameters: viscoelasticity and glass transition. Viscoelasticity is the property of materials that exhibit behavior intermediate between perfectly viscous (according to Newton's law) and perfectly elastic (according to Hooke's Law). Polymers are typical examples of viscoelastic materials due to their unique structures. Both rubbers and plastics belong to the class of polymers. But they vibrate differently under a certain force. When a rubber is subjected to vibration, it changes into a new conformation and relieves the vibrational energy. The damping of a polymeric sample is maximum at its glass-transition temperature (T_g).

Hence, a polymer is generally selected for damping purposes if its T_g is in the region of the required temperature. On the other hand, the T_g of plastic material is above room temperature. Hence, it is hard and brittle at room temperature. Therefore, it is less efficient in accommodating the vibration energy compared to rubber [3].

Damping strategies that use granular materials to attenuate structural vibrations generally rely on one or two different mechanisms for dissipating energy. For low vibration amplitudes, where particles always remain in contact and do not slip relative to one another, damping depends on the ability to maximize energy dissipation within individual particles. For high amplitudes, it has been sought to use dampers involving low-loss hard particles. However, limited literature is currently available for systems based on larger particles made from materials with significant internal energy dissipation capacity. Polymers are widely used as amplitude-independent damping elements in engineering structures. In general, the properties of polymers, as viscoelastic materials, change with frequency and temperature. Commonly used systems such as free and constrained layer damping for continuous or distributed mass structures are designed to operate in the transition region for optimum effectiveness [4].

The floating floor or the resilient layer can absorb the vibration occurring through the upper side,

depending on the mass-spring system. The frequency of the system dominates the vibrations resulting from the impact; thus, a lower frequency is sought to reduce the noise [5]. The resonance frequency is the main parameter in such systems. Resonance frequency is the natural frequency at which a system vibrates at a certain amplitude, which depends on the density and stiffness of the materials under consideration [6]. The goal is to achieve a resonance frequency less than 100 Hz [7] to ensure better damping, thus higher noise reduction. The reduction can be related mathematically to the resonance frequency, with an average decrease of 30- 40 dB in the noise level [8, 9].

By reviewing the previous literature, it was noted that few studies have addressed the issue of the effect of temperature on the noise resulting from vibration, shock, and impact. However, these studies showed different perspectives and objectives. The temperature may affect the noise level directly or relevant parameters such as the stiffness and corresponding factors. A study investigating the effects of temperature variation on reliable materials used in floating soil systems and dynamic stiffness is provided by Kim et al. (2016) [10]. This study used ethylene vinyl acetate (EVA) and expanded polystyrene (EPS) as damping materials. Dynamic stiffness was measured at three temperatures. The collected results showed that as the temperature increased, dynamic stiffness decreased by 35% for EVA and 20% for EPS. The work extended to measure the temperature changes on impact sound levels associated with building concrete slabs. The impact sound level on the floor tends to increase in winter and decrease in summer. Depending on the season, performance differences of 5 dB or more may occur. Yang et al. (2019) [11] examined the effect of indoor temperature on the perception of floor impact sounds in the room. This test received several combinations of three internal temperatures (20, 25, 30 °C), three background noise levels (35, 40, 45 dB), and four modes of impact sounds (walking, running, jumping, and stool movement). An increase in noise was observed with increased room temperature and increased background noise levels. However, indoor temperatures were not the dominant factors that contributed to the impact on noise levels. The impact noise in the floor was strongly influenced by background noise levels and impact sounds. The study proposed further investigation to combine and fully understand the recognition of these parameters. Liu et al. (2021) [12] proposed a new porous structure of the material to improve the absorption performance of acoustic energy at high temperatures (up to 500°C) and low

frequency ranges (100–2000 Hz). Theoretically, the model was determined by the assumption of the porosity relationship of the intermediate layer, and then uniformity was applied to the entire structure formed by comparable integrals and a porous matrix. Temperature-dependent air and material parameters are considered in the model and resolved by the finite element method. In general, improvements in acoustic energy absorption performance at very low frequencies and high temperatures have been found. At room temperature, the sound absorption coefficient was about 0.98 at a frequency of 270 Hz. At 100°C, the maximum coefficient position is shifted to 320 Hz. At 300°C, the peak is shifted to 390 Hz, while it is shifted to 410 Hz at 500°C. When the temperature rises, the peak position moves slightly to a higher frequency, but the peak value always remains close to 0.98. This is due to the improved acoustic performance value being affected by the surface impedance of the structure.

