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Removal torque effects of vibration and fatigue on discontinuous-thread closures

Maryam A. Daghigh
San Jose State University

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REMOVAL TORQUE EFFECTS OF VIBRATION AND FATIGUE ON
DISCONTINUOUS-THREAD CLOSURES

A Thesis

Presented to

The Faculty of the Department of Nutrition and Food Science

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Maryam A. Daghigh

December 2007

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APPROVED FOR THE DEPARTMENT
OF NUTRITION AND FOOD SCIENCE

Lucy McProud, Ph.D., R.D.

Panfilo Belo, Ph.D.

Herbert Schueneman, CPP-MH

APPROVED FOR THE UNIVERSITY

ABSTRACT

REMOVAL TORQUE EFFECTS OF VIBRATION AND FATIGUE ON DISCONTINUOUS-THREAD CLOSURES

Maryam A. Daghigh

This research investigated the effects of random vibration and warehousing on the removal torque of linerless discontinuous thread polymer closures. An application torque level of 12 in-lb was applied to cross linked high-density polyethylene (CL HDPE) and polypropylene (PP) type closures of the same design. Following vibration and warehousing, torque values were measured, and percent torque reduction was calculated and analyzed by t-test at 95% confidence level.

PP closures showed approximately 11.3% greater torque reduction compared to CL HDPE closures. Warehousing duration had a significant effect on removal torque. The average difference in torque loss between the 30 and 90 day warehousing was about 6.9%. Pre and post-warehousing vibration had no significant impact on torque loss. The data confirm that torque reduction is influenced by warehousing and polymer type and that CL HDPE linerless discontinuous thread closure is the better cap material selection on CL HDPE bottles used in the study.

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Preface

This document is a publication style thesis. Chapters 1 and 3 are written according to the style guidelines stated in the Publication Manual of the *American Psychological Association* (5th edition, 2001). The second chapter is written for submission to and according to *Packaging Technology and Science* guidelines.

Table of Contents

	<u>Page</u>
List of Tables.....	ix
List of Figures	x
List of Acronyms, Abbreviations, and Variables	xi
CHAPTER 1:	1
INTRODUCTION AND REVIEW OF LITERATURE	1
INTRODUCTION.....	1
<i>Significance</i>	1
<i>Hypothesis</i>	3
Literature Review	4
CHAPTER 2:	7
JOURNAL ARTICLE.....	7
Author's Title Page	8
ABSTRACT	9
INTRODUCTION.....	10
MATERIALS AND APPARATAUS	12
<i>Test Materials</i>	12
<i>Apparatus</i>	13
PROCEDURE.....	13
<i>Preliminary Experiment Design</i>	14

<i>Main Experiment</i>	15
RESULTS	18
<i>Preliminary Experiment Results</i>	18
<i>Main Experiment Results</i>	20
CONCLUSION	25
REFERENCES	27
CHAPTER 3:	29
SUMMARY AND RECOMMENDATIONS	29
SUMMARY	29
RECOMMENDATIONS	30
REFERENCES	32
APPENDICES	34
APPENDIX A: Application and Removal Torque Data	35
APPENDIX B: Test Equipment	40

List of Tables

	<u>Page</u>
<i>Table 1.</i> Mean and standard deviation (SD) of application and removal torque (Preliminary experiment)	19
<i>Table 2.</i> Mean and standard deviation (SD) of application and removal torque (Vibration first and then warehousing treatment-group 2).....	21
<i>Table 3.</i> Mean and standard deviation (SD) of application and removal torque (Warehousing first and then vibration treatment -group 3).....	21
<i>Table 4.</i> Comparison of samples with 95% confidence limit.....	24
<i>Table 5.</i> Vibration intensity and frequency used.....	29

List of Figures

	<u>Page</u>
<i>Figure 1.</i> Seal created by linerless closure	3
<i>Figure 2.</i> PP and CL HDPE linerless closures on HDPE bottles	13
<i>Figure 3.</i> Cap application to bottle using digital torque meter and chuck	15
<i>Figure 4.</i> ASTM D-4169 used for vibration test spectrum	17
<i>Figure 5.</i> Sample box on vibration table	18
<i>Figure 6.</i> Torque loss of CL HDPE and PP closures vs. vibration duration in group 1-a (Preliminary experiment)	20
<i>Figure 7.</i> Percent Torque Reduction of CL HDPE vs. PP closures in group 2 (Vibration first and then warehousing treatment)	22
<i>Figure 8.</i> Percent Torque Reduction of CL CL HDPE vs. PP closures in group 3 (Warehousing first and then vibration treatment)	22

List of Acronyms, Abbreviations, and Variables

ASTM	American Society for Testing and Materials
CL	Cross Linked
CL HDPE	Cross Linked High Density Polyethylene
in-lb	Inch-Pounds Force
ml	Milliliters
PP	Polypropylene
PSD	Power Spectral Density
Ta	Application Torque
Tr	Removal Torque
°C	Celsius degrees

CHAPTER 1:
INTRODUCTION AND REVIEW OF LITERATURE
INTRODUCTION

Significance

In response to growing consumer demand in a geographically diverse global market, packages travel long distances in a distribution environment (Williams, 1999). No matter what the mode of transportation, packaged products are exposed to random vibration. Transport vibration is generally considered to be present for relatively long periods of time (whenever the transport vehicle is in motion) and typically causes fatigue type damage such as the loosening of closures and fasteners (Singh & Syal, 1996). The package is further challenged by the warehousing duration. The important role of a packaging engineer is to make certain that the package sufficiently protects the product from damage resulting from the effects of the distribution environment hazards. If this is not done properly, all of the hard work by the people involved in the product and package development will be worthless when the consumer receives a damaged product (Singh & Cheema, 1996).

