2001

Effects of temperature on vibration transmission properties of cushion materials

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DOI: <https://doi.org/10.31979/etd.w3f3-5mfy>
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**EFFECT OF TEMPERATURE ON VIBRATION TRANSMISSION PROPERTIES OF
CUSHION MATERIALS**

A Thesis

Presented to

**The Faculty of the Departments of Nutrition and Food Science and Marketing/MIS/DS
San Jose State University**

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Jennifer Ann Graham

August 2001

UMI Number: 1405501

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ABSTRACT

EFFECT OF TEMPERATURE ON VIBRATION TRANSMISSION PROPERTIES OF CUSHION MATERIALS

by Jennifer Ann Graham

The purpose of this study was to investigate the effects of temperature on the vibration transmission properties of three of the most commonly used cushion materials to protect fragile products during distribution. It is a continuation of a previous research project where the effect of temperature on the shock absorption properties of the same materials was investigated.

The materials used in this study were expanded polyurethane (EPU), expanded polyethylene (EPE), and expanded polystyrene (EPS) foams. The temperature effects were investigated by testing cushion blocks that had been conditioned at four different temperatures. The tests measured how vibration is transmitted from transport vehicles, through these materials, to the products they cushion. The results showed that the vibration transmission properties of EPU and EPE foams varied more with temperature than EPS foam. This indicates that a cushioned package system that attenuates vibration at one temperature may amplify vibration when the temperature changes.

ACKNOWLEDGMENTS

I would like to express my appreciation to my graduate advisor, Dr. Jorge Marcondes, for his guidance and dedication to help me complete this research. I would also like to thank Mr. Herb Schunenman of Westpak, Inc. for his invaluable support and technical direction throughout this study. Thanks are also extended to Dr. Lucy McProud for her technical reviews and support, and to Dr. Aharon Hibshoosh for his advisement.

Furthermore, I would like to thank my husband, Jim Wise, for the strength, encouragement, and support he gave me throughout my studies at San Jose State University.

I am indebted to Westpak, Inc. for the use of the testing equipment, and to Foam Distributors, Inc. for providing the cushion materials used in this research.

PREFACE

The following is a publication style thesis. The third chapter is written in journal format and will be submitted to the *Test Engineering and Management Journal*. Chapters 1, 2 and 4 are written according to the guidelines outlined in the *Publication Manual of the American Psychological Association*, 4th edition, 1994.

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List of Acronyms and Abbreviations

ASTM = American Society for Testing and Materials

EPE = expanded polyethylene

EPS = expanded polystyrene

EPU = expanded polyurethane

List of Variables

f_1	= frequency boundary between coupling and amplification (Hz)
f_2	= frequency boundary between amplification and attenuation (Hz)
f_n	= natural frequency (Hz)
g	= gravitational acceleration (386.4 in./s ²)
K	= stiffness (lb/in.)
pcf	= pounds per cubic foot
T_g	= glass transition temperature
T_m	= melting point
W	= weight (lb)

CHAPTER 1

INTRODUCTION AND REVIEW OF LITERATURE

Introduction

Damage to goods during distribution is essentially considered an inevitable problem. For most commercial and industrial products, the complete elimination of damage is not a realistic goal since every hazard that packages meet cannot be predicted. For most commercial products, protection is required against the typical hazards encountered, and not against the most severe that might occur on any particular journey (Bakker, 1986).

A cushion is defined as, “anything interposed between one object and another to mitigate the effects of shock and vibration on the first object (Bakker, 1986).” The function of a cushioned package system is to provide a buffer between the product and the hazards of distribution. Without cushioning, most products will experience higher levels of vibration in the distribution environment than they are capable of withstanding (Schueneman, 1993).

Cushioning materials have different mechanical properties based on the material characteristics and cushion geometry. These properties are likely influenced by temperature. However, the effects of temperature on the mechanical properties of most cushioning materials, especially vibration transmission, have not been thoroughly studied (Hatton, 1998). Evidence of the lack of thorough research is the absence of a consensus standard to conduct a vibration evaluation of cushion material and generate transmissibility data.

Blocks of cushioning materials are commonly used in the packaging industry to protect products in the distribution environment. Therefore, this research will focus on three of the most common block cushioning materials and will be restricted to the vibration transmission properties, at various temperatures and static loadings, of these three cushioning materials.

