2013-12-01

Characterization and Processing Evaluation of Starch/High-Density Polyethylene Materials in Extrusion Blow Molding

Bradley Dale Bacigalupi
Brigham Young University - Provo

Characterization and Processing Evaluation of

Starch/High-Density Polyethylene Materials

in Extrusion Blow Molding

Bradley Bacigalupi

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

Alan J. Boardman, Chair
Michael P. Miles
Andrew R. George

School of Technology

Brigham Young University

December 2013

ABSTRACT

Characterization and Processing Evaluation of
Starch/High-Density Polyethylene Materials
in Extrusion Blow Molding

Bradley Bacigalupi
School of Technology, BYU
Master of Science

The growing negative impacts of non-biodegradable plastics derived from non-renewable materials have created increasing interest throughout the world for new materials that are both biodegradable and renewable, that can be combined with or replace traditional plastics.

Plant-based thermoplastic starch (TPS), a promising alternative material to traditional petroleum based resin, is both biodegradable and renewable and has great potential for use in plastic manufacturing processes. Two major obstacles that prevent more widespread use of TPS include; TPS base material, which is typically manufactured in a flake or powder, is incompatible with standard plastics production equipment that require pelletized resin, the second reason is that TPS is difficult to mix with standard plastic materials such as High Density Polyethylene (HDPE). BiologiQ of Blackfoot Idaho through a unique manufacturing process has created a new type of TPS called EcoStarch™ Resin (ESR) that overcomes these two obstacles the material can be both pelletized and combined with various standard base plastics such as HDPE.

This study evaluated and characterized the processability materials properties of ESR and HDPE blends in the Extrusion Blow Molding (EBM) by measuring wall thickness, tensile strength, tensile elongation, modulus of elongation and formability compared to 100% HDPE bottles. As the ESR content increased the uniformity of the wall thickness increased. The tensile strength increased from ESR content of 30% to 50% while the elongation decreased. Bottles were successfully extrusion blow molded with ESR content of 50%.

Keywords: Bradley Bacigalupi, thermoplastic starch, TPS, potato starch, extrusion blow molding, EBM, BiologiQ, tensile test, impact test

ACKNOWLEDGEMENTS

I would like to express my gratitude to all those have supported me in my research. Above all I would like to thank my wife Andrea for her constant support, patience and love. I would like to thank Alan Boardman, Michael Miles, Andy George, Ruth Ann Lowe and the faculty and staff in the BYU School of Technology.

TABLE OF CONTENTS

LIST OF TABLES ..... **vi**

LIST OF FIGURES ..... **vii**

1 Introduction **1**

1.1 Background 1

1.2 Objective 1

1.3 Problem Statement 2

1.4 Justification 2

1.5 Hypotheses 3

1.6 Testing 3

1.7 Delimitations and Assumptions 4

2 Literature Review **5**

2.1 Introduction 5

2.2 Biopolymers 5

2.3 Extrusion Blow Molding 6

2.4 High Density Polyethylene 7

2.5 Potato Based TPS and Extrusion Blow Molding 7

3 Research Methodology **9**

3.1 Introduction 9

3.2 Materials 9

3.3 Equipment 9

3.3.1 Preparation Equipment 10

3.3.2 Sample Processing Equipment 10

3.3.3 Testing Equipment 11

3.4 Experimental & Data Collection 12

3.4.1 Sample Preparation 12

3.5 Data Analysis Methods 14

4 Results and Analysis 15

4.1 Processing 15

4.2 Mechanical Properties Characterization 20

4.2.1 Wall Thickness 20

4.2.2 Tensile Strength Tensile Strength 23

4.2.3 Tensile Elongation 24

4.2.4 Tensile Modulus 25

4.2.5 Formability 26

5 Conclusions and Recommendations 27

5.1 Summary 27

5.2 Conclusion 27

5.3 Discussion 28

5.4 Recommendations 29

References 30

Appendix A: Tensile Testing Data 32

Appendix B: Wall Thickness Measurements 39

Appendix C: Tensile Elongation Measurements 40

Appendix D: Extrusion Blow Molding Machine Specifications 41

Appendix E: Descriptive Comparitive Statisitcal Analysis Data 42

LIST OF TABLES

Table 1: Wall Thickness 21

Table 2: Wall Thickness Variation 21

Table 3: Max Load at Break 23

Table 4: Maximum Extension...24

Table 5: Combined Parting Line Modulus...25

Table 6: Combined Side Wall Modulus..25

LIST OF FIGURES

Figure 1: Pelletized Potato Starch Called EcoStarch™ Resin (40% ESR, 60% HDPE)......6

Figure 2: Caosheing Company Extrusion Blow Molding Machine......................................10

Figure 3: Instron 4204 Tensile Testing Machine..11

Figure 4: Federal Micrometer Model KP-119-r2..11

Figure 5: Dogbone Sample Template 12

Figure 6: Gallon Bottle Sample 13

Figure 7: Bottles with Samples Removed (L-R 0% ESR, 30% ESR, 40% ESR, 50% ESR)...13

Figure 8: Bottle Samples (Upper left 0% ESR, Upper right 30% ESR, Lower left 40% ESR, Lower right 50% ESR) 13

Figure 9: Bubbling Parison 16

Figure 10: Example of Handle Defect 17

Figure 11: Example of Bottom Defect...17

Figure 12: Sidewall Defect, Example 1 17

Figure 13: Sidewall Defect, Example 2 18

Figure 14: Sidewall Defect, Example 3 18

Figure 15: Bottle Defect, Example 4 18

Figure 16: Parting Line Test Samples...19

Figure 17: Sidewall Test Samples...19

Figure 18: Example of Standard HDPE Parison (L) and HDPE/ESR Parison (R)................22

Figure 19: Example of Standard HDPE Parison (L) and HDPE/ESR Parison (R) with Mold Lines (Red) 22

1 INTRODUCTION

1.1 Background

There is great interest in the plastic industry in non-petroleum based resin as there is growing concern relating to environmental and economic issues surrounding petroleum-based resins (Song) as approximately 80 million tons of oil and natural gas and are consumed each year for use in plastics (Gerngross). These concerns include; increasing accumulation of non-compostable and non-degradable consumer packaging waste, speculation regarding the sustainability and cost of fossil fuels, and the negative environmental impacts from petroleum based resin. Plant-based Thermo Plastic Starch (TPS) is one option that holds great potential as an alternative to traditional petroleum based resin. Under the trade name of EcoStarch™ Resin (ESR), a new type of TPS, is currently in production. This purely natural material has great potential in the plastics industry as it is produced in pellet form and can be used on standard plastic processing equipment.

