Experimental Study on Vibration Transmissibility of Pre-loaded XPE and PE Packaging Cushioning Material

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Most of the shipped products are sensitive against shock and vibration events during the distribution. Various cushioning materials are usually used to prevent the product damages. During the design process the protective packaging system is developed by the engineers based on the cushion and vibration transmissibility features (ie. cushion curve) of the material used. However, after the assembly of the packaged-product, these are stored for various long periods in warehouse. During this time the products pre-load the cushioning material and its parameters can be changed. The main goal of this study is to evaluate the vibration transmissibility of PE and XPE cushioning material at varied storage (pre-loaded) time and static load conditions. Four different kinds of duration (1 hour, 10 hours, 100 hours and 1000 hours) were used for the pre-loading period at three different static loads (3.488 kPa, 4.651 kPa, and 6.976 kPa), and then at 0.5 oct/min sine sweep vibration the peak frequencies of response and vibration transmissibility, and damping ratio were determined. The results show that the effect of pre-loading is minimal by PE material, but can influence the resonance frequencies by XPE cushioning material. The findings of this study help the packaging engineers to understand better the mechanism of these cushioning materials and to design suitable protective packaging systems.

Keywords): *pre-loading, XPE (cross-linked polyethylene); PE (polyethylene); packaging; vibration transmissibility*

1. INTRODUCTION

Vibration and shock may cause significant product damage during shipping of packaged products. Pac–kaging systems are designed and developed to reduce and avoid these hazards. One of the primary hazards is the resonance, which has the potential to damage the product or the critical elements of the product due to the repetitive application of impacts. Therefore, the com–plete understanding of the shipping environment and the response of the cushioning material to this environment is required.

In general, the cushioning material in any packaging system gives a necessary isolation between the pac–kaged item and the container. This can be modelled as a critical element attached to the product by a spring and a damper (Figure 1a and 1b). This protection element in the packaging system is known as a package cushion and usually is applied using plastic foams [1,2]. The usual packaging material is for cushioning a kind of lightweight, inexpensive material and holds a high strength-to-weight ratio and stiffness-to-weight ratio that has favourable cushioning characteristics and vibration transmissibility. These materials usually are plastic foam and paper packaging and have been widely applied in secondary (master) and tertiary (trans–portation) packaging to protect products such as medical or electronic devices and instruments, or fragile products, etc. [3–5]. Foams are also applied by other industries; these materials have significant effect on the ride comfort in the vehicle seats [6-9].
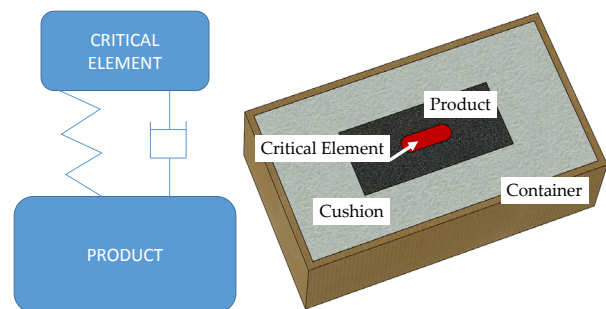

Figure 1a, b. The conceptual structure of packaging system using cushion material

After the packing process, the packaged-product is usually stored for a while before it will be shipped to the temporary or final destination. During this storage the mechanical properties of the cushion material can be influenced due to the static load of the product.

Previous research on PE materials cushioning characteristics focused mainly on the shock absorption properties [10], compression stress properties [11], and determining stress-energy based cushion curves [11-14]. Ref 14 and ref 15 also observed the temperature effect on the vibration transmissibility properties.Two research studied vibration transmissibility for packaging cushion

using sine sweep, but not for PE foams, instead it used experimental paperboard materials [3, 16].The mecha–nical properties of cushion material were evaluated in both static and impact loading conditions by several authors [17-19]. The resonance behavior of cushioning materials was studied and mathematical models were developed by Parker and Batt [20, 21].

However, the authors of this paper could not find any published laboratory cushioning research that mea–sures and analyzes the vibration transmissibility and damping ratios of PE or XPE for packaging cushion with various pre-loading conditions. Therefore, this pa–per presents new measured and analyzed data that can help packaging engineers to gain a better understanding of the characteristics of these materials and for desig–ning appropriate protective packaging for sensitive goods.