Objectives

The objective of this study was to determine if temperature affects the vibration transmission properties of three of the most widely used cushioning foams. These three types of foams were expanded polyurethane (EPU), expanded polyethylene (EPE), and expanded polystyrene (EPS).

Review of Literature

Preliminary Research

This thesis builds upon, and is a continuation of the project conducted by Kayo Hatton titled, Effect of temperature on shock absorption properties of cushioning materials. Hatton's thesis was used as a reference for the cushion types, and conditioning temperatures.

Hatton investigated the effect of temperature on the shock absorption properties of EPE, EPS, and EPU foams. This was accomplished by shock testing the three types of cushioning blocks at four different temperatures (-17°C, +3°C, +23°C, and +43°C) and five static loadings (Hatton, 1998).

The results indicated that the shock absorption properties of EPE and EPU foams significantly varied with temperature. The EPE foam displayed high transmitted

deceleration with low static loading and high temperature, and less transmitted deceleration at a low temperature. In comparison, the EPU foam transmitted low deceleration shock with low static loading and high temperature, while displaying high transmitted deceleration at low temperature. Conversely, no notable temperature effect was noted when the EPS foam was tested. These effects of temperature on the shock characteristics of foam precluded that vibration characteristics are likely to be affected by temperature as well (Hatton, 1998).

Conditioning

Hatton determined that the three foam materials reached their equilibrium temperature after two hours. This was achieved by using a temperature chamber to condition the samples at the two temperature extremes of -17°C and $+43^{\circ}\text{C}$. The temperature was measured by thermocouples inserted into the foam samples. A reading of the temperature was recorded every 30 minutes for 15 hours (Hatton, 1998).

Vibration

Vibration can be described as a movement or oscillation about a fixed reference point. The number of oscillations per second is reported as Hertz (Hz), and the distance moved about the reference point is the amplitude. Vibration is associated with all transport modes and can be a source of damage. However, each transport mode has its characteristic frequencies and amplitudes (Soroka, 1995).

Vibration damage can be defined by two broad categories. First, damage due to relative motion of one part against another is most commonly observed as scuffing or abrasion. Second, damage due to resonance conditions may be observed as a range of

physical damage. The majority of damage occurs in the frequency ranges of 3 to 30 Hz (Soroka, 1995).

Sinusoidal and random vibration are the two types of vibration inputs utilized for package and product testing. Random vibration is the preferred input for cushion vibration testing. A study conducted by Schueneman and Wong compared the effects of utilizing sinusoidal and random vibration input to collect cushion response data. Their research concluded that sine and random vibration displayed similar results when collecting vibration transmission properties of cushion materials (Schueneman and Wong, 1996).

Resonant response frequencies and peak acceleration at several static loadings displayed nearly identical results for both types of vibration. Random vibration required a significant reduction in the time necessary to capture a vibration response plot as opposed to sine. With random vibration it is possible to collect the resonant response frequency in less than one minute (Schueneman and Wong, 1996).

Consensus Standard

In the protective packaging business, the development of cushion vibration data using the transmissibility plot has been common practice, although no formal standard exists. In the mid-1980's, the ASTM D10 Sub-committee was challenged with the task of creating a standard for collecting cushion vibration data. They were not successful, due to inconsistencies in the data depending on variations in top loading, and have continued to fail at developing a standard test protocol. The only extensively publicized

cushion vibration data is found in MIL Handbooks 304 A and B (Schueneman and Wong, 1996).

Most of the current published data, such as MIL Handbook 304B, were produced using the Fixture Method. The fixture restrains a test block in two axes while allowing it free movement in the vertical axis. A cushion sample is positioned above and below the block and the cushion assembly is attached to the table of a vibration test machine. The vibration characteristics of the cushion materials are determined by subjecting them to random vibration inputs typical of the distribution environment (Soroka, 1995).

CHAPTER 2

DEVELOPING VIBRATION TRANSMISSIBILITY CURVES

In vibration transmission, cushioning materials will alter the level of vibration that is received and transmitted through the material. Depending on the input frequency, cushioning materials will either: transfer vibration at the same level it is received, amplify vibration, or attenuate the input vibration (Marcondes, 1999). These are the three areas of interest in vibration transmission plots and curves.