1.2 Objective

The main objectives of this research are; produce bottles through extrusion blow molding (EBM) process in varying EcoStarch™ (ESR)/high density polyethylene (HDPE) with Amplify™ compatibilizer blends and characterize the materials post processing per the measurement of wall thickness, tensile strength, elongation, modulus and formability.

1.3 Problem Statement

Process and material characterization of potato starch resins blended with high density polyethylene in extrusion blow molding applications is required to understand the benefits and limitations of such structures at various blend ratios. Detailed understanding of these structures will allow for use of the materials in various applications.

1.4 Justification

Due to the lack of research regarding the use and characterization of potato based natural starch resin as a material for use in EBM little is known about its performance in such applications. There is limited to no references regarding the performance of ESR blended with the most common packaging applications polymer HDPE as any ratio of ESR/HDPE blend. Therefore to assist manufacturers with the implementation and to understand the advantages or disadvantages of using ESR in EBM it is necessary to perform this work.

To characterize and understand the effects of combining ESR with HDPE for EBM applications and products, several important performance measures must be investigated. Previous research has investigated the materials properties of ESR/HDPE blend ratios by injection molding (Boardman) and blown film (Mościcki). For EBM these properties are to be investigated post EBM processing of the materials. The performance measures to be investigated include; tensile strength, tensile modulus, tensile elongation, and uniformity of wall thickness. Understanding the performance of various ESR/HDPE bled ratios in its various forms according to these standard metrics will help manufacturers better implement this material.

1.5 Hypotheses

The following hypotheses will guide the direction of this research regarding the performance of ESR in the EBM process.

Hypothesis 1: *As the proportion of ESR increases there will be a less uniform wall thickness in sidewall and parting line regions.*

Hypothesis 2: *As the proportion of ESR increases there will be an increase in tensile strength*

Hypothesis 3: *As the proportion of ESR increases tensile elongation will decrease*

Hypothesis 4: *As the proportion of ESR increases then the tensile modulus will decrease*

Hypothesis 5: *There is a threshold of ESR content above which bottles will not form*

1.6 Testing

Various ESR/HDPE blends will be tested to measure and record their performance at different mix ratios. Testing will follow the following guidelines.

1. Uniform wall thickness: sidewall vs. parting line regions
2. Tensile testing: Strength of the product
3. Elongation: Plasticity of the product

Take materials with different percentage blends and perform the following tests. Take specimens and test hypotheses.

BiologiQ employs several trade secrets in order to create their proprietary pellet which include a multiphase drying and refining process. Pellets were supplied for this research according to the mix ratios requested. The machines used are an EBM machine., Instron tensile tester and micrometer with a spring loaded drop ball probe.

1.7 Delimitations and Assumptions

This study will focus on only extrusion blow molding and ESR blended with HDPE with Amplify™ compatibilizer. The ESR-HDPE mixes will be made by BiologiQ according to the mix ratios specified to perform this necessary research. Definition of Terms

ESR- EcoStarch™ resin is the proprietary resin manufactured by BiologiQ which contains plant starch and is produced in pellet form. This resin can be manufactured from a wide variety of starch-based plants.

EBS- Extrusion blow molding is the process used to create bottles and hollow containers by pressing a tube or parison of molten plastic into a mold that is pressurized to take on the shape of the mold.

HDPE- High-density polyethylene is a common thermoplastic material used a plastic processes for its high strength, low reactivity and ease of use thanks to its low processing temperature.

TPS- Thermoplastic starch is a form of bioplastic based on plant starch and requires a plasticizer such as glycerin in order to be processed in typical plastic production equipment.

2 LITERATURE REVIEW

2.1 Introduction

This section will draw from published works and research related to biodegradable resins. This review begins with broad explanations of plastics and plastic processes and will then narrow in focus on research more specific to TPS in EBS.

2.2 Biopolymers

Alternative resin for plastics processing is a topic of great interest. A large portion of waste in landfills is a result of petrochemical based polymers. These plastics accumulate quickly as they are typically used for many single use consumer goods such as packaging material (Barnes). These plastics can be difficult to gather, clean and recycle. Many will not degrade and incineration is also an unfavorable method of disposal as the burning waste releases a host of toxic and environmentally harmful chemicals. Along with this there is growing concern about the sustainability of plastics based on the finite reserves of petroleum. Scientists are actively searching for ways to reduce the amount of petrochemical based polymers.

There are a variety of materials that are undergoing research and development that may prove to be competitive alternatives to petroleum based resin that includes TPS (Harrington). While there is research regarding various TPS applications few exist that focus on potato starch resin in EBM.

Figure 1: Pelletized Potato Starch Called EcoStarch™ Resin (40% ESR, 60% HDPE)

2.3 Extrusion Blow Molding

Extrusion Blow molding is a common manufacturing process used to make hollow containers such as bottles. This process was first patented on February 1, 1881 with U.S. Patent 0,237,168 to Celluloid manufacturing Company, New York. It was rarely used until the advent of LDPE. Its use became more widespread in the 1950's grow as HDPE was introduced for use with popular consumer containers to hold water, milk, detergent and oil. The more common materials used in EBM include; Polypropylene (PP), Polyethylene (PE), Polyethylene Terephthalate (PET) and Polyvinylchloride (PVC).

Extrusion blow molding, the more common of the various blow molding methods, is different than Injection Blow Molding (IBM) and Stretch Blow Molding (SBM) in that it uses resin pellets that are pressed through extruder into hollow tube or parison. The parison is formed as molten resin passes through a male pin or mandrel and a female die or bushing. As more resin presses through the die the parison lowers between two mold halves. The mold halves close around the parison and a blow pin/nozzle inserts and pressurizes the parison to forming the polymer to the shape of the mold. (Brandau). The mold scores any excess material called flash that is typically found at the top and bottom of the part. This flash can be removed from the part and collected to be ground and reprocessed. Most modern EBM machines are equipped with controls for the mandrill and die to regulate wall thickness to ensure wall thickness is uniform throughout the vertical length of the part. This is particularly important in cases when the parison is very long. In cases where parts are oblong or require a unique blow pattern, expert die makers can adjust the typically round shape of the parison to be more oblong by changing the shape of the extrusion die. This change in die shape causes the parison to form is such a way that when it is blown into the mold wall thicknesses will be more uniform throughout the bottle.

2.4 High Density Polyethylene

Polyethylene is a petroleum-based plastic that is used in many applications in plastics processes. Polyethylene comes in two major forms; high density polyethylene (HDPE) and low density polyethylene (LDPE). HDPE typically is a more rigid material and has excellent chemical and corrosion resistant properties. HDPE has a density value of .935 to .96 g/cm^3 (IDEAS). It is also a favorable material as it is relatively low cost and easy to process with over 30 million tons used each year, 28% of which is used in EBS.