The final goal of this study is to present the effect of pre-compression or pre-loading on cushioning features of foams to the critical frequency bands and damping ratios of PE and XPE cushion materials beside real circumstances as preloading. This paper also analyzes the effect of the pre-compression period and gives relevant information for varied static loads along them. This new data can be a useful technical support for packaging engineers in packaging design.

In the remainder of the paper first an overview of the materials and test methods are presented (Section 2), then the details of pre-compression of the samples are shown, as well as the applied testing equipment and static loads. Methods for determination of vibration transmissibility and estimation of damping ratios are also presented in this section. In Section 3 the results are provided and compared with the result of previous studies. This section also discusses the implications of the result in the package design process. Section 4 provides concluding remarks and future directions of the study.

2. MATERIALS AND METHOD

2.1 Experimental materials

Two types of PEs and one type of XPE closed-cell foams were used for this study.

Figure 2. Foams used for this study, 1) XPE 30, 2) PE 25 and 3) PE30

Figure 2 shows the samples. The densities of PE foams were 25.25 kg/m^3 (PE25) and 30.12 kg/m^3 (PE30), and with a density of 29.55 kg/m^3 for XPE foam. The samples were cut into blocks with dimensions of 150 mm x 150 mm x 20 mm (length x width x thickness) by Green Packaging Ltd (supplier). The microscope images (N=1x) of the microstructure of the investigated foam materials can be seen in Figure 3.
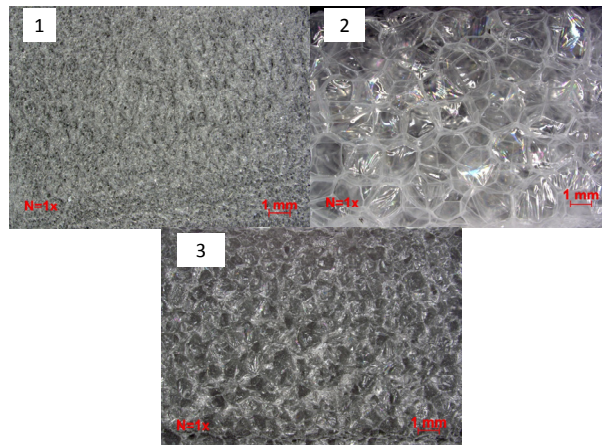

Figure 3. Scanning electron microscope images of the foams of this study, 1) XPE, 2) PE 25 and 3) PE 30

2.2 Method for pre-loading

Before each test, the test samples were pre-compressed for 1, 10, 100 and 1000 hours with different static loads at 20 temperature and this temperature condition was maintained during the entire measurement process. The static loads were 3.488 kPa, 4.651 kPa, and 6.976 kPa by weighted concrete mass blocks. The blocks were placed to the top of the foam and then a fixture was clamped to hold the static load in the required centered position. The same static load was maintained during the vibration test.

2.3 Method for vibration transmissiblity

The theory of vibration transmissibility for cushioning material of packages is generally described as the ratio of the force transmitted to the force applied at different static loads [22]. Transmissibility is a non-dimension ratio of output to input vibration of the packaged product.

Figure 4 shows the test system of this measurement containing a TIRA TV59355AIT electrodynamic vibra–tion tester, a VR 9500 vibration testing controller and an acquisition system with a software VibrationView for the processing of the measurement. During the measurements one acceleration sensor controlled the excitation input at the platform of the vibration head expander, and another sensor was attached to the mass block to measure the response acceleration.

The details of the vibration test setup for all measurements was sine sweep at 0.5 oct/min with an amplitude of 0.5g (zero-to-peak). The frequency range was 3 to 300 Hz by fitting to the most common test standards for transportation simulation of goods, because the most common and relative high amplitude vibration can be found at this frequency band.

The measured acceleration data were analyzed and presented in the form of vibration transmissibility and frequency curve. Then, after the series of tests, the vibration transmissibility and frequency curves at different static loads were evaluated. The numerical results for resonance frequency bands, and their values, are naturally reported for this study.
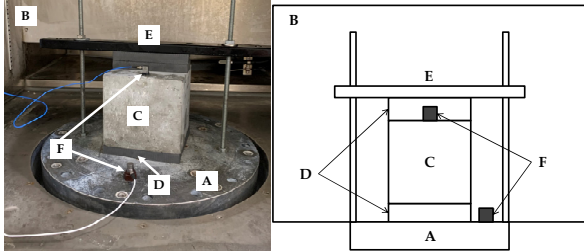