The aim of the current study is to investigate the effect of ambient temperature in an enclosed space on the performance of the damping material (polyurethane foam), which is expressed by the impact noise reduction. This investigation is required when the temperature increases to a certain level in hot climate areas, which may have some effects on the performance of the damping material. Take into consideration that only a few studies have involved the role of temperature on resultant noise reduction from the shock and impact in the building.

2. MATERIALS AND METHODS

The noise reduction through the upper floor mainly depends on two important parameters: the specific mass of the floor (m) in kg/m^2 and the specific stiffness of the layer (s) in MN/m^3 [13]. Since the mass is fixed within the floors, it is reasonable to assume that the specific mass is unchanged with the temperature rise. Therefore, the dynamic stiffness is the dominant factor, which changes considerably with temperature. The dynamic stiffness of the layered material due to the applied load is given by [14];

$$S_m = \frac{E}{L} \quad (1)$$

where; E is the modulus of elasticity of the material used for the layer (MN/m^2). And L is the thickness of the layer (m).

As the temperature increases, polymeric material becomes more flexible and less stiff. Therefore, the modulus of elasticity typically decreases [14]. The elastic modulus is related to the temperature (T) inversely, as follows [15];

$$E \propto \frac{1}{T} \quad (2)$$

But it is used to represent this relation by a linear formula [16]. A suitable relation can be expressed as follows [17];

$$E = E_i(1.36 - 0.022 T + 4.24 \times 10^{-4} T^2 - 3.19 \times 10^{-6} T^3) \quad (3)$$

where E_i is the initial value of the modulus of elasticity at room temperature (RT).

Furthermore, there is an additional stiffness due to the air occupied inside the layer [18], which can be given by [19];

$$s_a = \frac{\gamma P}{\phi L} \quad (4)$$

where; P is the air pressure, which is atmospheric (0.101325 MPa), and γ is the heat capacity ratio of the air. Also, ϕ is the porosity of the layer. The air's heat capacity ratio is a temperature-dependent factor, as given in Table 1 [20];

Table 1. Variation of air's heat capacity ratio [20]

Temperature (°C)	Heat capacity ratio
25	1.400
50	1.398
75	1.396

Moreover, the effect of temperature on the thickness of the layer can be considered as well. The thickness increases with the rise in temperature due to thermal expansion [21]. The formula describing the linear thermal expansion (α) is given by [15];

$$\alpha = \frac{1}{L} \frac{\Delta L}{\Delta T} \quad (5)$$

The change in the thickness (ΔL) during the temperature change (ΔT) is;

$$\Delta L = \alpha L \Delta T \quad (6)$$

Hence, the total stiffness is;

$$s = s_m + s_a \quad (7)$$

The resonance frequency is an important parameter that shows the acoustical performance of the floor, which is designed to be low. This parameter can be lowered by decreasing the dynamic stiffness (s) of the material or increasing the mass of the floor (m) [8]. The resonance frequency (f_o) can be given by [6];

$$f_o = 160 \sqrt{\frac{s}{m}} \quad (8)$$

The ratio between the applicable frequency and the resonance frequency (f/f_o) is related approximately to the noise reduction (NR) in the impact transmission, as follows [8]:

$$NR = 40 \log \frac{f}{f_o} \quad (9)$$

where f is greater than f_o .

Following the current analysis, it is clear that the main parameters affected by the temperature rise are: modulus of elasticity, coefficient of thermal expansion, and air's heat capacity ratio. However, the analysis is limited to the following assumptions:

1. The properties of the material used in the damping of the impact source are listed in Table 2 at room temperature.
2. The layer has a certain thickness of 1 cm.
3. The layer has a porosity between 70-90%.
4. The specific mass of the floor is constant at 200 kg/m² [13].
5. The range of temperature is between the room temperature (25 °C) and the maximum value. Assume the maximum temperature in an upper-floor enclosure can reach up to 75 °C in a hot region [22].
6. Range of frequencies between 100-1500 Hz.

Table 2. Properties of the polyurethane foam under consideration (average values at RT)

Property	Value
Modulus of elasticity (MN/m ²)	0.3 [13]
Coeff. of thermal expansion (1/K)	20x10 ⁻⁵ [23]

Note that the procedure of calculation is listed in Table 3.

Table 3. Procedure of calculation

- Input: $E_i=0.3$, $m=200$, $L=0.01$, $\alpha=20E-5$
- Use T from 25- 75 °C
- Calculate E from Eq. (3)
- Calculate S_m from Eq. (1)
- Use ϕ from 70-90
- Calculate ΔL from Eq. (6)
- Find the final thickness from $L_f = L_i + \Delta L$
- Calculate S_a from Eq. (4)
- Calculate S from Eq. (7)
- Calculate f_o from Eq. (8)
- Use f from 100-1500 Hz
- Calculate NR from Eq. (9)

3. RESULTS AND DISCUSSIONS

The calculation has been done to find the values of many parameters at the selected range of temperatures (25-75 °C). These parameters are: modulus of elasticity, stiffness, resonance frequency, and level of noise reduction. Note that the calculation assumes uniform temperature distribution over the foam (one-dimensional heat direction) and isotropic behaviour which generalizes the physical properties.