2.5 Potato Based TPS and Extrusion Blow Molding

Starch or amylin is a material found in abundance in nature. It can be found in cereals and tubers; these plants includes; potatoes, cassava, rice, corn, wheat and cassava. Starch is composed of two polysaccharides, amylose and amylopectin and starch crops have their own unique amylose: amylopectin ratio which results in a slightly different form of starch (Hunealt).

Previous research by Boardman indicated that various blends of ESR can successfully be injection molded and Ellingson further researched the performance of ESR by testing the effects of moisture content on various ESR blends. Ellingson's research showed that moisture content had a significant effect on tensile properties of various TPS/HDPE blends.

Studies confirm that through the correct processes TPS can be pelletized (Weidman) and that TPS and HDPE can successfully be used in the EBM process (Andersen). US Patent 6,844,380 (Favis) and US 6,605,657 further prove that HDPE can be combined for plastic processing.

3 RESEARCH METHODOLOGY

3.1 Introduction

As stated above, the purpose of this research is to measure and record processability and characteristics of various HDPE/ESR blends.

3.2 Materials

This research will test the performance of ESR/HDPE blends in varying ratios. The two base materials, ESR and HDPE, will be blended, extruded and cut into pellet form. ESR is the product manufactured by BiologiQ, Inc. and is coded GS270. The ESR resin is made of a blend of potato starch and 27% glycerol, which acts as a plasticizer. The ESR and HDPE materials will be blended according to the following ratios: 30/70, 50/50, and 70/30. Materials were supplied by BiologiQ. Per previous research and initial testing of ESR/HDPE "dry" blends in EBM processing the blends for this research were also combined with a compatibilizer at 5% by weight. The compatibilizer used for this work was Amplify™ manufactured by Dow Chemical Company.

3.3 Equipment

Equipment for this research consisted of machines and tools used to blow 1 gallon bottles, create testing specimens and to test the specimens.

3.3.1 Preparation Equipment

Pellets were prepared by BiologiQ through a pelletizing and compounding process on a series of machines that employ a proprietary pelletizing process for the ESR and a twin screw compounder to formulate the ESR/HDPE/Amplify blends and pelletized.

3.3.2 Sample Processing Equipment

Figure 2: Caosheing Company Extrusion Blow Molding Machine

Design-Tek Plastics of Ogden Utah supplied both the EMB machine and machine operator to perform the testing.

3.3.3 Testing Equipment

There were three pieces of equipment used for evaluating samples. The first the Type-I tensile testing specimens were analyzed using a computer-controlled Instron 4204 machine, conforming to ASTM D 638-0 (ASTM International 2004).

The second piece of testing equipment used was Federal Micrometer Model KP-119-R2 used to measure wall thickness at sidewall and parting line.

Third was a Federal Micrometer Model KP-119-R2 ballpoint drop micrometer gage.

Figure 3: Instron 4204 Tensile Testing Machine

Figure 4: Federal Micrometer Model KP-119-R2

3.4 Experimental & Data Collection

Samples with varying proportions of HDPE/ESR were analyzed per the test methodology, tensile, elongation, modulus and wall thickness with the appropriate test apparatus. Data was collected by recording the values of the individual test results then using excel to compile and graph the data for analyzing.

3.4.1 Sample Preparation

A mold for a one-gallon bottle with handle was chosen to create bottles for the various blends. This was mold was chosen as it provided favorable features including good overall bottle length, wide bottle diameter and good features including screw neck and handle. Once bottles were formed they were used to create samples for testing (Figure 6). Two types of samples were prepared. A “dog bone” sample was prepared for tensile testing according to standard dimensions (Figure 5). These samples were taken from two locations on the bottle; the sidewall and from the parting line regions (Figure 7). The second type of sample that was prepared was taken from the bottom of the bottle to measure wall thickness (Figure 8).

Figure 5: Dogbone Sample Template

Figure 6: Gallon Bottle Sample

Figure 7: Bottles with Samples Removed (L-R 0% ESR, 30% ESR, 40% ESR, 50% ESR)

Figure 8: Bottle Samples (Upper left 0% ESR, Upper right 30% ESR, Lower left 40% ESR, Lower right 50% ESR)

3.5 Data Analysis Methods

Data was gathered from Instron tensile testing machine according to ASTM D638 Tensile Strength Modulus and Elongation for 10 samples of each HDPE/ESR blend at wide wall and parting line locations. This data was collected and used to determine average; tensile strength, tensile elongation and modulus.

Material Thickness was gathered using micrometer on 10 samples of each HDPE/ESR blend. Measurements were taken at sidewall and parting line locations and this data was used to find average wall thickness.

4 RESULTS AND ANALYSIS

4.1 Processing

The EBM machine was setup to the 100% HDPE process parameters and several control bottles were processed. After several samples of the 100% HDPE were prepared the machine was purged of the 100% HDPE material to ensure a pure blend of ESR/HDPE was processed for this testing. During the sample runs, measures were taken to ensure that the material from previous sampling was flushed from the machine to ensure that blends were not mixed with previous blends. This process included adding color markers to the pellet hopper to indicate when all old material had passed through the screw. Once the desired blend of ESR/HDPE was passing from nozzle there were several adjustments that needed to be made to improve processability of the parison in the mold. In the testing it was observed that steam emitted from the nozzle and it appeared to cause the parison to expand and inflate. It was also noted that as the ratio of ESR increased the amount of steam increased. Based on this observation the nozzle pressure was reduced to compensate for the additional pressure caused by the buildup of steaming gasses.

Figure 9: Bubbling Parison

It was also noted that each blend of ESR/HDPE flowed differently and required adjustments were made to the screw speed to change flow speed to ensure walls and features formed correctly. It was observed that the handle portion of the bottle frequently did not form correctly. (See Figure 10) This may be caused by a number of factors including; cold fronts in the resin causing knit lines and preventing blending of the ESR/HDPE flow. It was also observed that the flashing became more difficult to remove as the ESR content increased and that as flashing was removed parts began to tear along parting lines more easily. Several bottles did not form correctly as there appeared to be unformed pellets or particles in the walls of the bottles that caused the bottle to rupture and therefore not inflate correctly (Figure 13).