The main function of a closure is to retain seal integrity during the product's life cycle, from assembly and storage to the time it reaches the end customer (Crawford, 1997). Torque is the resistance to application or removal of a closure. Removal torque is a measure of seal integrity on a rigid container with threaded closure and influences ease of use properties. Closure materials have different mechanical properties such as friction,

creep, tensile strength, and elastic modulus which can be influenced by random vibration and warehousing duration. Torque loss is unique to every closure design and should be established for each closure system with the right adjustments made to the application torque to compensate for loss. Torque loss is unique because of the design of closure and the material used for it (Soroka, 1999). The optimum relationship between applied and removal torque and good sealing characteristics under physical and environmental conditions must be established for each individual package design in order to establish proper application torque.

Plastic closure provides the opportunity to create a so-called linerless cap which is 20 percent less expensive than lined caps (Figure 1). As seen in Figure 1, linerless closures have molded- in ribbed structures that seal against the container finish. A small protrusion eliminates the need for a liner on the closure (Hanlon, 1998). Some types of plastic closures are continuous thread style and lug style (discontinuous) thread. Continuous threads are molded continuously around the entire bottle finish, whereas discontinuous threads are only molded a portion of the way around the bottle (Borchers, 2005). One of the advantages of a discontinuous thread closure over a continuous thread closure is the ease of removing the closure with a partial cap rotation. The effect of random vibration and warehousing duration on the removal torque characteristics of linerless discontinuous thread closures has not been studied.

Figure 1. Seal created by linerless closure

Note. From *Fundamentals of Packaging Technology*, 3d Edition, by Walter Soroka, 1999.

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Hypotheses

It is generally accepted that the distribution environment (the environment through which the package travels from manufacturer to consumer) affects the removal torque. Transport vibration is generally considered the cause of fatigue type damage such as loosening of closures and fasteners (Singh & Syal, 1996). Based on prior studies (Singh & Cheema, 1996; Singh & Syal, 1996 & Thompson, 1999), and general opinion about plastic material properties, several hypotheses can be formulated.

First, it is predicted that samples exposed to random vibration and warehousing will demonstrate higher torque reduction compared to control samples. Within this group, samples exposed to warehousing followed by random vibration will experience more reduction in removal torque than samples exposed to vibration followed by warehousing due to plastic fatigue.

Second, samples with the same materials in the cap and body will experience less torque loss compared to samples with different types of materials.

Literature Review

A diverse set of designs such as discontinuous and continuous thread and materials such as metal, glass, and plastic are available for use as closures. Plastic is becoming the closure of choice (Selke, 1997). In the pharmaceutical industry, the use of plastic containers and closures is very popular (Van Houten, 2004). Two reasons for this preference are the low cost of some plastics such as CL HDPE, and the good mechanical properties of some other materials such as polypropylene (Hanlon, Kelsey, Focinio 1998, & Soroka, 1999). Cross-linked plastic is the polymer material that has been chemically processed to cross-link the molecules and therefore enhance strength and change other properties (Packaging Institute International [PI/INT'L], 1988). Threaded plastic linerless closures have some type of resilient surface on the underside in the form of a “lip” that is engineered to serve the functions of a liner or seal (Figure 1). Plastic linerless closures can provide a positive seal in certain circumstances, forgoing the need for intermediary materials and secondary liner insertion operations (Crawford, 1997). As packaging engineers look for more cost effective packaging solutions, linerless closures may be an attractive design choice. The use of a linerless cap generally dictates a more precise control of the closure finish dimensions and design (Brody & Marsh, 1997). Linerless closures can be used only if they can maintain seal integrity throughout the distribution environment (Soroka, 1999).

Many factors such as application and removal torque need to be considered to achieve proper sealing integrity. Application torque is the force required to seal the closure securely and removal torque is the force necessary for the consumer to remove it

(Crawford, 1997). One way to ensure that customers can conveniently open a closure while providing an adequate degree of seal integrity is to determine the removal torque characteristics after exposure to controlled lab testing (ASTM D2063-91, 2002).

Applying the proper torque is one way to minimize torque decay (Thompson, 1999). General recommendations on proper application torque for commonly used threaded container finish sizes and styles are widely available, but there is usually a wide range of possible torque specified for each finish size, and diameter of bottle opening (Hanlon et al., 1998). Removal force is less than application force for all closure designs (Selke, 1997).

Removal torque typically declines over time because of stress relaxation and creep in the closure and bottle (Soroka, 1998). Creep is the dimensional change with time of a material under load (PI/INT'L, 1988). In a 1999 torque study, it was discovered that removal torque increased in the early stages following cap application. As the elapsed time increased beyond 10 days, the cap removal torque decreased. Authors explained that the phenomenon is due to having two different materials in the closure system (Lai and Greenway, 1999).

Transport vibration is generally considered to be present for relatively long periods of time and typically causes the loosening of closures and fasteners. Torque loss is considered a type of fatigue damage in closures (Kipp, 1999). With the increased use of palletization, reduction in manual handling, and the consequent reduction in drop hazards, vibration testing has become increasingly significant (Caldicott, 1991). Past torque studies (Kipp, 1999; Singh & Syal, 1996 & Caldicott, 1991) have used random

vibration testing as an accurate presentation of the distribution environment. While sinusoidal vibration is still a useful technique in certain applications, it is not realistic for distribution vibration (Kipp, 1999). Many random vibration power density spectra (acceleration as function of frequency) are available in commonly used test standards such as ASTM D-4728.