Transmissibility Plot

In producing a vibration transmissibility plot, a test block is placed on top of a cushion to form a spring-mass system. The resonant frequency of this system is determined by placing it on the table of a vibration test machine programmed with inputs over the frequency range typical of the distribution environment (Bakker, 1986).

The response data collected is expressed in a vibration transmissibility plot. On the vertical axis, the data is displayed as a ratio. The ratio is the response of the vibration level measured from the accelerometer located on the test block, divided by the vibration input response of the table. The ratio is not represented in terms of units; therefore, the data is expressed numerically as an amplification level. The horizontal axis represents the frequency (Hz) band of the vibration input (Wise, 1999). An example of a vibration transmissibility plot is demonstrated in Figure 1.

The three regions of interest in a transmissibility plot are coupling, amplification, and attenuation. Coupling is when the plot reads a value of one on the vertical axis. It is when the mass (or test block) is vibrating at the same intensity level as the vibration

[*Note: static loading for transmissibility plot above]

Figure 1. Transmissibility curve construction

table, which is also referred to as one-to-one. This is an area of little concern (Wise, 1999).

The region of amplification is between the points where the plot rises above one (f_1) and then falls below a value of one. The highest point on this curve identifies the resonant frequency (f_n) of the spring mass system. This represents the frequency where the mass is vibrating at the greatest intensity in relation to the vibration table. This is the greatest area of concern, since it is the range of frequencies that may cause product damage (Wise, 1999).

The third region is attenuation, and it is where the plot drops below a value of one (f_2). At attenuation, the mass is actually moving at a lower intensity than the vibration input; this is considered a desired response (Wise, 1999).

Transmissibility Curve

The information from several transmissibility plots is transferred onto one graph in the form of a transmissibility curve. Each transmissibility plot represents one set of data collected at a specific static loading. Static loading is the ratio between the product weight and the effective cushion area (Marcondes, 1999). The information derived from the individual plots is f_1 , f_n , and f_2 . This information is inserted into the transmissibility curve for each static loading. The points are connected via an intersecting line, which ultimately establishes three curves on the graph. The bottom curve, identified as f_1 , represents the interface between coupling and the beginning of resonance. The middle curve, f_n , represents the peak amplification. Between f_1 and f_n is where the resonance approaches the peak. Above f_n is where the resonance tapers off. The top curve, f_2 ,

represents the interface between the end of resonance and the beginning of attenuation.

The relation between the transmissibility plot and curve is demonstrated in Figure 1.

Designing with Transmissibility Curves

Packaging engineers use cushions in a packaging design not only to provide protection from mechanical shocks, but also to attenuate vibrations of high intensity that result from transport vehicles. This can be accomplished by a cushion system with a resonant frequency that is different from the product. The goal of the design is to have the attenuation zone of the package system in line with the product's amplification zone (Refer to Figure 2). This will result in the package system's ability to attenuate the intensity at the frequencies that cause damage to the product (Wise, 1999).

Transmissibility curves may be utilized when designing or modifying a package system. When utilizing transmissibility curves in design, the bearing area must be used to calculate the static loading. The bearing areas are the places where the cushion is in contact with the product (Marcondes, 1999).

In some cases, cushion manufacturers and suppliers will provide transmissibility curves to designers. Cushioning materials that are intended for use as vibration attenuation devices are recommended to have a transmissibility curve to display their vibration transmission characteristics. However, many cushion manufacturers do not have this information for all of their materials. This is, due in part, to the lack of standards for evaluating vibration transmission of cushioning materials (Marcondes, 1999).

Figure 2. Optimum design for vibration protection

CHAPTER 3

JOURNAL ARTICLE

This article is to be submitted to the

Test Engineering and Management Journal

and, therefore, has a different format from that of Chapters of 1, 2, and 4.

**EFFECT OF TEMPERATURE ON VIBRATION TRANSMISSION PROPERTIES OF
CUSHIONING MATERIALS**

Jennifer A. Graham

ABSTRACT

The purpose of this study was to investigate the effects of temperature on the vibration transmission properties of three of the most commonly used cushioning materials for constructing packages to protect fragile products during distribution. It is a continuation of a previous research project where the effect of temperature on the shock absorption properties of the same cushioning materials was investigated.