Figure 4. The measurement system used in this study (a) vibration system, (b) climate chamber, (c) concrete block, (d) test specimen, (e) fixtures and (f) acceleration sensors

2.4 Method for estimation of damping ratio

The transmissibility value (T_r) for a linear spring-mass system with single degree of freedom system with viscous damping may be calculated from the following equation using Fourier transform of equation of motion [23].

$$T_r = \sqrt{\frac{1 + \left[2\xi \left(\frac{f_f}{f_n} \right) \right]^2}{\left[1 - \left(\frac{f_f}{f_n} \right)^2 \right] + \left[2\xi \left(\frac{f_f}{f_n} \right) \right]^2}} \qquad (1)$$

where f_f is the forcing frequency [Hz], f_n is the natural frequency [Hz] and ξ is the damping ratio. When $f_f \cong f_n$ the damping ratio can be estimated from Equation (1) [24]

$$\xi = \frac{1}{2} \times \sqrt{\frac{1}{T_r^2 - 1}} \qquad (2)$$

When $T_r \gg 1$ the damping ratio can be estimated from Equation (2) [24]

$$\xi \cong \frac{1}{2T_r} \qquad (3)$$

As a summary of this section, the evaluation of the effects of pre-compression on vibration transmissibility is the following.

1. Preparation of samples and mass blocks (size, weight, number)
2. Pre-compression of samples (static load, time)
3. Assembly of test measurement system (fixture, static stress)
4. Parameter setting for vibration measurement (fre–quency band; sweep rate; amplitude; frequency range;
5. Calculation and analysis of measured result (applied equations; units).

3. RESULTS AND DISCUSSION

3.1 Experimental results

On the pre-compressed cushion materials according to the test method defined in Section 2, the sine sweep tests were performed. Frequency ranges and vibration transmissibilities were measured from vibration tests directly. Vibration transmissibility and frequency curves of the tested cushion materials are shown in Figure 5-7. The curves with different pre-loading duration of PE 25 at static loads 3,488 kPa, 4,651 kPa and 6.976 kPa can be see in Figure 5. Figure 6 and 7 provide the same for PE30 and for XPE materials.

The damping ratios were calculated from the experimental data by Equation (2) and Equation (3). Both experimental and calculated values can be seen in Table 1 to Table 3. Each table separately provides the experimental results of PE25, PE 30 and XPE cushion materials at different temperatures and at different static loads such as 3.488 kPa, 4.651 kPa, and 6.976 kPa.

3.2 Findings from the Experimental Results

By comparing and analyzing the experimental results of vibration transmissibility and frequency curves of the pre-loaded PE25, PE30 and XPE cushion materials at different static loads the following observations may be discussed.

a) The result of PE25 and PE30 show a minimal influence of the duration of pre-compression to the transmissibility plots. The maximum changes of the resonant frequency were 10% at all static loads. The effect of pre-loading of XPE shows a stronger influence when compared with PE25 and PE30. The resonant frequency values were between 80.9064 Hz and 94.6497 Hz at 3.488 kPa, moved from 61.3398 Hz to 79.4268 Hz at 4.651 kPa and changed from 46.078 Hz to 58.0356 Hz at 6.976 kPa.

b) The duration of static load does not influence the effect of the static loads value. When the value of the static load is increased, the value of the resonant frequency is decreased by all investigated materials at all static loads and at all durations of pre-loading.

c) Over 55 Hz the attenuation zone of PE25 was reached at all pre-loading. This value was 86 Hz and 126 Hz for PE30 and for XPE.

d) 54.9094 Hz was the start point of the attenuation zone of PE25 at 3.488 kPa for pre-loading of 1, 10 and 1000 hours. This value was 51.4743 Hz for pre-loading of 100 hours.

e) XPE has the same resonant frequency value (80.9064 Hz) at 3.488 kPa static load for pre-loading of 10 and 100 hours.

f) The average value of transmissibility was influenced by the duration of the pre-loading only by XPE. The deviation from the average was under 5% of all other materials. The values are summarized in Table 2.