Torque testing is usually guided by following ASTM D2063-91 which allows for measurement of removal torque after exposure to laboratory simulation of the distribution environment (ASTM D2063-91, 2002). Some previous studies on removal torque measurement emphasized the importance of calculating the percent reduction of torque, not just the ultimate removal torque. The researchers argued that using data of average immediate removal torque in determining torque reduction is impractical once subjected to testing. The percent reduction torque can be calculated by the following equation (Singh and Syal, 1996):

$$\%R = \frac{T_A - T_R}{T_A} \times 100$$

T_A = Application Torque

T_R = Removal Torque

CHAPTER 2:
JOURNAL ARTICLE

Author's Title Page

Full Title: REMOVAL TORQUE EFFECTS OF VIBRATION AND FATIGUE ON
DISCONTINUOUS-THREAD CLOSURES

Short Title: Fatigue and Vibration Effect on Removal Torque

Authors: Maryam Daghigh, MS, Herbert Schueneman, CPP-MH, Panfilo Belo,
Ph.D and Lucy McProud, PhD, RD.
San Jose State University, One Washington Square, San Jose, California
95192-0058.
Ph: 408-924-3100

Address questions and comments to: Mr. Herbert Schueneman, CPP-MH,
Department of Nutrition and Food Science, San Jose State University, One Washington
Square, San Jose, California 95192, 408-924-3210

ABSTRACT

This research investigated the effects of random vibration and warehousing on the removal torque of linerless discontinuous thread polymer closures. An application torque level of 12 in-lb was applied to cross linked high-density polyethylene (CL HDPE) and polypropylene (PP) type closures of the same design. Following vibration and warehousing, torque values were measured, and percent torque reduction was calculated and analyzed by t-test at 95% confidence level.

PP closures showed approximately 11.3% greater torque reduction compared to CL HDPE closures. Warehousing duration had a significant effect on removal torque. The average difference in torque loss between the 30 and 90 day warehousing was about 6.9%. Pre and post-warehousing vibration had no significant impact on torque loss. The data confirm that torque reduction is influenced by warehousing and polymer type and that CL HDPE linerless discontinuous thread closure is the better cap material selection on CL HDPE bottles used in the study.

Keywords: random vibration, plastic closures, removal torque, linerless closures

INTRODUCTION

In response to the growing consumer demand in a geographically diverse global market, packages travel long distances in the distribution environment [11]. No matter which mode of transportation is used, packaged products are exposed to random vibration. Transport vibration is generally considered to be present for relatively long periods of time (whenever the transport vehicle is in motion), and typically causes fatigue type damage such as loosening of closures and fasteners [8]. The package is further challenged by the warehousing duration. The important role of a packaging engineer is to make certain that the package sufficiently protects the product from damage resulting from the effect of the distribution environment hazards [7].

A diverse set of designs such as screw caps and materials such as metal, glass, and plastic are available for use as closures. Plastic is becoming the closure of choice [6]. A liner is lining material which is inserted into the interior of a closure to affect a seal against leakage [10]. In the pharmaceutical and medical device industries, the use of plastic containers and closures is very popular [12]. Plastic linerless closures can provide a positive seal in certain circumstances, forgoing the need for intermediary materials and secondary liner insertion operations [3]. However, linerless closures can be used only if they can maintain seal integrity throughout the distribution environment [9].

The main function of a closure is to provide a good seal during the product's life cycle [3]. Torque loss is unique to every closure design and material and should be investigated for each closure system. The proper application torque is necessary to compensate for torque loss [9].

Closure materials have different mechanical properties which are most likely influenced by random vibration and warehousing duration [9]. It is generally accepted that the distribution environment impacts the removal torque. Distribution vibration is generally considered the cause of fatigue damage such as loosening of closures [8]. In 1996, Singh and Syal studied the effect of vertical vibration (vertical linear motion) and drop on plastic bottles in a small parcel distribution environment [8]. They found that the bottles subjected to vibration and 18 inch drop, after 72 hours of atmospheric conditioning, showed higher reduction in removal torque than control samples. Many researchers [8] [2] have studied sinusoidal vibration versus random vibration, which is more representative of the distribution environment for the effect of torque reduction [1] [4].

In 1999, Dr. Ching-Sung Lai and Dr. Gerald Greenway studied the effect of time on the removal torque of vinyl lined caps made of PP on polyethylene terephthalate (PET) bottles. They discovered that removal torque increased in the early stages following cap application due to the interaction between the liner and finish causing adhesion. As the elapsed time increased beyond 10 days, the cap removal torque decreased because the interaction became weaker [5].

Understanding the response of packaged products to different distribution inputs, such as random vibration, would provide useful information for packaging engineers in designing a bottle cap system. Engineers can use the information obtained by researchers in optimizing a package design. All of these can remarkably affect the success of a product.

In this study, the effect of random vibration and warehousing on the torque reduction percentile has been investigated. The effect of polymer type on removal torque has also been studied. To conduct this experiment, a conventional method of torque measurement was utilized due to the accessibility of required equipment and procedures.

MATERIALS AND APPARATAUS

Test Materials

The 28 mm linerless discontinuous thread closures and 50 ml volume bottles used in this experiment had matching finish and thread specifications, and were manufactured by Sanner of America/Wheaton. These bottles are used as containers to hold glucose test strips used for blood sugar detection for diabetes patients. Black CL HDPE polymer bottles had 1/3-turn discontinuous thread, which is a special type used in the pharmaceutical industry for ease in opening. Bottles were made by injection molding in order to achieve the highest possible consistency from sample to sample, from HDPE “Marlex BN” resin with the mean weight of 11.1grams. The white closures were made by injection molding from PP “Huntsman H1200” resin and from CL HDPE using the same resin as was used in the bottle. The CL HDPE closures weighed 3.4 grams and PP closures 3.3 grams each, on average. In order to simulate a normal sample, three different cavities (molds) and five samples from each cavity were used for each sample group (15 HDPE bottles with CL HDPE closures or 15 HDPE bottles with PP closures). Cap to cap variation was considered to be minimal due to the process of mold validation

required for the multiple cavity injection mold process. Based on this validation, mold cavities were not tracked for the caps used in this study.

Figure 2. PP and CL HDPE linerless closures on HDPE bottles

Apparatus

A Digital Torque meter, KAPS-ALL model EB-550, was used for application and removal torque measurement. A random vibration table, MTS model 840 Electro-Hydraulic Vibration Test Machine, was used for transportation vibration simulation purposes.

PROCEDURE

In order to set up the experimental design parameters, a preliminary experiment was designed to determine the vibration duration required to show a significant effect on removal torque.