The cushioning materials used in this study were expanded polyurethane (EPU), expanded polyethylene (EPE), and expanded polystyrene (EPS) foams. The temperature effects were investigated by testing cushioning blocks that had been conditioned at four different temperatures (-17°C , $+3^{\circ}\text{C}$, $+23^{\circ}\text{C}$, and $+43^{\circ}\text{C}$). The tests were conducted to measure how vibration is transmitted from transport vehicles, through these materials, to the products they cushion.

The results showed that the vibration transmission properties of EPU and EPE foams varied more with temperature than EPS foam. This indicates that a cushioned package system that attenuates vibration at one temperature may amplify vibration when the temperature changes.

INTRODUCTION

Most products will experience higher levels of vibration in the distribution environment than they are capable of withstanding without protection. A protective package system, which normally uses some type of cushion material, provides this protection. Cushion materials are rated according to their ability to provide essential protection in terms of inputs such as shock or vibration. For vibration, the information normally consists of transmissibility curves that describe the spring characteristics of cushion materials when loaded at various static stresses (Schueneman, 1993).

When expanded foam cushion materials are conditioned at different temperatures, they may soften or harden. As a result, the vibration transmission properties are assumed to change. Depending on the structure of each material, there could be a shift in the resonant frequency and the amount of amplification induced by the spring mass system.

The purpose of this paper is to determine whether temperature affects the vibration transmission properties of expanded polyurethane (EPU), expanded polyethylene (EPE), and expanded polystyrene (EPS) foam materials. In addition, it will be determined if there is a correlation between the results of this research and the research conducted by Kayo Hatton.

BACKGROUND

Test Fixture

A compression-compression cushion test apparatus has been shown to display similar results with sine and random vibration inputs (Schueneman, 1993). As described in MIL Handbook 304B, this fixture contains an enclosed free-floating test block. A

cushion sample is positioned above and below the block, and the cushion fixture assembly is attached to the table of a vibration test machine. The fixture restrains a test block in two axes while allowing it free movement in the vertical axis. This eliminates the need for adhesive bonding to the interface between the mass and cushion. The fixture also restricts airflow and offers insulation (MIL-HDBK-304B, 1978).

The vibration characteristics of the cushion materials are determined by subjecting the fixture assembly to random vibration inputs typical of the distribution environment. An area of concern for this test fixture has been the preloading of the top plate onto the top cushion. The problem associated with the preloading did not materialize in the most recent article on the subject (Schueneman and Wong, 1993).

Validation of Test Fixture

The test fixture utilized for this research was the compression-compression model. However, the compression-tension is a more common model that is routinely utilized to capture and record cushion vibration response data. In this model the mass is adhered to the foam and as the mass is excited it initially deflects the cushion in compression. As it bottoms out the mass changes direction and pulls the foam in tension.

Both models were tested side by side in order to validate the compression-compression model against the compression-tension model (Refer to Figure 1). It was noted during this validation that a top static load of approximately 0.1 psi was necessary to achieve consistent results between the two models.

Figure 1. Compression-tension and compression-compression test fixtures

EXPERIMENTAL DESIGN

Materials and Design Overview

The three types of cushioning materials that were used for this study were Crain Industry's expanded polyurethane (EPU, 1.8 pcf) foam, DOW Chemical's expanded polyethylene (EPE: ETHAFOAM 220, 2.2 pcf) foam, and Western Insulfoam's expanded polystyrene (EPS, 1.0 pcf) foam. All samples were cut into 6" x 6" x 2" dimensions by Foam Distributor, Inc (Hayward, CA), and were stored in ambient conditions until they were utilized for the experiment. It should be noted that in order to obtain the higher static loadings, some of the EPE and EPS foam blocks were further reduced in their overall dimensions.

The cushioning materials were conditioned at four different temperatures (-17°C, +3°C, +23°C, +43°C). The static loadings that were utilized differed according to the material type and were chosen in the range where cushion curves displayed low impacts. Following conditioning, the samples were subjected to a vibration transmissibility test. The responses, at different temperatures, were compared to one another.

Conditioning

For the purpose of preliminary testing, the three foam materials were conditioned at the high and low temperature extremes of the proposed temperature levels. This was conducted in order to validate the foams ability to maintain the required temperature range during the data collection process. The two temperature extremes were -17°C and 43°C.

The temperature of the foam materials, as measured by the thermocouple in the center, maintained a constant precise temperature for approximately two minutes after being removed from the temperature chamber.