Figure 5. Vibration transmissibility and frequency curve for (a) PE25 at a static load of 3.488 kPa, for (b) PE25 at a static load of 4.651 kPa, for (c) PE25 at a static load of 6.976 kPa

Figure 6. Vibration transmissibility and frequency curve for (a) PE30 at a static load of 3.488 kPa, for (b) PE30 at a static load of 4.651 kPa, for (c) PE30 at a static load of 6.976 kPa
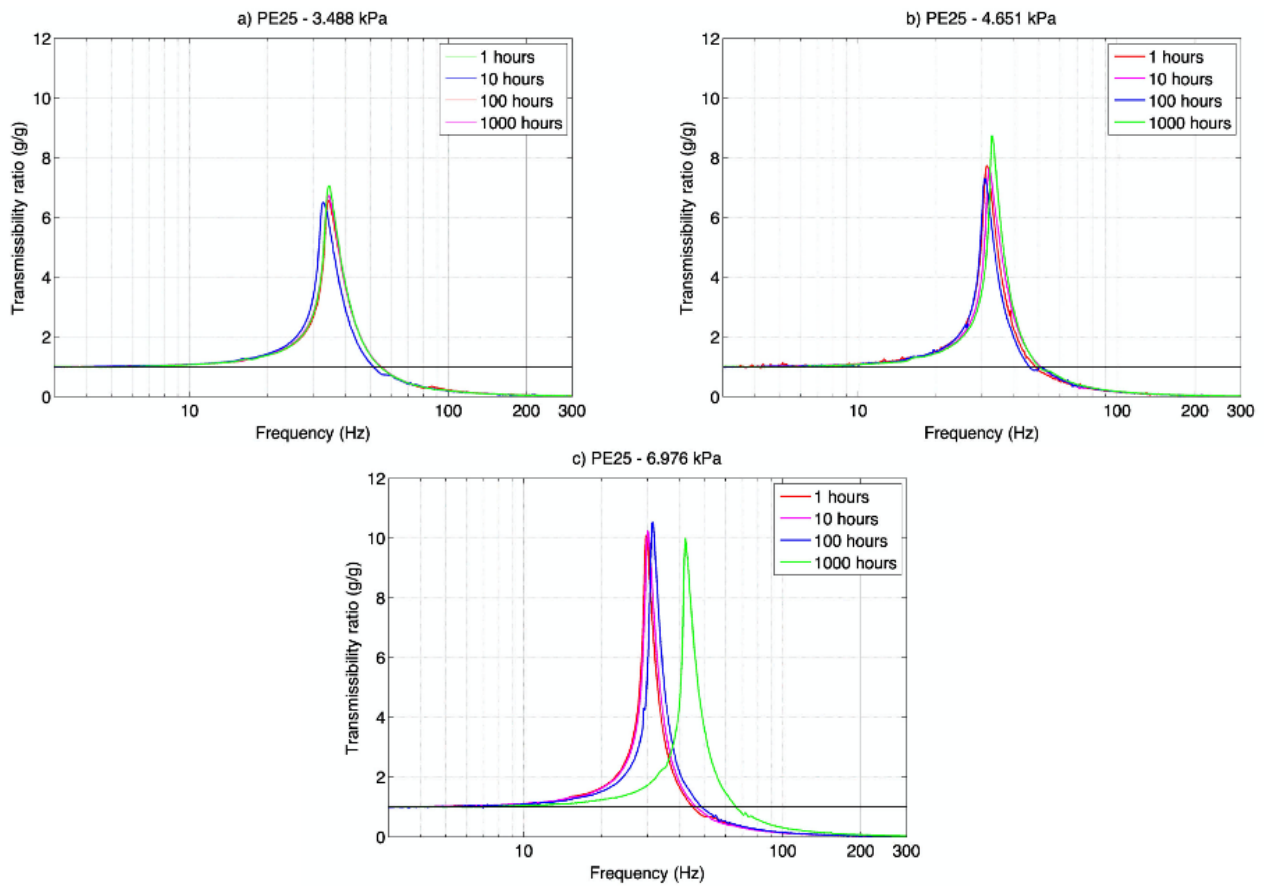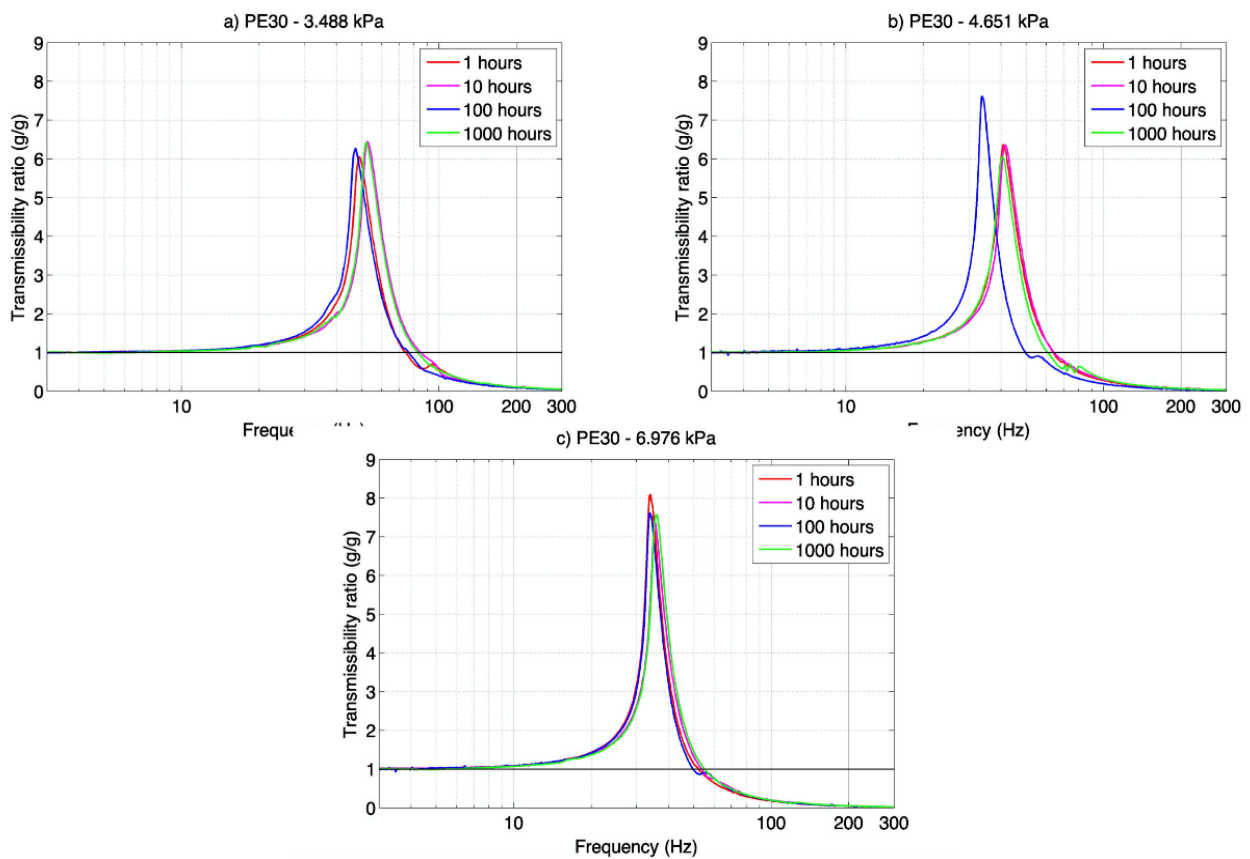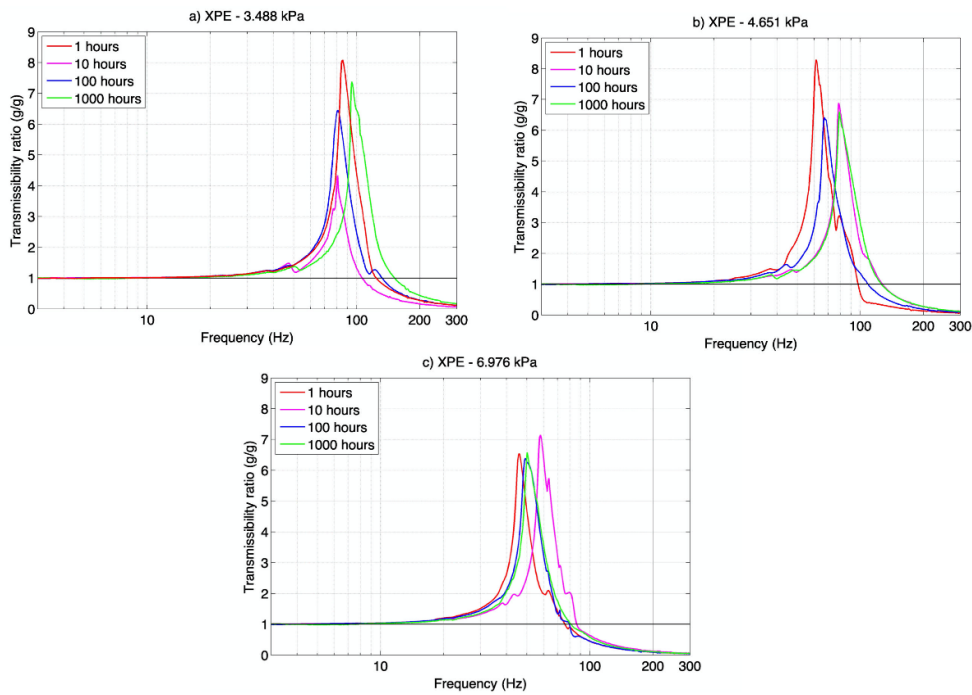
Figure 7. Vibration transmissibility and frequency curve for (a) XPE at a static load of 3.488 kPa, for (b) XPE at a static load of 4.651 kPa, for (c) XPE at a static load of 6.976 kPa