Preliminary Experiment Design

To verify that a realistic application torque value would be used on the discontinuous thread closures in this experiment, a pre-test was carried out. A total of ten empty bottles were secured into the torque meter console and the cap was applied manually to an optimum amount of application torque. A custom fitting chuck was used to apply cap application torque and cap removal torque. Five bottles were capped by PP closures with 12 ± 1 in-lb torque, five with 14 ± 1 in-lb torque, and the last five with 16 ± 1 in-lb torque. After the removal of the caps, the bottles were thoroughly examined under a Clausing model 4314 Optical Comparator for thread distortion. Based on the observations, it was decided that the bottles with 12 in-lb application torque had no visible thread deformation due to cap application. The rest of the samples showed some type of apparent deformation due to application torque. Therefore, 12 ± 1 in-lb torque was considered the optimum value for this study.

In the preliminary experiment (group 1-a), capped bottles were exposed to different vibration durations. The purpose of this experiment was to determine how long it took for the torque loss to reach a plateau. A total of 150 bottles were used with vibration exposure intervals of 30 minutes, 1 hour, 2 hrs, 3 hrs, and 4 hrs. This experiment was replicated 3 times. Each trial for both bottle and cap material combination consisted of 30 bottles: 15 with CL HDPE and 15 with PP caps. Percent torque loss (%R) was calculated for each group using the following equation:

$$\%R = \frac{T_A - T_R}{T_A} \times 100$$

T_A = Application Torque

T_R = Removal Torque

The experiment was conducted under ambient temperature conditions to reduce error due to different variables other than cap material and vibration duration time. The optimum vibration duration time acquired from this part of the experiment was then used for the main experimental design study.

In the second part of the preliminary experiment (group 1-b), a total of 30 bottles (fifteen bottles with CL HDPE closures and the other fifteen bottles with PP closures) with a combination of caps were only exposed to 180 minutes of elapsed time as the control. By comparing the data, it was discovered that 180 minutes of vibration provided the minimum required time to observe some measurable torque loss.

Main Experiment

One hundred and eight empty bottles were capped as explained in the preliminary experiment using a custom fitting chuck to apply a torque value of 12 ± 1 in-lb as seen in Figure 3.

Figure 3. Cap application to bottle using digital torque meter and chuck

To avoid possible operator/instrument inconsistency, the same operator and torque meter were used throughout the experiment as recommended in ASTM D-2063. Bottles were packed into a B flute regular slotted container with dividers. Fifteen vials were placed in the box and the box was taped shut for sealing purposes. After capping the bottles, the samples were divided into two groups. One group was first exposed to 180 minutes of random vibration (based on preliminary experiment) and then subjected to different warehousing duration periods of 30, 60 and 90 days (group 2). Group 2 had a total of 90 bottles with both closure material combinations. Each warehousing interval had 15 bottles of each closure type. The other group, (group 3), was first subjected to different warehousing conditions of 30, 60, and 90 days and then exposed to 180 minutes of random vibration. Some samples in group 3 were used as controls and were only exposed to warehousing and not vibration. A total of 108 bottles with both closure material combinations were used in group 3.

Vibration intensity and spectrum guidelines of ASTM D-4169 were used for this experiment test profile (Refer to Figure 4). The profile consisted of random vibration covering a frequency of 1-200 hertz at an intensity level of 0.73 GRMS. The time intervals used to simulate the warehousing process were 30 days, 60 days, and 90 days. These time intervals are used in many industries such as the medical device industry (Elboudwarej, 1997).

Figure 4. ASTM D-4169 used for vibration test spectrum

After each time interval, the caps were removed and the removal torque was measured. The bottles were uncapped in the same order as they were capped to control systematic errors. As before, torque reduction percentile [$\%R = 100 \times (T_A - T_R) / T_A$], mean and standard deviation were calculated. The main experiment had few independent variables: bottle and cap material combination, bottle forming molds, warehousing time interval, and the sequence of warehousing first or last. The only dependent variable was removal torque.

The full experiment design consisted of 18 boxes of 3 columns x 5 rows, six boxes of 3 columns x 6 rows (Refer to Figure 5), 378 bottles, 189 CL HDPE caps, and 189 PP caps. This large sample size was selected to reduce statistical variations due to bottle variability, operator error, and other factors.

Figure 5. Sample box on vibration table

RESULTS

Preliminary Experiment Results

Statistical means, standard deviation (SD), and application and removal torque for group 1-a (preliminary experiment group) are presented in Table1.

Table 1. Mean and standard deviation (SD) of application and removal torque

(Preliminary experiment)

		Replicates of Experiment					
		Replicate 1		Replicate 2		Replicate 3	
		Torque,in-lb (SD)		Torque,in-lb (SD)		Torque,in-lb (SD)	
Closure Type	Vibration Duration (min)	Application	Removal	Application	Removal	Application	Removal
CL HDPE	30	12.6 (0.4)	6.9 (1.4)	12.5 (0.3)	6.9 (1.3)	12.2 (0.3)	6.9 (0.9)
	60	12.4 (0.2)	6.4 (1.5)	12.2 (0.2)	8.0 (1.5)	12.2 (0.4)	6.6 (1.2)
	120	12.2 (0.1)	6.9 (0.7)	12.2 (0.2)	7.3 (1.5)	12.2 (0.1)	6.1 (0.8)
	180	12.4 (0.2)	5.9 (1.0)	12.4 (0.3)	7.1 (1.9)	12.2 (0.1)	5.6 (0.8)
	240	12.2 (0.2)	5.9 (1.2)	12.3 (0.3)	7.3 (1.3)	12.4 (0.1)	5.6 (1.0)
PP	30	12.4 (0.4)	6.9 (0.6)	12.3 (0.2)	7.0 (1.0)	12.3 (0.2)	6.3 (0.5)
	60	12.4 (0.8)	6.1 (0.4)	12.3 (0.4)	6.3 (0.4)	12.3 (0.2)	6.6 (0.3)
	120	12.2 (0.4)	6.5 (0.9)	12.2 (0.2)	6.7 (0.7)	12.4 (0.3)	6.7 (0.5)
	180	12.3 (0.3)	6.1 (0.6)	12.4 (0.4)	6.2 (0.4)	12.2 (0.2)	6.2 (0.6)
	240	12.1 (0.1)	5.9 (0.4)	12.4 (0.2)	6.1 (0.6)	12.3 (0.1)	6.0 (0.6)
CL HDPE preliminary Control	180 (dwell)	12.2 (0.2)	6.6 (0.9)	12.4 (0.3)	7.4 (0.5)	12.3 (0.3)	6.6 (0.8)
PP preliminary Control	180 (dwell)	12.1 (0.13)	6.2 (0.1)	12.1 (0.1)	5.9 (0.2)	12.1 (0.1)	6.1 (0.2)

As can be seen in Figure 6, PP caps had higher torque reduction than CL HDPE caps. The preliminary data indicates that both closures, PP and CL HDPE, showed similar patterns in percent torque reduction versus vibration duration. Both closures reached a torque loss steady state condition after being exposed to 180 minutes of random vibration.