Vibration

ASTM Designation D3580-95, "Standard Test Methods for Vibration (Vertical Linear Motion) Test of Products," Method B, was utilized for the vibration portion of the testing (ASTM, 1998). Prior to testing, an accelerometer was fixed in the center of the ballast weight inside of the compression-compression test fixture to measure the vibration response of the spring mass system. The weights were then adjusted to obtain desired static loadings of the particular material, and the fixture was fastened to the vibration table.

The vibration test procedure included rapidly placing two conditioned EPU, EPE, or EPS foam blocks into the test fixture. In order to determine the transmissibility data, the two cushion blocks were placed on the top and bottom of a free floating mass (as described in MIL Handbook 304B). The assembly was immediately subjected to a vibration input. The input consisted of a random vibration spectrum covering the frequency band of 1-200 Hz at an intensity level of 0.5 g rms (Refer to Figure 2). The response from the spring mass system was recorded on a transmissibility plot, utilizing a vibration control data acquisition system, within one minute of the vibration input. The data were then collected and used to create a transmissibility curve.

Figure 2. Power spectral density (PSD) control plot

Equipment

The testing was conducted using an Unholtz-Dickie electro-dynamic vibration test machine Model RTS-5, configured with a Data Physics vibration controller Model DP-350. The response was measured with a PCB Model 353B15 piezoelectric accelerometer attached to the mass of the test fixture. A Sunstrand Model 2085 piezoelectric accelerometer was fixed to the table of the vibration test machine.

The testing equipment was in good working order and was recently calibrated using traceable National Institute of Standards and Technology (NIST) standards.

Data Collection

The vibration transmissibility data were transferred onto a spreadsheet and plotted onto a graph to identify trends in the data. Ultimately, this test determined if temperature extremes have a significant effect on the vibration characteristics of the specified foam cushion materials. Specifically, it identified if the resonance response frequency shifts to a higher or lower frequency. The results obtained from the different temperatures were compared to one another for each static loading tested (Bakker, 1986). Refer to Figure 3 for an example of an EPE foam transmissibility plot.

Material: EPE Foam Thickness: 2 Inches
Static Loading: 0.5 psi Temperature: +23°C

$f_1=24\text{Hz}$ $f_n=58\text{Hz}$ $f_2=89\text{Hz}$

Figure 3. Vibration transmissibility plot for EPE

RESULTS

EPU Foam

The EPU foam samples were tested using static loadings of 0.2, 0.3, 0.4, 0.5, and 0.75 psi. The mean natural frequency (f_n) obtained from four replicates, at each static loading, for each respective temperature is summarized in Figure 4.

Figure 4. EPU foam f_n comparison

EPE Foam

Static loadings of 0.5, 0.75, 1.00, and 1.5 psi were used to test the EPE foam samples. The mean f_n was obtained from four replicates, at each static loading, for each respective temperature. The results can be found in Figure 5.

Figure 5. EPE foam f_n comparison

EPS Foam

Calculated static loadings of 0.5, 0.75, 1.00, 1.25, and 1.5 psi were utilized to test the EPS foam samples. The mean f_n was obtained from four replicates, at each static loading, for each respective temperature. The results can be found in Figure 6.

Figure 6. EPS foam f_n comparison

DISCUSSION

It can be observed that temperature had a notable influence on the vibration transmission properties of the EPU and EPE foams, and only a minimal effect on the EPS foam (Refer to figures 4, 5 and 6).

The results indicated that with lower temperatures (-17°C and +3°C) both EPU and EPE foam materials demonstrated higher natural frequencies. With higher temperatures (+23°C and +43°C) the materials exhibited lower natural frequencies. This can be explained by the hardening/softening of the foam materials, as the temperatures were lower/higher. For example, a higher temperature softened the foams, which made them less stiff. The natural frequency of a spring mass system is given by:

$$f_n = (1/2\pi) * (K/W)^{1/2} \quad (1)$$

With a softer foam, the value for K decreases, which lowers the value for f_n in Equation 1. It can be noted that the difference in f_n decreased as the static loading increased. Particularly for EPU foam, the difference is almost non-existent at the highest static loading tested (Refer to figure 7).