The variation of the modulus of elasticity of the damping material with temperature is shown in

Figure 1. It can be seen that there is a significant reduction in the modulus value with the rise in temperature. This explains how the polymer becomes more flexible and less stiff.

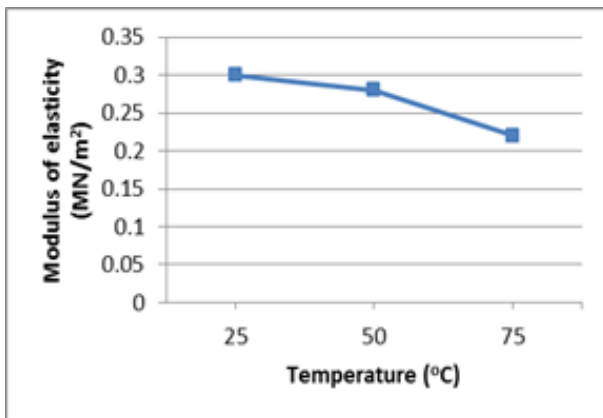


Figure 1. Variation of modulus of elasticity at different temperatures

The decrease in the modulus of elasticity leads to a potential change in the value of the stiffness, as shown in Figure 2. A decrease of up to 25% at 75 °C can be reached compared to room temperature. This decrease in the stiffness value has a positive influence on enhancing the acoustic performance of the resilient layer [24].

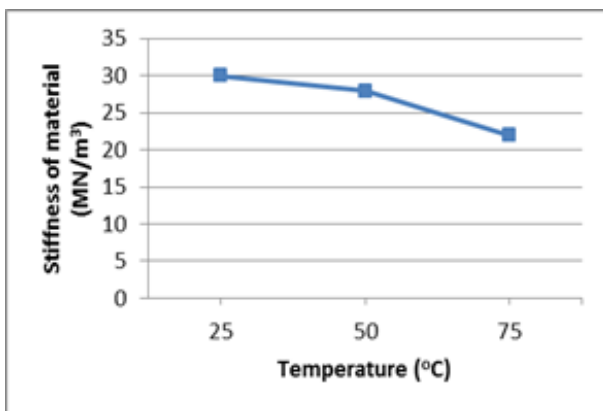


Figure 2. Variation of stiffness of material at different temperatures

The stiffness of the air content within the material does not change significantly with temperature due to the relative stability of air properties within a certain limit. Therefore, the decrease was not significant ($\leq 1\%$), as shown in Figure 3. However, this value is changeable depending on the value of the porosity. Note that temperature fluctuations may affect the density of air, which consequently impacts the transmission of sound. When the air is hotter, it will be less dense, and sound waves cannot travel easily, thus leading to lower levels of noise [25]. However, this

phenomenon has not appeared clearly due to the limited air content within the bulk material.

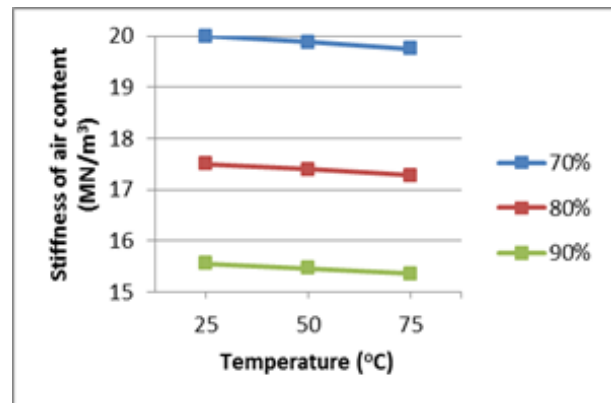


Figure 3. Variation of stiffness of air content at different temperatures and porosities

The total stiffness of the resilient layer at different temperatures can be shown in Figure 4 for several porosities. There is a decrease in the value of the total stiffness by 15-18% at 75 °C comparing to room temperature.