Figure 6. Torque loss of CL HDPE and PP closures vs. vibration duration in group 1-a (Preliminary experiment)

For the control group (1-b), which was exposed to 180 minutes of dwell time, CL HDPE closures showed lower torque reduction than PP closures as well.

Main Experiment Results

For each time interval of warehousing, statistical means and standard deviations (SD) of application and removal torque are presented in Tables 2 and 3. Percent mean reduction of replicates as a function of time is shown in Figures 6 and 7.

Table 2. Mean and standard deviation (SD) of application and removal torque

(Vibration first and then warehousing treatment-group 2)

		Trials of Experiment					
		Trial 1		Trial 2		Trial 3	
		Torque,in-lb (SD)		Torque,in-lb (SD)		Torque,in-lb (SD)	
Closure Type	Warehousing Duration (days)	Application	Removal	Application	Removal	Application	Removal
CL HDPE	30	12.3 (0.2)	5.9 (0.6)	12.3 (0.1)	6.2 (0.4)	12.2 (0.0)	6.0 (0.3)
	60	12.4 (0.2)	5.7 (0.4)	12.3 (0.3)	5.2 (0.6)	12.2 (0.1)	5.3 (0.3)
	90	12.4 (0.2)	5.4 (0.2)	12.3 (0.1)	5.3 (0.4)	12.3 (0.1)	5.5 (0.3)
PP	30	12.2 (0.1)	4.3 (0.2)	12.2 (0.2)	4.4 (0.4)	12.3 (0.2)	4.8 (0.2)
	60	12.4 (0.2)	4.1 (0.2)	12.2 (0.1)	4.4 (0.0)	12.3 (0.2)	4.3 (0.4)
	90	12.3 (0.3)	4.1 (0.2)	12.2 (0.3)	4.0 (0.3)	12.1 (0.1)	4.0 (0.3)

Table 3. Mean and standard deviation (SD) of application and removal torque

(Warehousing first and then vibration treatment -group 3)

		Trials of Experiment					
		Trial 1		Trial 2		Trial 3	
		Torque,in-lb (SD)		Torque,in-lb (SD)		Torque,in-lb (SD)	
Closure Type	Warehousing Duration (days)	Application	Removal	Application	Removal	Application	Removal
CL HDPE	30	12.3 (0.2)	6.4 (0.3)	12.1 (0.1)	7.1 (0.9)	12.2 (0.1)	4.5 (0.2)
	60	12.0 (0.0)	5.4 (1.2)	12.4 (0.2)	5.2 (2.2)	12.3 (0.3)	5.7 (1.0)
	90	12.3 (0.2)	5.5 (0.6)	12.5 (0.1)	5.5 (0.6)	12.3 (0.3)	4.8 (0.4)
PP	30	12.3 (0.3)	5.0 (0.4)	12.4 (0.3)	4.6 (0.2)	12.4 (0.2)	4.3 (0.1)
	60	12.4 (0.3)	4.3 (0.2)	12.3 (0.2)	4.5 (0.3)	12.2 (0.2)	4.0 (0.3)
	90	12.3 (0.2)	3.9 (0.1)	12.4 (0.3)	3.9 (0.1)	12.2 (0.1)	3.8 (0.3)
CL HDPE Control	30	12.2 (0.3)	5.6 (1.3)	12.3 (0.2)	8.1 (0.7)	12.4 (0.2)	6.1 (1.3)
	60	12.0 (0.0)	6.0 (0.9)	12.2 (0.1)	5.0 (0.7)	12.1 (0.1)	5.4 (1.0)
	90	12.5 (0.2)	4.7 (1.2)	12.2 (0.1)	5.9 (0.2)	12.8 (1.2)	6.1 (0.3)
PP Control	30	12.5 (0.5)	4.7 (0.3)	12.4 (0.3)	5.2 (0.5)	12.1 (0.1)	4.6 (0.2)
	60	12.2 (0.1)	4.5 (0.2)	12.3 (0.3)	4.2 (0.1)	12.5 (0.2)	4.3 (0.5)
	90	12.4 (0.1)	4.0 (0.2)	12.4 (0.2)	4.0 (0.1)	12.2 (0.2)	4.0 (0.2)

Figure 7. Percent torque reduction of CL HDPE vs. PP closures in group 2
(Vibration first and then warehousing treatment)

Figure 8. Percent torque reduction of CL HDPE vs. PP closures in group 3
(Warehousing first and then vibration treatment)

As can be seen in Figures 6 and 7, both PP and CL HDPE caps show an increase in percent torque reduction over a period of 90 days. However, percent torque reduction for polypropylene was higher than that for high density polyethylene. Both show a positive linear trend over the time tested.

Results revealed several facts. First, it is clear that PP closures showed approximately an 11.3% greater torque reduction compared to CL HDPE closures. The average torque loss for PP caps was 64.9% and for CL HDPE was 53.6%. In other words, PP caps were easier to remove, as was also evident subjectively during testing. Second, a comparison between the control (time only) and treated (time and vibration) samples revealed that there was a slight difference in magnitude due to vibration; the effect of vibration is about 1.6% and is lower for PP closures. Finally, the comparison between different warehousing duration groups showed that the effect of warehousing over 60 days (from day 30 to day 90) is, on average, about 6.9% for both closure types.