Figure 10: Example of Handle Defect

Figure 11: Example of Bottom Defect

Figure 12: Sidewall Defect, Example 1

Figure 13: Sidewall Defect, Example 2

Figure 14: Sidewall Defect, Example 3

Figure 15: Bottle Defect, Example 4

Figure 16: Parting Line Test Samples

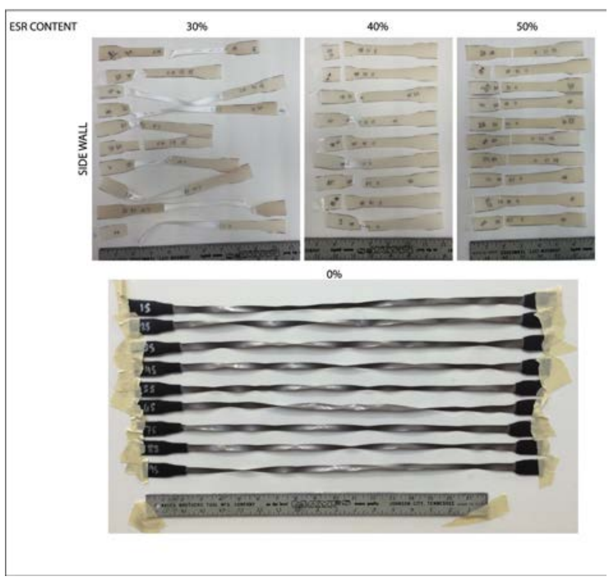


Figure 17: Sidewall Test Samples

4.2 Mechanical Properties Characterization

4.2.1 Wall Thickness

Tests showed that average wall thickness for both sidewall and parting line samples decreased from 100% HDPE to 70% HDPE. Average wall thickness increased from 70% HDPE to 60% HDPE and 50% HDPE. Parting line wall thickness at the 50% HDPE did not return to the same wall thickness as the control whereas the sidewall sample at 50% HDPE nearly matched the control. This data rejects hypothesis in that the wall thickness became less uniform as ESR content increased.

There may be a number of factors that influence this behavior. This may be a result of a pre-stretching the bottle caused by bubbling of the parison. This bubbling appeared to be a result of steam emitted from the molten resin that accumulated inside the enclosed parison. It was observed that the amount of steam increased as the ERS content increased. This pre-stretching of the parison may be a reason for the trend in wall thickness. Figures 18 and 19 illustrate this concept in that a parison that is slowly stretched may form a more uniform wall thickness and once the mold closes around the parison the walls of the parison travel a smaller distance to the extremity of the mold. This idea may be further supported by the subsequent tensile strength and tensile elongation data.

Other factors that may affect the uniformity of wall thickness may involve varying cooling and shrinking effects of each blend. Each blend may flow differently from the extrusion nozzle, stretch and cool at different rates thereby changing the wall thickness.

The comparative statistical data of minimum wall thickness collected shows that variation from side wall and parting line thickness decrease and that walls become more uniform between parting line and sidewall regions as ESR content increased (Figure 19).

Table 1: Wall Thickness

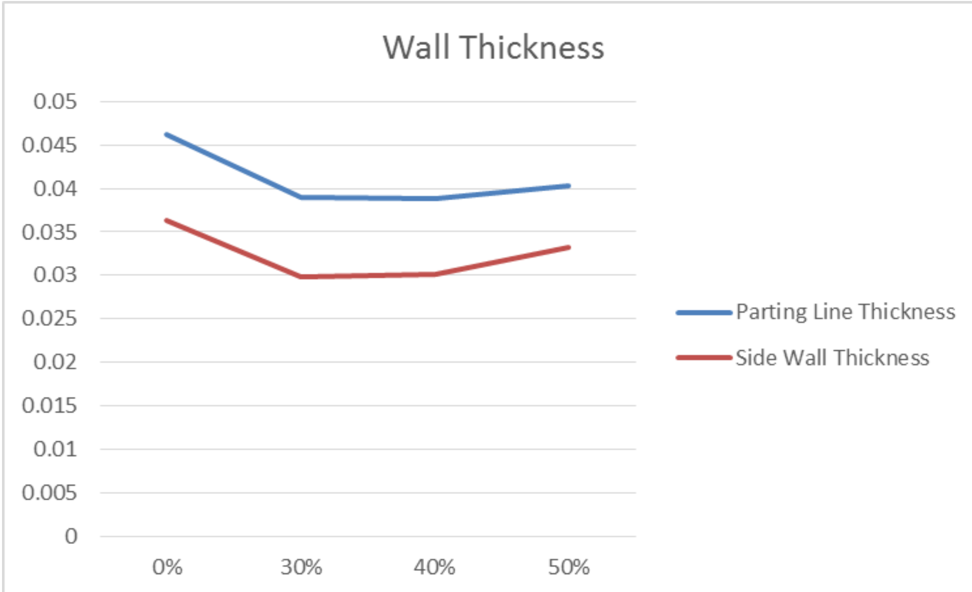
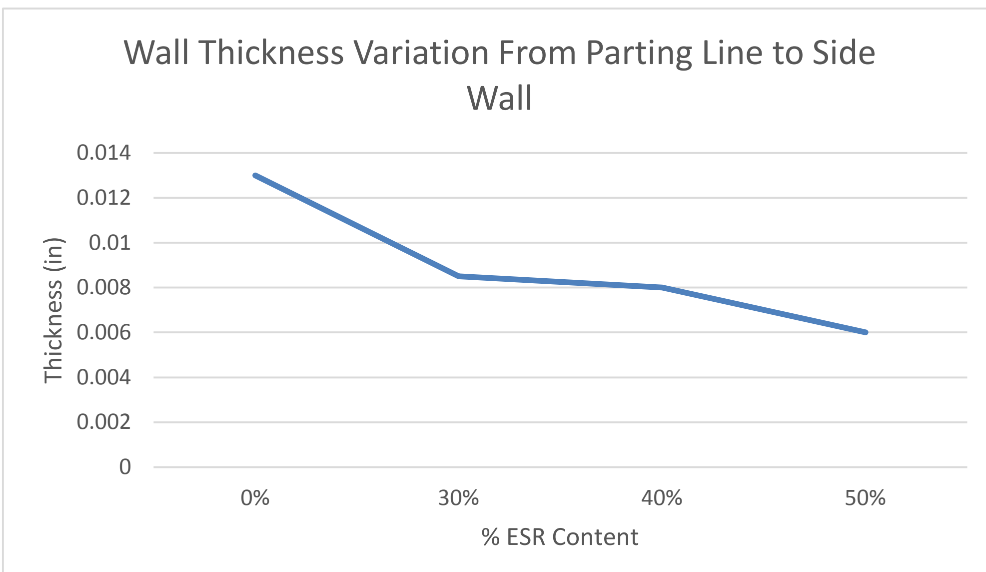