For packaging design, for example, this indicates that a package that attenuates vibration at one temperature may amplify vibration when the temperature changes. For instance, in Figure 5, for almost any static loading used in one design the package that amplifies vibration to the maximum (resonance) when the package is at +43°C, will most likely attenuate vibration at -17°C. Attenuation occurs when the frequency is higher than

$1.41 * f_n$ (Marcondes, 1999). For example, at $+43^{\circ}\text{C}$, 1.5 psi: $f_n = 29\text{Hz}$ and attenuation will occur at frequencies higher than $1.41 * 29\text{Hz} = 40.89\text{Hz}$. If the temperature is dropped to -17°C , the frequency of 40.89Hz , (which at $+43^{\circ}\text{C}$ attenuates) will now amplify vibration. If the product has a critical f_n at 41 Hz, damage will occur.

The minimal effect of temperature on the vibration transmission properties of EPS foam was most likely due to its brittle, non-elastic characteristics under the temperature conditions with which the cushioning samples were tested. The approximate T_g of EPS is between the range of $+74^{\circ}\text{C}$ to $+105^{\circ}\text{C}$, which was not reached in the temperature range (-17°C to $+43^{\circ}\text{C}$) that was utilized for this research (Elboudwarej, 1999). If EPS foam is an acceptable material for the package design, and if there is a concern of temperature extremes, it should be utilized in order to have a minimal affect from temperature on the vibration transmission properties of the package system.

Figure 7. Relationship of natural frequency, static loading, and temperature
(Length of arrows indicate the range of resonances between -17°C to 43°C)

COMPARISON TO HATTON'S RESULTS

When the results of Hatton's research were compared to the observations of this study, the EPU and EPS foams displayed similarities. The EPU foam was significantly affected by temperature, and the results of this temperature influence are consistent in both studies. The EPU foam becomes softer at higher temperatures and stiffer at lower temperatures. In Hatton's research, the EPU foam produced lower deceleration levels at higher temperatures. This study showed similar results with lower natural frequencies. The temperature range of -17 to $+43^{\circ}\text{C}$ did not significantly affect the EPS foam; both sets of research support this finding. The results of the EPE foam were similar in each study.

For the EPE foam, Hatton's results display the effect of the overall cushion stiffness on two parameters: the peak acceleration transmitted (which increased) and the static loading for the lowest point on the curve (which decreased). These two trends cannot be viewed separately.

For the lowest point on the EPE foam cushion curve, Hatton's results agreed with the trend found in this study (the material is softer, since the curves move to the left as the temperature increases). Furthermore, a connection can be developed that shows similarities between the two sets of research when one views two curves for two different temperatures at the same static loading; the higher temperatures display lower transmitted peak acceleration (Refer to Figure 8).

Figure 8. Cushion curves for EPE foam at +3°C and +23°C (Hatton, 1998)

CONCLUSION

It was observed that the vibration transmission properties of EPU and EPE foams varied with temperature, whereas EPS foam varied less. This was a predictable change in the material properties that directly correlated to changes in temperature.

When a package system travels through its distribution environment, it will experience changes in temperature. The ability of the cushioning material to protect the product through this cycle is dependent upon its integrity characteristics. From a vibration standpoint, in most cases, higher temperatures do not cause concern to packaging designers because the package f_n decreases. However, package systems shipped in freezing environments can change characteristics and cause damage by shifting the product f_n from the attenuation zone into the amplification zone of the cushion material.

The results from this study determined the vibration transmission characteristics that can be expected at common temperatures found in a typical distribution cycle. Therefore, these results can be utilized as a guide for developing a cushion design or as a validation of protective packaging.

ACKNOWLEDGEMENTS

The author would like to thank Westpak, Inc. of San Jose, CA for the use of their testing equipment and facilities, and Foam Distributors, Inc. of Hayward, CA for providing the cushion materials used in this study.

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CHAPTER 4

SUMMARY AND RECOMMENDATIONS

Summary

This study investigated the effects of temperature on the vibration transmission properties of three of the most common cushioning materials. It is a continuation of a research project conducted by Kayo Hatton on the effect of temperature on shock absorption properties of cushioning materials. The materials that were utilized for this study included Crain Industry's expanded polyurethane (EPU, 1.8 pcf) foam, DOW Chemical's expanded polyethylene (EPE: ETHAFOAM 220, 2.2 pcf) foam, and Western Insulfoam's expanded polystyrene (EPS, 1.0 pcf) foam cushioning blocks. The temperature effects were investigated by testing cushioning blocks that were conditioned at four different temperatures (-17°C, +3°C, +23°C, +43°C) and different static loadings. Following conditioning, the samples were subjected to a vibration transmissibility test.