The data collected seem to support the research hypotheses since the torque loss was higher for the groups exposed to warehousing compared to the control groups. To determine whether the difference was statistically significant, the data were analyzed by t-test with a P-value of 0.05 (95% confidence level). The analysis was conducted for the following:

- Comparison between treated samples and control samples
- 90 day samples and 30 day samples
- PP caps and CL HDPE caps

The statistical values are calculated and listed in Table 4.

Table 4. Comparison of samples with 95% confidence limit

Comparison	Average difference in torque loss between variables	Lower 95% confidence limit	Upper 95% confidence limit
PP- CL HDPE	11.3%	8.6%	13.8%
Treated (vibration exposed)– Control	1.6%	-0.9%	4.2%
90day – 30day Warehousing	6.9%	3.7%	10.0%

The torque loss was significantly different between the PP caps and CL HDPE caps. It was found that PP caps experienced a statistically significant reduction in torque loss compared to CL HDPE caps. The average difference in torque loss was about 11.3% higher for PP caps compared to CL HDPE caps, with 95% confidence limits, (P-value 0.05), for the difference indicated by 8.6 and 13.8 (Table 4). More importantly, this difference is large in magnitude (between 8.6% and 13.8%), and hence may be of practical significance also.

The torque loss was not significantly different between the treated samples (vibration exposed) and the control samples. The average difference in torque loss between the treated and the control samples was about 1.6%, with 95% confidence limits, (P-value 0.05), for the difference indicated by -0.9 and 4.2 (Table 4). The confidence interval (-.09, 4.2), includes zero, which means that the difference could be zero and not statistically significant. Also, the difference of 1.6% is minimal meaning not practically significant.

The torque loss was significantly different between the 30 day warehousing group and the 90 day warehousing group. The average difference in torque loss was about

6.9%, with 95% confidence limits, (P-value 0.05), for the difference indicated by the confidence interval of 3.7 and 10.0 (Table 4). In spite of the expectation of having more torque loss in group 3 (warehousing first and then vibration), pre-warehousing and post-warehousing vibration had no significant effect on torque loss.

CONCLUSION

The primary goal of this experiment was to compare torque loss for two different closure materials when exposed to vibration and different warehousing durations. Preliminary data indicated that at a specific vibration exposure level, torque loss reaches a maximum level and then, for both polymers, percent torque reduction decreases. This is due to an interaction between the closure and bottle interface during vibration exposure, which increases surface friction. This experiment clearly revealed that warehousing has a significant effect on removal torque for both PP and CL HDPE caps. The effect of warehousing was about 6.9% with a P-value 0.05, meaning more torque loss over time. The results of warehousing simulation and vibration tests showed that the PP linerless closure had significantly greater torque loss, about 11.3% with a P-value 0.05, compared to the CL HDPE linerless closure. Also, the effect of warehousing and vibration seem “additive,” that is, it does not matter which one is done first, the net effect is the same, and is equal to the sum of the two individual effects.

It is important to note that results seem to contradict “conventional wisdom” among closure manufacturers, which states that dissimilar materials for bottle and closure will yield greater torque retention than similar materials. The discrepancy of the notion of the torque retention by closure manufacturers and results of this experiment might be

caused by colorants and additives in materials, which in turn results in a higher degree of friction, or an inherent factor in thread pitch or design. Another important factor for this discrepancy could arise from the use of CL HDPE caps, because CL HDPE consists of long polymer chains that are connected chemically at different locations and forming chemical bonds. This “web-like” structure is more resistant from being pulled apart versus non-CL HDPE polymer chains that are linear.

The findings of this experiment can help the packaging community understand the effect of warehousing and random vibration on linerless discontinuous CL HDPE and PP closures. Vibration and warehousing are some of the elements of the distribution cycle; other factors such as temperature and shock might also affect torque reduction. This study could serve as a reference for researchers investigating other factors affecting removal torque.

There are few studies published in the literature using these types of materials and conditions. The gathered data in this experiment can be used to optimize the relationship between application and removal torque, and in achieving good sealing characteristics under different physical and environmental conditions. These conclusions could result in cost improvement, extended shelf life, fewer damaged products, and ultimately better customer satisfaction.

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CHAPTER 3:
SUMMARY AND RECOMMENDATIONS

SUMMARY

This research examined the effects of random vibration and warehousing duration on the removal torque characteristics of discontinuous-thread PP and CL HDPE linerless closures applied to HDPE bottles.

The vibration intensity and spectrum used for this experiment were recommended for the performance testing of shipping containers and systems in ASTM D 4169 (Table 5).

Table 5. Vibration intensity and frequency used

Truck	
Frequency Hz	Level g^2/Hz
1	0.00005
4	0.01
16	0.01
40	0.001
80	0.001
200	0.00001
Over Level, g rms	0.52

The effects of random vibration and 30, 60, and 90 days of warehousing on percent torque reduction with 12 in-lb application torque were studied. For torque measurement, the KAPS-ALL model EB-550 digital torque meter was used. For vibration simulation, the MTS model 840 Electro-Hydraulic Vibration Test system was

used. For simulation purposes, vibration intensity and frequency specified in Table 6 were used.

Application and removal torques were measured for all control and treated groups (as shown in Tables A-1 through 4). Mean torque loss for all groups with CL HDPE and PP caps are graphically shown in Figures 5 through 7. It was observed that within each specific group (i.e., bottles with PP caps in group exposed to warehousing, then vibration), the percent torque changed over the warehousing time intervals of 30 to 90 days. Bottles with PP closures experienced a significantly higher reduction of removal torque compared to bottles with CL HDPE closures.

RECOMMENDATIONS

Polypropylene and CL high density polyethylene are only two of the closure materials in closure selection. Due to a lack of resources and time, none of the other common types of plastic materials could be used in this study. Using different plastic types for closures and bottles would further validate the findings of this study. Having a more diverse group of samples would also have likely produced additional useful data.