Table 2: Wall Thickness Variation



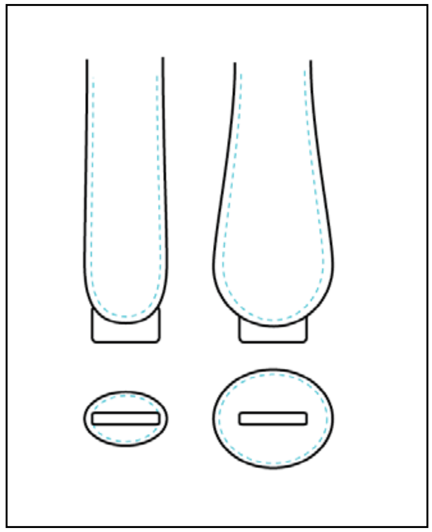


Figure 18: Example of Standard HDPE Parison (L) and HDPE/ESR Parison (R)

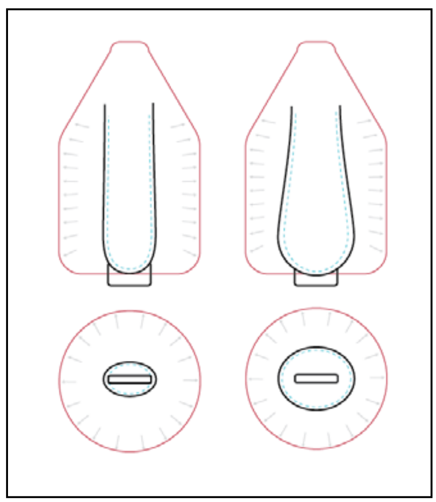
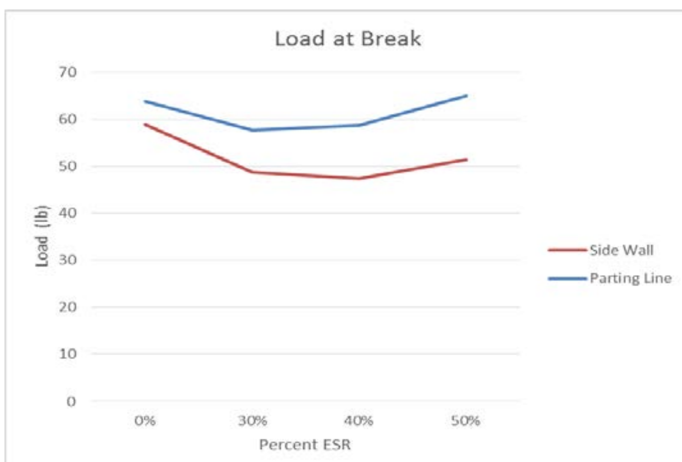


Figure 19: Example of Standard HDPE Parison (L) and HDPE/ESR Parison (R) with Mold Lines (Red)

4.2.2 Tensile Strength Tensile Strength

Testing showed that 30% ERS had a weaker tensile strength than the control for both sidewall and parting line samples and that as the content of ERS increased tensile strength generally increased. While this data generally supports hypothesis two the data is useful but difficult to compare as dog bone sample had a varying wall thickness and is therefore difficult to compare with each blend. The general increase in tensile strength may be attributed to the highly crystalline structure of starch resins. In the low ESR blends there may have not been enough material to create a strong polymer chain and as the content of ESR increased the additional starch may have created a stronger crystalline structure thereby increasing overall tensile strength.

Table 3: Max Load at Break

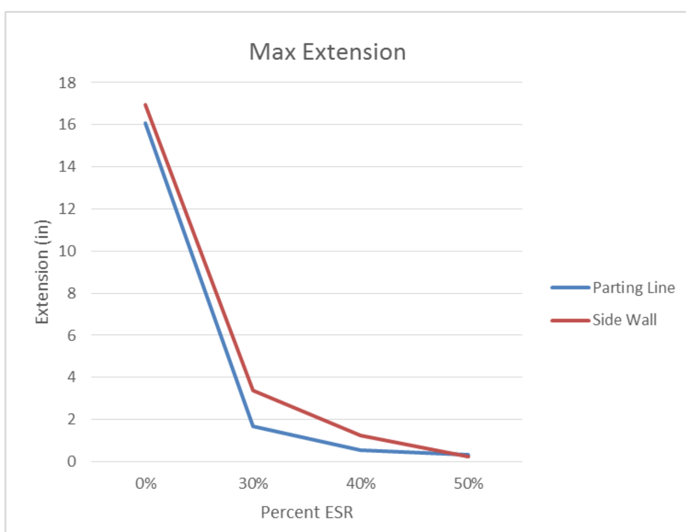


4.2.3 Tensile Elongation

Test results supported hypothesis 4 in that the data showed that as ESR content increased elongation decreased. The results were very pronounced as even the lowest content of ESR at 30% yielded only a fraction of the elongation of the control. As seen in images and testing data the length of elongation became shorter and shorter as ESR content increased and the 50% ESR showed nearly no elongation and appeared to fracture rather than stretch. See appendix A for the complete charts of the tensile data.

This data further supports the idea that the crystalline structure of the plastic increases as starch content increases as each sample become losses plasticity as the amount of HDPE decreases. One might compare an increase in starch content to a bottle transitioning from plastic to glass. While a plastic bottle may swell under pressure as side walls stretch and eventually rupture a glass bottle will not exhibit nearly the same type of swelling and will eventually result in a much more energetic explosion.

Table 4: Maximum Extension



4.2.4 Tensile Modulus

This hypothesis was confirmed in the fact that as ESR is added to the HDPE the modulus decreases as the crystalline structure of the material in increased. However the results of the addition of more ESR to the blend met with mixed results. Where the modulus comparison of the 50% and 60% HDPE showed the declining trend of modulus as the HDPE was reduced and replaced with ESR. However the average modulus of the 70% HDPE/ 30% ESR had a similar modulus result. Further investigation into why this is the case is necessary to understand this better.

Table 5: Combined Parting Line Modulus

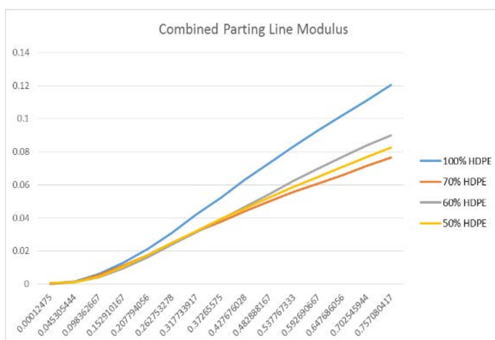
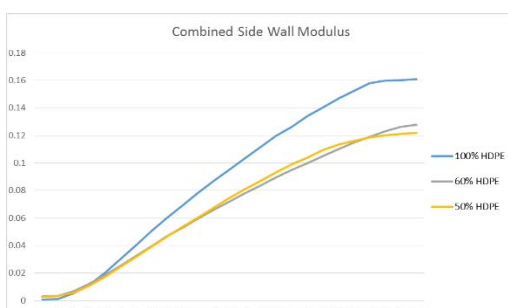