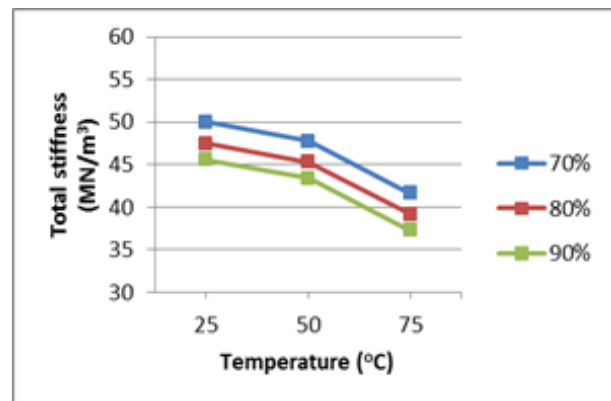


Figure 4. Variation of total stiffness at different temperatures and porosities

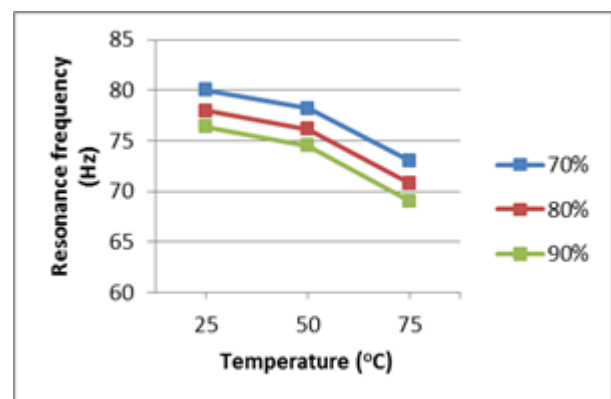
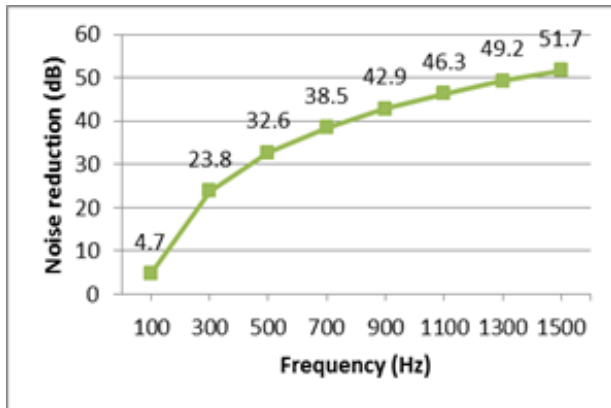


Figure 5. Variation of resonance frequency at different temperatures and porosities

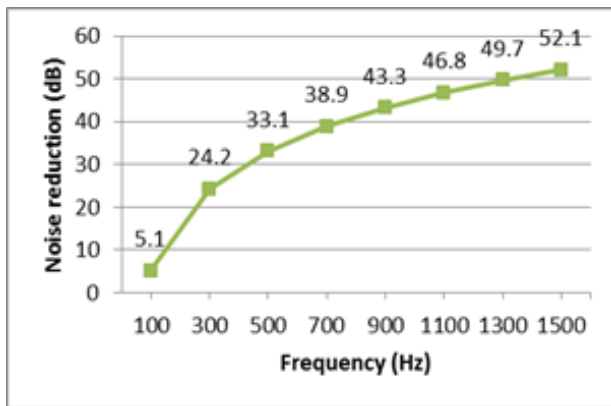
The decrease in stiffness affects the resultant value of the resonance frequency. It leads to a decrease in the range of 8- 10% at 75 °C comparing

to room temperature, as shown in Figure 5. This decrease is desirable to enhance the noise reduction of the damping layer [24].

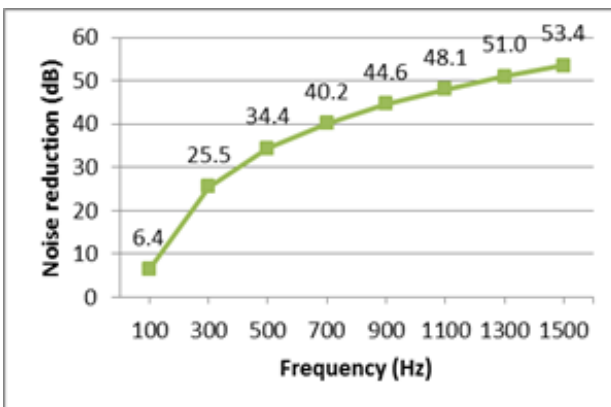
Figures 6-8 show the variation of noise reduction at different frequencies (100-1500 Hz) for the selected temperatures (25, 50 and 75 °C) and for a certain porosity (90%). It can be seen clearly that the noise level decreases as the sound frequency increases. The depression starts at 4 dB at 100 Hz and can reach 53 dB at 1500 Hz.