For this kind of linerless discontinuous thread closure, no prior experiments were found in the literature to support or provide a background for this research. This study generated data as a basis to be used for future studies and testing parameters.

The use of CL HDPE and PP material types in closures and bottles is popular due to their excellent physical characteristics and their low cost. However, it should be noted that with the rise in the cost of petroleum and market fluctuations, the selection of

packaging material will be cost driven, too. If a less expensive material can perform equally well in a specific area of interest such as torque retention, then that will be the first choice for packaging manufacturers.

More research is required to validate the results of this study. The same design of cap used with other plastic material types can be tested to confirm if the results were design related or material related.

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APPENDICES

APPENDIX A: Application and Removal Torque Data

Table A.1 through *A.4* display the individual application and removal torque raw data for all bottles tested and computed averages and standard deviations for all control and treated groups

Table A.1 Application torque, mean, and standard deviation (SD) of group 2 (Vibration first and then warehousing treatment)

		Mold Number	Trials						
30 days	PP Sample		Ta1	Ta2	Ta3	Ta4	Ta5	Ta Mean.	(SD)
		31	12.3	12.1	12.2	12.1	12.3	12.2	0.1
		32	12.0	12.1	12.4	12.3	12.1	12.2	0.2
		33	12.5	12.2	12.2	12.5	12.0	12.3	0.2
	CL HDPE Sample		Ta1	Ta2	Ta3	Ta4	Ta5	Ta Mean.	(SD)
		31	12.0	12.4	12.5	12.3	12.2	12.3	0.2
		32	12.3	12.3	12.3	12.2	12.4	12.3	0.1
		33	12.2	12.2	12.2	12.3	12.2	12.2	0.0
60 days	PP Sample		Ta1	Ta2	Ta3	Ta4	Ta5	Ta Mean.	(SD)
		31	12.2	12.4	12.5	12.5	12.2	12.4	0.2
		32	12.2	12.4	12.2	12.2	12.1	12.2	0.1
		33	12.5	12.4	12.3	12.2	12.0	12.3	0.2
	CL HDPE Sample		Ta1	Ta2	Ta3	Ta4	Ta5	Ta Mean.	(SD)
		31	12.3	12.5	12.6	12.5	12.1	12.4	0.2
		32	12.1	12.8	12.1	12.3	12.3	12.3	0.3
		33	12.2	12.2	12.2	12.0	12.2	12.2	0.1
90 days	PP Sample		Ta1	Ta2	Ta3	Ta4	Ta5	Ta Mean.	(SD)
		31	12.2	12.4	12.0	12.7	12.3	12.3	0.3
		32	12.1	12.0	12.6	12.3	12.0	12.2	0.3
		33	12.3	12.2	12.0	12.0	12.0	12.1	0.1
	CL HDPE Sample		Ta1	Ta2	Ta3	Ta4	Ta5	Ta Mean.	(SD)
		31	12.6	12.4	12.6	12.3	12.3	12.4	0.2
		32	12.4	12.1	12.4	12.4	12.3	12.3	0.1
		33	12.4	12.1	12.4	12.4	12.3	12.3	0.1

Table A.2 Removal torque, mean, and standard deviation (SD) of group 2 (Vibration first and then warehousing treatment)

		Mold Number	Trials						
30 days	PP Sample		Tr1	Tr2	Tr3	Tr4	Tr5	Tr Mean.	(SD)
		31	4.4	4.1	4.1	4.4	4.6	4.3	0.2
		32	3.9	4.4	4.3	5.0	4.4	4.4	0.4
		33	4.8	4.8	4.9	4.8	4.5	4.8	0.2
	CL HDPE Sample		Tr1	Tr2	Tr3	Tr4	Tr5	Tr Mean.	(SD)
		31	4.9	5.8	6.3	6.3	6.1	5.9	0.6
		32	5.9	6.0	6.3	6.1	6.8	6.2	0.4
		33	6.2	6.4	5.7	5.8	6.0	6.0	0.3
60 days	PP Sample		Tr1	Tr2	Tr3	Tr4	Tr5	Tr Mean.	(SD)
		31	3.8	4.1	4.3	4.3	4.2	4.1	0.2
		32	4.4	4.4	4.4	4.4	4.5	4.4	0.0
		33	3.9	4.7	4.2	4.9	4.0	4.3	0.4
	CL HDPE Sample		Tr1	Tr2	Tr3	Tr4	Tr5	Tr Mean.	(SD)
		31	5.2	5.7	6.2	5.5	6.1	5.7	0.4
		32	4.6	6.2	5.0	5.2	4.9	5.2	0.6
		33	4.9	5.3	5.8	5.3	5.2	5.3	0.3
90 days	PP Sample		Tr1	Tr2	Tr3	Tr4	Tr5	Tr Mean.	(SD)
		31	4.4	4.1	3.9	4.1	4.0	4.1	0.2
		32	4.1	3.7	4.5	4.0	3.7	4.0	0.3
		33	3.6	4.2	4.2	3.9	4.2	4.0	0.3
	CL HDPE Sample		Tr1	Tr2	Tr3	Tr4	Tr5	Tr Mean.	(SD)
		31	5.1	5.5	5.3	5.7	5.6	5.4	0.2
		32	5.4	4.6	5.1	5.6	5.7	5.3	0.4
		33	5.9	5.5	5.2	5.1	5.6	5.5	0.3

Table A.3 Application torque, mean, and standard deviation (SD) group 3 (Warehousing first and then vibration treatment)