Table 1. Vibration transmissibility and damping ratio of PE25, PE30 and XPE cushion materials

Duration of Static Load [hours]	Static load [kPa]	Frequency Range of PE 25 [Hz]	Transmissibility of PE25	Damping ratio of PE25	Frequency Range of PE30 [Hz]	Trans. of PE30	Damping ratio of PE30	Frequency Range of XPE [Hz]	Trans. of XPE	Damping ratio of XPE
1	3.488	11.5423 34.2955 54.9094	1.1015 6.5726 0.9907	1.0828 0.0761	15.6515 49.153 75.1482	1.1024 6.0573 0.9514	1.0778 0.0825	26.2425 85.5128 124.842	1.1028 8.0871 0.9681	1.0744 0.0618
	4.651	9.9578 31.5621 48.7015	1.1008 7.7097 0.9704	1.0864 0.0649	13.256 40.8686 64.2366	1.1002 6.3715 0.9642	1.0897 0.0785	19.8959 61.3398 98.2090	1.1022 8.2944 0.8719	1.0787 0.0603
	6.976	9.77569 29.5876 45.2354	1.1006 10.0856 0.9537	1.0874 0.0496	10.8202 33.9805 52.4332	1.1009 8.1068 0.9750	1.0859 0.0617	16.5426 46.078 76.5482	1.1023 6.5385 0.9554	1.0784 0.0765
10	3.488	11.3312 34.6135 54.9094	1.1026 6.7413 0.9943	1.0763 0.0742	16.3907 52.9193 85.5128	1.1006 6.4451 0.9800	1.0874 0.0776	28.2533 80.9064 106.715	1.101 4.3367 0.9682	1.0858 0.1153
	4.651	10.7208 32.1500 51.0014	1.1006 7.6240 0.9714	1.0875 0.0656	13.2560 41.6299 64.2366	1.1003 6.3560 0.9980	1.0893 0.0787	25.0591 78.6971 128.3460	1.1010 4.3367 0.9682	1.0858 0.1153
	6.976	9.68588 30.1388 46.5053	1.1004 10.2513 0.9820	1.0886 0.0488	11.0218 35.2583 53.9052	1.1002 7.4006 0.9833	1.0902 0.0676	17.3238 58.0356 87.1058	1.1003 6.8835 0.9608	1.0894 0.0726
100	3.488	11.1240 32.7490 51.4743	1.1005 6.5204 0.9742	1.0884 0.0767	15.5077 47.3716 76.5482	1.1020 6.2766 0.9764	1.0798 0.0797	26.0014 80.9064 133.173	1.1044 6.4616 0.9714	1.0669 0.0774
	4.651	9.9578 30.7002 46.0780	1.1108 7.3106 0.9686	1.0340 0.0684	12.5419 39.3874 61.3398	1.1025 6.1148 0.9950	1.0770 0.0818	19.7132 67.2702 109.71	1.1009 6.4106 0.9493	1.0858 0.0780
	6.976	10.0501 31.5621 48.7015	1.1036 10.5259 0.9845	1.0712 0.0475	10.4281 33.6683 50.0687	1.1002 7.6248 0.9604	1.0897 0.0656	15.6515 49.153 80.1632	1.1002 6.3935 0.9374	1.0899 0.0782
1000	3.488	11.5423 34.6135 54.9094	1.1004 7.0716 0.9714	1.0886 0.0707	17.8102 51.9515 83.1777	1.1017 6.4217 0.9819	1.0817 0.0779	29.0465 94.6497 151.54	1.1022 7.3796 0.9971	1.0789 0.0678
	4.651	11.3312 32.7490 50.0687	1.1061 8.7476 0.9863	1.0575 0.0572	13.3789 40.4932 60.7763	1.1035 6.0509 0.9938	1.0714 0.0826	25.0591 79.4268 125.999	1.1049 6.5957 0.9856	1.0643 0.0758
	6.976	13.8820 42.0159 66.0399	1.1031 10.0053 0.9789	1.0737 0.0500	11.7573 35.9151 55.4184	1.1013 7.5780 0.9718	1.0836 0.0660	17.6466 50.0687 81.6565	1.1012 6.5808 0.9815	1.0841 0.0760