Prior to testing, an accelerometer was fixed to the bottom of the ballast weight inside of the compression-compression test fixture, as described in MIL Handbook 304B, to measure the vibration response of the spring mass system (Refer to Appendix A). The weights were then adjusted to obtain the desired static loadings of the particular material, and the fixture was fastened to the vibration table.

The vibration test procedure included rapidly placing two conditioned EPU, EPE, or EPS foam blocks into the test fixture. In order to determine the transmissibility data, the two cushion blocks were placed on the top and bottom of a free floating mass. The assembly was then immediately subjected to a vibration input following ASTM

Designation D3580-95, "Standard Test Methods for Vibration (Vertical Linear Motion) Test of Products," Method B. The input consisted of a random vibration spectrum covering the frequency band of 1-200 Hz at an intensity level of 0.5 g rms. The response from the spring mass system was recorded on a transmissibility plot utilizing a vibration control data acquisition system within one minute of the vibration input. The data were then collected and used to create transmissibility curves (Refer to Appendix B).

The results indicated that temperature had a notable influence on the vibration transmission properties of the EPU and EPE foams, and only a minimal effect on the EPS foam. At lower temperatures (-17°C and +3°C) both EPU and EPE foam materials demonstrated higher natural frequencies. With higher temperatures (+23°C and +43°C) the materials exhibited lower natural frequencies. This can be explained by the hardening/softening of the foam materials, as the temperatures were lower/higher.

The minimal effect of temperature on the vibration transmission properties of EPS foam was most likely due its brittle, non-elastic characteristics under the temperature conditions with which the cushioning samples were tested. The glass transition temperature (T_g) of EPS is between the ranges of 74 to 105°C, which was not reached in the temperature range (-17°C to +43°C) that was utilized for this research.

When a package system travels through its distribution environment, it will experience changes in temperature. The ability of the cushioning material to protect the product through this cycle is dependent upon its inherent characteristics. The results from this study determined the vibration transmission characteristics that can be expected at common temperatures found in a typical distribution cycle. Therefore, these results

can be utilized as a guide for developing a cushion design or as a validation of protective packaging.

Recommendations

Temperature extremes in the distribution environment are commonplace. Any given package system has a strong likelihood of experiencing temperatures between -17°C and +43°C. Vibration characteristics for cushioning material are developed at ambient conditions in a laboratory. The effects of temperature on these cushion materials should be taken into consideration.

The results of this research should be considered in designing protective package systems with EPU, EPE, or EPS, especially if the distribution environment has known temperature extremes.

Further studies may be necessary to determine if altitude, and humidity variations have an effect on the transmission properties of foam at various temperatures. In addition, this investigation should be expanded to other types of energy absorption materials, such as cellulose based molded pulp or corrugated cushioning.

The trends observed in this study only apply to the type and densities of the foam that were utilized. Other types and densities of foam may display different behaviors and should also be evaluated.

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APPENDICES

Appendix A

Test Equipment

Figures A.1 to A.3 display the vibration test equipment and cushion test fixture utilized for this research.

Figure A.1: Test equipment diagram

Figure A.2: Test equipment

Figure A.3: Cushion vibration test fixture

Appendix B

Transmissibility Curves

Figures B.1 through B.12 display the transmissibility curves for EPU, EPE, and EPS at the four temperatures (-17°C, +3°C, +23°C, +43°C) utilized in this study.

Figure B.1: EPU Transmissibility Curve (-17°C)

Figure B.2: EPU Transmissibility Curve (+3°C)

Figure B.3: EPU Transmissibility Curve (+23°C)

Figure B.4: EPU Transmissibility Curve (+43°C)

Figure B.5: EPE Transmissibility Curve (-17°C)

Figure B.6: EPE Transmissibility Curve (+3°C)

Figure B.7: EPE Transmissibility Curve (+23°C)

Figure B.8: EPE Transmissibility Curve (+43°C)

Figure B.9: EPS Transmissibility Curve (-17°C)

Figure B.10: EPS Transmissibility Curve (+3°C)

Figure B.11: EPS Transmissibility Curve (+23°C)

Figure B.12: EPS Transmissibility Curve (+43°C)