		Mold Number	Trials									
			Experimental					Control (dwell)				
			Ta1	Ta2	Ta3	Ta Mean	Std. Dev	Ta4	Ta5	Ta6	Ta Mean	(SD)
30 days	PP Sample											
		31	12.2	12.7	12.1	12.3	0.3	12.2	12.2	13.0	8.2	6.8
		32	12.4	12.1	12.7	12.4	0.3	12.5	12.1	12.6	8.4	7.0
		33	12.2	12.4	12.5	12.4	0.2	12.0	12.1	12.2	8.3	7.0
	CL HDPE Sample		Ta1	Ta2	Ta3	Ta Mean	Std. Dev	Ta4	Ta5	Ta6	Ta Mean	(SD)
		31	12.4	12.1	12.3	21.6	13.4	12.5	12.0	12.2	12.6	0.7
		32	12.2	12.1	12.0	22.1	14.1	12.1	12.5	12.2	12.9	1.1
		33	12.3	12.1	12.3	22.6	14.8	12.6	12.4	12.2	13.2	1.4
60 days	PP Sample		Ta1	Ta2	Ta3	Ta Mean	Std. Dev	Ta4	Ta5	Ta6	Ta Mean	(SD)
		31	12.2	12.3	12.7	21.7	13.2	12.1	12.3	12.3	12.7	0.5
		32	12.4	12.1	12.4	22.1	14.1	12.6	12.0	12.3	12.8	1.1
		33	12.0	12.3	12.3	22.7	14.6	12.6	12.5	12.3	13.1	1.3
	CL HDPE Sample		Ta1	Ta2	Ta3	Ta Mean	Std. Dev	Ta4	Ta5	Ta6	Ta Mean	(SD)
		31	12.0	12.0	12.0	21.5	13.4	12.0	12.0	12.0	12.5	0.8
		32	12.6	12.2	12.3	22.1	14.0	12.1	12.2	12.2	12.8	1.0
		33	12.6	12.3	12.1	22.7	14.6	12.0	12.1	12.1	12.9	1.5
90 days	PP Sample		Ta1	Ta2	Ta3	Ta Mean	Std. Dev	Ta4	Ta5	Ta6	Ta Mean	(SD)
		31	12.1	12.3	12.5	21.7	13.2	12.5	12.3	12.4	12.4	0.5
		32	12.5	12.6	12.0	22.3	13.7	12.2	12.4	12.6	12.7	0.9
		33	12.2	12.3	12.1	22.7	14.6	12.4	12.1	12.2	12.9	1.5
	CL HDPE Sample		Ta1	Ta2	Ta3	Ta Mean	Std. Dev	Ta4	Ta5	Ta6	Ta Mean	(SD)
		31	12.1	12.4	12.5	21.7	13.2	12.3	12.7	12.4	12.8	0.3
		32	12.5	12.6	12.5	22.3	13.7	12.2	12.2	12.1	12.8	0.8
		33	12.2	12.6	12.1	22.8	14.4	12.1	14.2	12.1	13.6	1.3

Table A.4 Removal torque, mean, and standard deviation (SD) of group 3 (Warehousing first and then vibration treatment)

			Trials									
			Mold Number	Experimental					Control (dwell)			
30 days	PP Sample		Tr1	Tr2	Tr3	Tr Mean	Std. Dev	Tr4	Tr5	Ta6	Tr Mean	(SD)
		31	4.6	5.3	5.2	5.0	0.4	4.9	4.4	4.7	4.7	0.3
		32	4.8	4.5	4.4	4.6	0.2	5.3	4.7	5.6	5.2	0.5
		33	4.3	4.4	4.2	4.3	0.1	4.4	4.8	4.7	4.6	0.2
	CL HDPE Sample		Tr1	Tr2	Tr3	Tr Mean	Std. Dev	Tr4	Tr5	Ta6	Tr Mean	(SD)
		31	6.1	6.4	6.6	6.4	0.3	5.8	4.2	6.7	5.6	1.3
		32	6.3	8.0	6.9	7.1	0.9	8.3	7.3	8.6	8.1	0.7
		33	4.3	4.6	4.7	4.5	0.2	6.6	4.6	7.0	6.1	1.3
60 days	PP Sample		Tr1	Tr2	Tr3	Tr Mean	Std. Dev	Tr4	Tr5	Ta6	Tr Mean	(SD)
		31	4.1	4.4	4.3	4.3	0.2	4.4	4.3	4.7	4.5	0.2
		32	4.1	4.7	4.7	4.5	0.3	4.3	4.2	4.2	4.2	0.1
		33	4.1	3.6	4.2	4.0	0.3	3.8	4.5	4.7	4.3	0.5
	CL HDPE Sample		Tr1	Tr2	Tr3	Tr Mean	Std. Dev	Tr4	Tr5	Ta6	Tr Mean	(SD)
		31	4.4	6.7	5.1	5.4	1.2	5.1	6.0	6.8	6.0	0.9
		32	3.0	7.3	5.4	5.2	2.2	5.8	4.4	4.8	5.0	0.7
		33	4.6	6.4	6.1	5.7	1.0	6.1	4.6	4.3	5.4	1.0
90 days	PP Sample		Tr1	Tr2	Tr3	Tr Mean	Std. Dev	Tr4	Tr5	Ta6	Tr Mean	(SD)
		31	3.9	3.9	4.0	3.9	0.1	4.2	3.8	4.0	4.0	0.2
		32	3.8	3.9	3.9	3.9	0.1	4.1	4.0	4.0	4.0	0.1
		33	4.1	3.8	3.6	3.8	0.3	4.4	4.0	4.0	4.0	0.2
	CL HDPE Sample		Tr1	Tr2	Tr3	Tr Mean	Std. Dev	Tr4	Tr5	Ta6	Tr Mean	(SD)
		31	5.4	6.2	5.0	5.5	0.6	4.0	4.0	6.0	4.7	1.2
		32	5.3	5.0	6.1	5.5	0.6	6.1	5.8	5.9	5.9	0.2
		33	5.1	4.4	4.8	4.8	0.4	5.8	6.2	6.3	6.1	0.3

APPENDIX B: Test Equipment

Table B.1 displays the test equipment utilized for this research

Table B.1 List of test equipment

Instrument	Model #	Calibration Date
KAPS-ALL model	EB-550	May 2004
MTS Electro-Hydraulic Vibration Test Machine	204.61	Not required
Kistler Coupler	5126A	3/2/2005
Dytran Accelerometer	3100B	1/17/2005
Data Physics Vibration ControllerDP550		2/22/2005