Table 2. Effect of the duration of pre-loading to the transmissibility

Duration of Pre – Loading [h]	Static load [kPa]	Peak Transmissibility of PE25	Average values	Peak Transmissibility of PE30	Average values	Peak Transmissibility of PXPE	Average values
1	3.488	6.5726		6.0573		8.0871	
1	4.651	7.7097	8.1226	6.3715	6.84524	8.2944	7.6400
1	6.976	10.0856		8.1068		6.5385	
10	3.488	6.7413		6.4451		4.3367	
10	4.651	7.6240	8.2055	6.3560	6.733889	6.8835	6.1224
10	6.976	10.2513		7.4006		7.1471	
100	3.488	6.5204		6.2766		6.4616	
100	4.651	7.3106	8.1190	6.1148	6.672063	6.4106	6.4219
100	6.976	10.5260		7.6248		6.3935	
1000	3.488	7.0716		6.4217		7.3796	
1000	4.651	8.7476	8.6082	6.0509	6.683546	6.5957	6.8520
1000	6.976	10.0053		7.5780		6.58084	
			8.2638		6.7337		6.7591

4. CONCLUSIONS

Polyethylene is a widely used material for protective packaging in distribution. This paper provides important properties of cross-linked and non-cross-linked poly–ethylene foam relevant to their application after dif–ferent storage time and offers advice on the cushioning design of packaging through the measured resonant frequencies and the calculated damping ratios. The results show that PE25 and PE30 are less influenced by the duration of pre-loading compared to XPE. Over 86 Hz for non-cross-linked PE and over 126 Hz for cross-linked PE the frequency is in the attenuation zone at all investigated static loads and duration.

The results of this paper provide new information on cushion materials for PE and XPE foams for packaging engineers, which can help obtain optimal packaging solutions that give suitable protection to the products and can reduce the packaging mass used in practice.

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NOMENCLATURE

T_r	Transmissibility value
f_f	Forcing frequency
f_n	Natural frequency

Greek symbols

ξ	Damping ratio

ЕКСПЕРИМЕНТАЛНО ПРОУЧАВАЊЕ ПРЕНОСИВОСТИ ВИБРАЦИЈА ПРИ ПРЕДОПТЕРЕЋЕЊУ XPE И PE МАТЕРИЈАЛА ЗА АМОРТИЗАЦИЈУ И ПАКОВАЊЕ

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Већина производа за транспорт осетљива је на удар и вибрације. Како би се спречило оштећење производа користе се разни материјали за амортизацију удара и вибрација. У процесу пројектовања система за заштиту паковања инжењери користе материјале са карактеристикама амортизације и преносивости вибрација. Међутим, паковани производи остају у складишту краће или дуже време, због чега долази до предоптерећења материјала за амортизацију а тиме и до промене његових параметара. Циљ рада је да се изврши евалуација преносивости вибрација код XPE и PE материјала у различитим условима складиштења (предоптерећења) и статичког оптерећења. Узета су 4 периода трајања предоптерећења (1, 10, 100 и 1000 сати) за три статичка оптерећења (3488, 4651, 6976 кРа) и потом су одређене вршне фреквенције одзива и преносивост вибрација, као и однос пригушења, при 0,5 окт/min синусне вибрације. Резултати показују да је утицај предоптерећења PE материјалом минималан, али да XPE материјал може да има утицаја на резонантне фреквенције. Налази истраживања су од помоћи инжењерима који се баве проблемом паковања у бољем разумевању механизма наведених материјала и пројектовању адекватних заштитних система паковања производа.