Figures 6. The variation of noise reduction at different frequencies (T = 25 °C & φ = 90%)

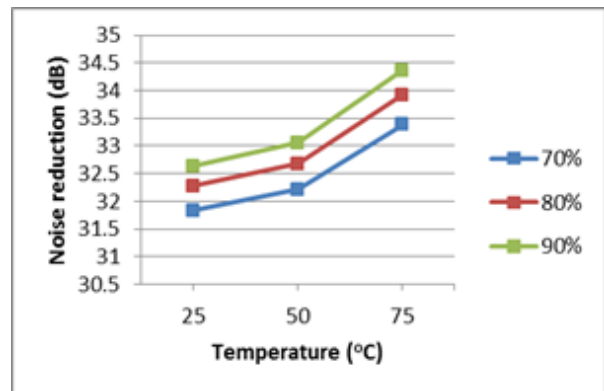


Figures 7. The variation of noise reduction at different frequencies (T = 50 °C & φ = 90%)



Figures 8. The variation of noise reduction at different frequencies (T = 75 °C & φ = 90%)

As a result, when the temperature rises up the value of noise reduction increases. The average increase at 75 °C is in the range of 5- 7% compared to the value at room temperature for a frequency of 500 Hz, as shown in Figure 9. Theoretically, there is an increase in the value of noise reduction by 2-3 dB. Therefore, a correction value is required when the temperature of the ambient exceeds the standard room temperature. Geluykens et al. [26], in their study regarding road traffic noise measurements, have also reported that a correction coefficient is found for the mid- and high-frequency noise ranges. When temperature increases from 5 to 30 °C, a decrease in the sound level of 4- 10% is observed.



Figures 9. The variation of noise reduction at different temperatures and porosities (500 Hz)

The summary of the results at certain frequencies (100, 500 and 1500 Hz) and porosity of 90% can be listed in Table 4. During the temperature rise, it can be observed that the average decrease in the total stiffness is about 18%. The average decrease in the resonance frequency is about 10%. The average increase in noise reduction is about 36% at 100 Hz. The average increase in noise reduction is about 6% at 500 Hz. The average increase in noise reduction is about 3% at 1500 Hz.

Table 4. Summary of the results at selected frequencies

Parameter	25 °C	50 °C	75 °C
Total stiffness (MN/m ³)	45	43	37
Resonance frequency (Hz)	77	75	69
Noise reduction (dB) at:			
100 Hz	4.7	5.1	6.4
500 Hz	32.6	33.1	34.4
1500 Hz	51.7	52.1	53.4

Since the study is entirely theoretical, a comparison is required for the purpose of validation.

The limited experimental data extracted from published works enhances the credibility of the current work. Table 5 shows a comparison between the general results of the current study and those obtained from measured data of some sources. The overall results have similar behavior and reveal an approximately close range of values.

Table 5. Comparison with experimental data

Ref.	Description	Range of Temp. (°C)	Average values	Results
Current work	PU foam in hot arid region (10 mm layer)	25-75	- S=35-50 MN/m ³ - NR=30-40 dB	- Change in S by 20%. - Change in NR by 7%.
[10]	EPS foam in cold region (20 mm layer)	0-25	- S=15-20 MN/m ³ - NR=25-30 dB	- Change in S by 25%. - Change in NR by 5%.
[11]	Measurements are according to acoustical judgment.	20-30	- S=N/A - NR=N/A	- Change in noise level by 15%.

4. CONCLUSIONS

The work investigated the behavior of polyurethane foam in reducing the impact noise through the upper floor during a theoretical temperature rise. The calculation included the effect of temperature on the values of some parameters, such as stiffness, resonance frequency, and the value of noise reduction. The results exhibit the following conclusions:

- There is a significant decrease in the value of the material's stiffness up to 25% at 75 °C compared to that at room temperature.
- The stiffness of the air content within the material does not vary significantly with temperature due to the stability of air properties.
- The decrease in the value of the total stiffness can reach up to 18% at 75 °C compared to RT.
- The decrease in stiffness decreases the resultant value of the resonance frequency in the range of 8- 10% at 75 °C compared to RT.
- As the temperature rises, the value of noise reduction increases. The average increase at 75 °C can reach 3 dB (about 7%) compared to RT (for a frequency of 500 Hz).
- The reduction in the impact noise can be enhanced further at higher frequencies.

The work has some limitations due to many assumptions about material uniformity, properties, and stability in indoor conditions. The lack of experimental validation can be recognized as a limitation. Even though the study is primarily theoretical, it included a comparison with available experimental data from published sources. This comparison supports the validity of the proposed trends.

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