Table 6: Combined Side Wall Modulus



4.2.5 Formability

Bottles were able to be successfully formed up to the 50% ESR blend. Unfortunately samples with higher percentages of ESR were not available for testing. These higher ESR content pellets will be important to find if bottles can be formed with up to 100% ESR. It was observed throughout processing that several features of the bottles changed as the ESR content increased. It was observed that handles often did not form correctly. Impurities in the resin created voids that caused leaks that prevented proper inflation of the parison. It was also noted that as the ESR content increased flashing became more difficult to remove from bottles particularly after the bottles had cooled. It was also noted that during the flashing removal processes material tended to tear along parting lines.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Through a series of tests this study helped to characterize and measure processability of various HDPE/ESR blends. Notwithstanding an increase in processing challenges it was proven that blends with 30%, 40% and 50% ESR content can successfully be formed in the extrusion blow molding process.

Testing on the sample bottles revealed information regarding the uniformity of wall thickness at the mold parting lines and sidewalls, tensile strength, tensile elongation and Young's Modulus.

5.2 Conclusion

In order to characterize and measure processability of various blends of HDPE/ESR the following hypotheses were tested:

Hypothesis 1: *As the proportion of ESR increases there will be a less uniform wall thickness.* The hypothesis was not supported as the data showed there was more uniform wall thickness from the parting line to the sidewall regions as the proportion of ESR increased.

Hypothesis 2: As the proportion of ESR increases there will be an increase in tensile strength. This hypothesis was supported as there was initially a decrease in tensile strength at 30% ESR compared to the control which then increased slightly as the sidewall at 50% ESR was slightly stronger than the control and the parting line average was slightly weaker than the control.

Hypothesis 3: As the proportion of ESR increases tensile elongation will decrease. The hypothesis was supported as each blend decreased in tensile elongation as the ESR content increased.

Hypothesis 4: As the proportion of ESR increases the tensile modulus will decrease. This hypothesis was inconclusive. Although each sample decreased in tensile modulus compared to the control the data did not support a downward trend as ESR content increased.

Hypothesis 5: There is a threshold of ESR above which a bottle will not form. This hypothesis is inconclusive as the testing was limited to 50% ESR content and bottles were able to be successfully formed up to this ESR percent.

5.3 Discussion

This research uncovered a variety of valuable information surrounding a new biopolymer blend that may have interesting applications in production to reduce the amount of petroleum-based plastics being used. This new material reacted in interesting ways that vary significantly from pure HDPE in the blow molding process. One interesting reaction the appeared to greatly affect the formability and performance of the various blends is in the steam that each blend emitted.

5.4 Recommendations

While this research did much by exploring a new material in a widely used manufacturing process much can be gathered through additional testing. It would be valuable to continue the research to process bottles with higher ESR content to discover if bottles can be formed with up to 100% ESR content and the physical characteristics and performance of these higher ESR content blends. Additional testing involving the pre-drying of ESR/HDPE pellets to see if there is any reduction in steam output through a reduction in moisture content would also be valuable to review the effects of moisture and steam in the processability and formability of HDPE/ESR bottles. While it was noted that flashing tore away with more difficulty as ESR content increased and bottles appeared to fracture along parting lines additional research around the impact strength and burst strength of various HDPE/ESR blends would also be very valuable to more fully understand the viability of this product. It would also be very valuable to perform each tensile strength, elongation and modulus testing at the processing temperature see how a hot parison and bottle react in processing.

REFERENCES

Barnes, D.K.A., F. Galgani, R.C. Thompson, and M. Barlaz. 2009. “Accumulation and Fragmentation of Plastic Debris in Global Environments.” *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences,* 1985.

Boardman, A., Lindmark, J. “Characterization and Comparison of Mechanical Properties and Processability of 100% Maize/Glycerrol, Potato/Glycerol and Cassava/Glycerol Starch Composite Blends”. Eurotec 2013 Conference Proceedings.

Brandau, O. “Six Common-Sense Tips: Optimize Resin Management in Extrusion Blow Molding.” *Plastics Technology* 59, no. 1 (2013): 23.

Ellingson, J. “Starch Resin Moisture Level Effect on Injection Molding Processability and Molded Part Mechanical Properties with Pure Starch Resin and Polymer Blends”. Brigham Young University Masters Thesis, 2013.

Favis, B.D., F. Rodriguez, and B.R. Ramsay. United States Patent 6,844,380. 2002.

______. United States Patent 6,605,657. 2002.

Gerngross, T. "How Green Are Green Plastics." *Scientific American*, 2000: 36-41.

IDEAS. “Polyethylene (PE) Plastic.” http://plastics.ides.com/generics/27/polyethylene-pe (accessed 4/22/13).

Kaseem, M., K. Hamad, and F. Deri. 2012. “Thermoplastic starch blends: A review of recent works.” *Polymer Science Series A,* 165.

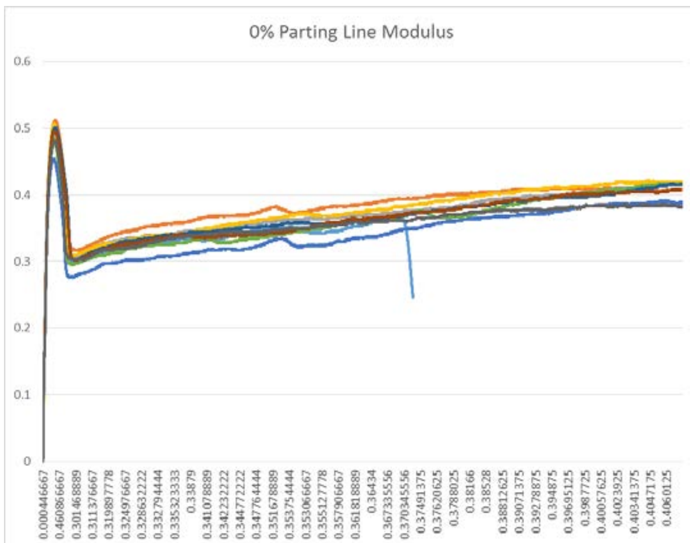
Mościcki, L. “Application of Extrusion-Cooking for Processing of Thermoplastic Starch” *Food Research International* 47, no. 2 (2012): 291-299.

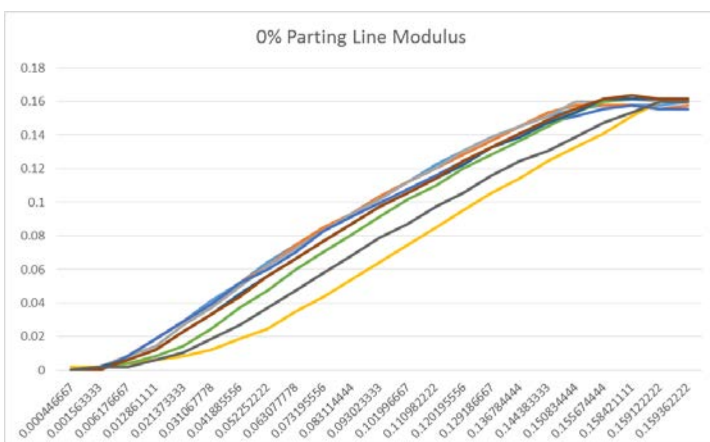
Song, J.H., R.J. Murphy, R. Narayan, and G.B.H. Davies. “Biodegradable and Compostable Alternatives to Conventional Plastics.” *Philosophical Transactions of the Royal Society Biological Sciences,* 2009: 2127.

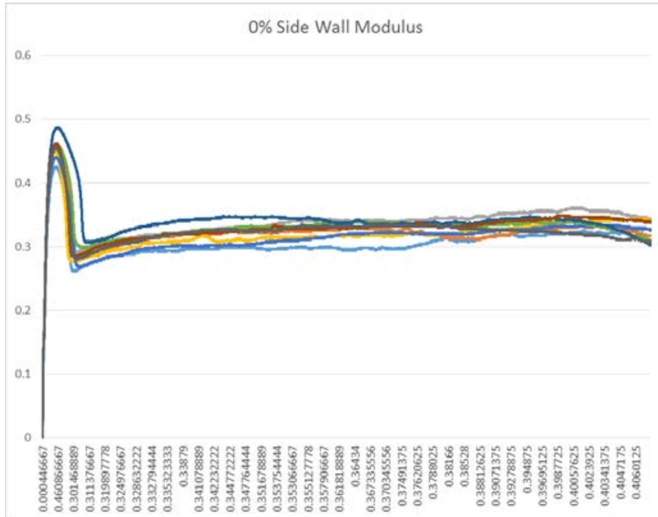
Weidman, W. and E. Strobel. “Compounding of Thermoplastic Starch with Twin-screw Extruders.” *Starch/Stärke* 43, no. 4 (1991): 138-145.

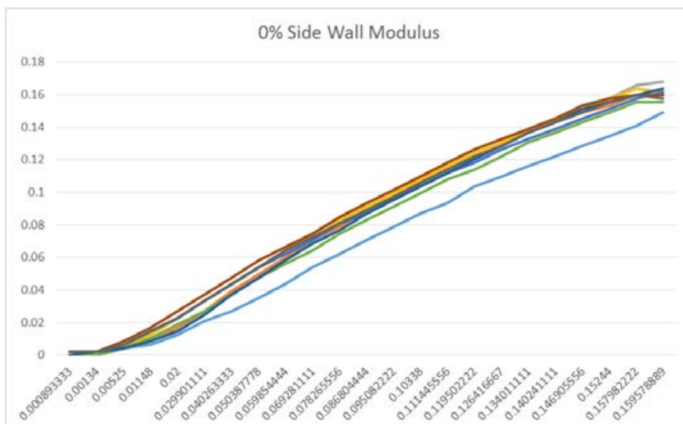
APPENDICES

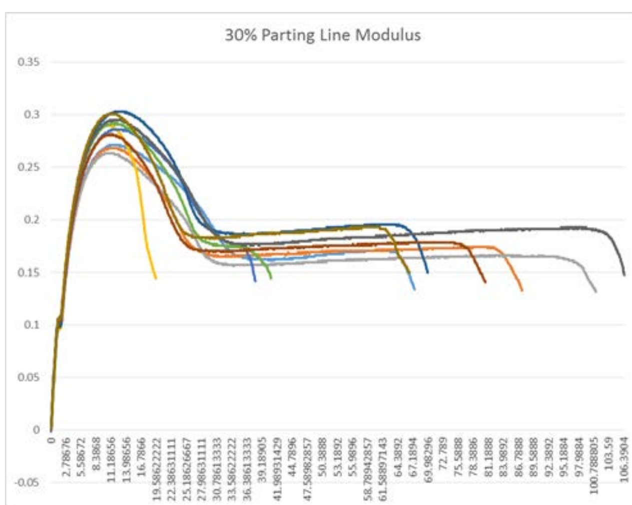
APPENDIX A: TENSILE TESTING DATA

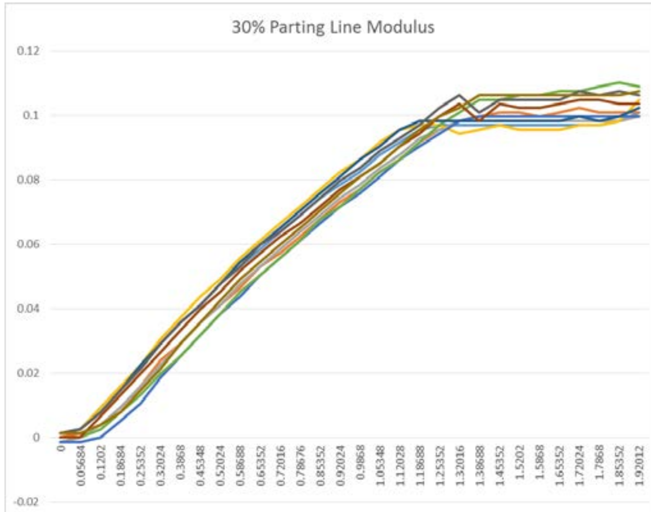


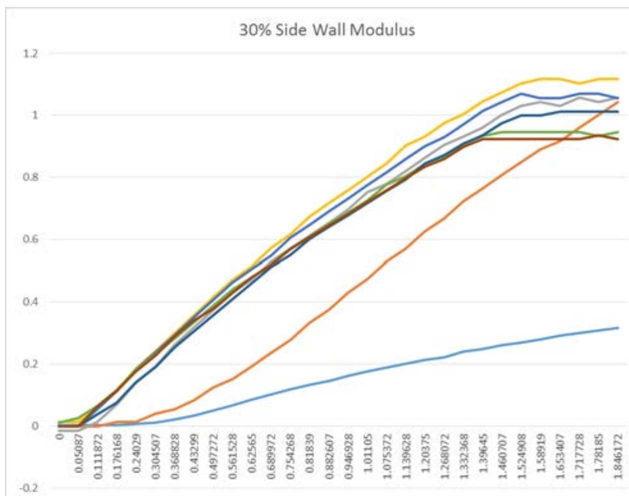


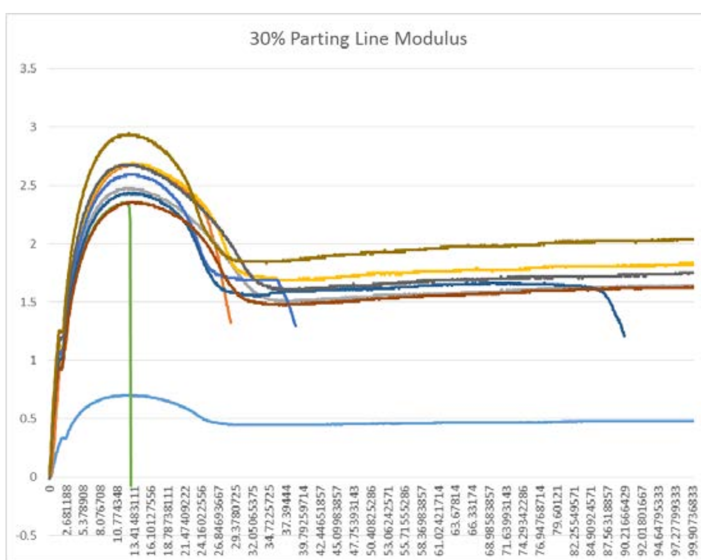

0% Side Wall Modulus

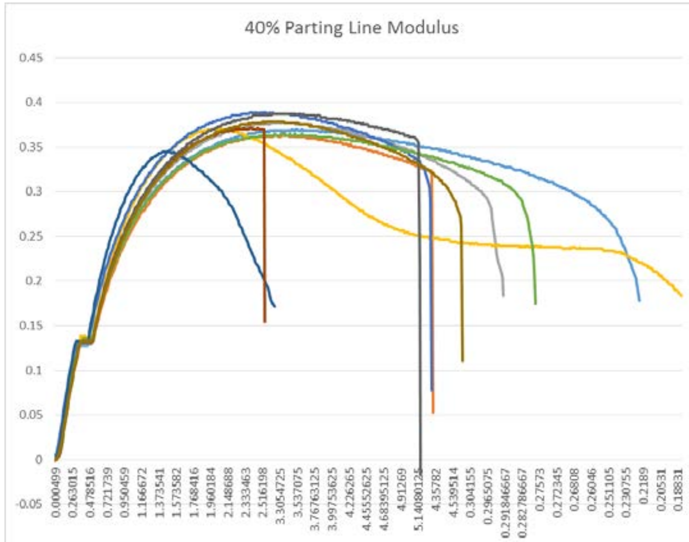

0% Side Wall Modulus

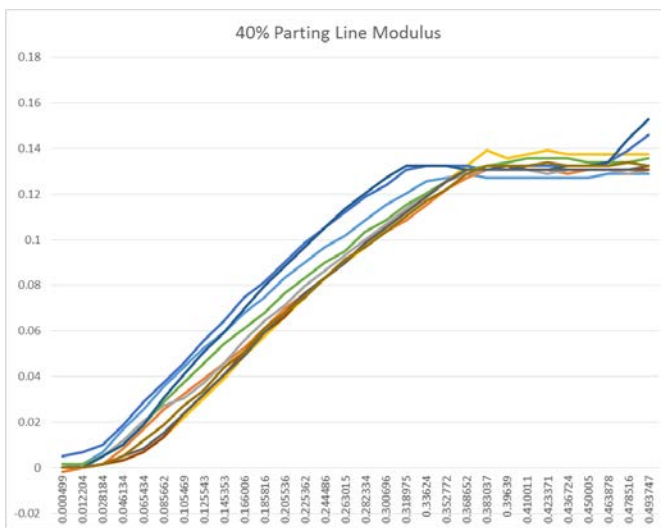

30% Parting Line Modulus

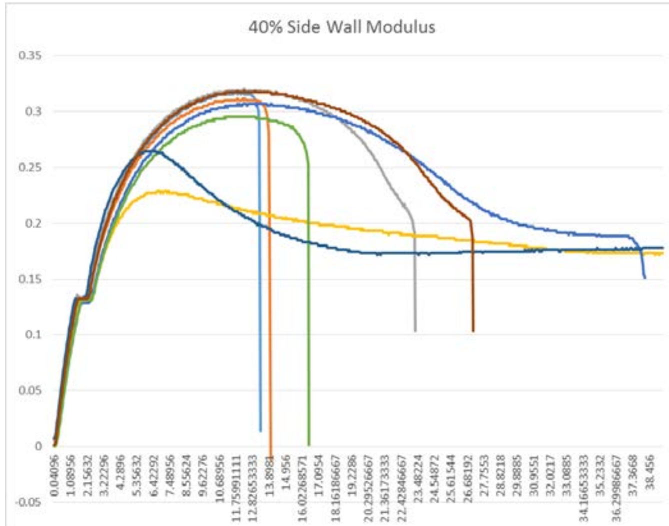

30% Parting Line Modulus
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
0
0.05684
0.1202
0.18684
0.25352
0.32024
0.3868
0.45348
0.52024
0.58688
0.65352
0.72016
0.78676
0.85352
0.92024
0.9868
1.05348
1.12028
1.18688
1.25352
1.32016
1.38688
1.45352
1.5202
1.5868
1.65352
1.72024
1.7868
1.85352
1.92012

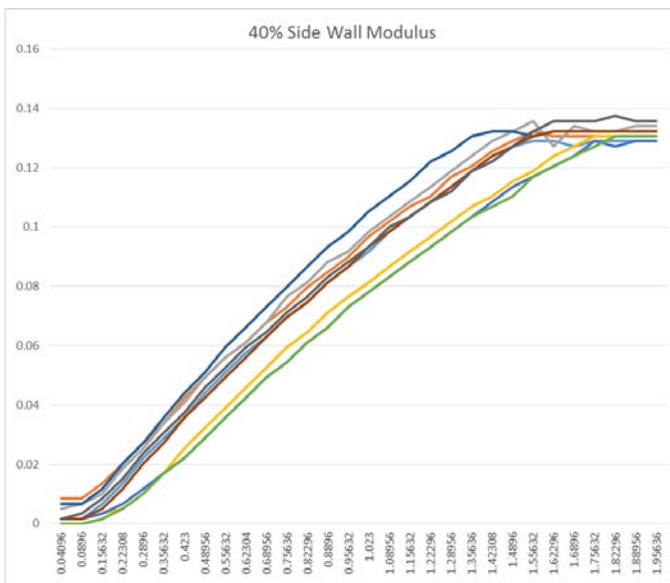

30% Side Wall Modulus
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
0.05087
0.111872
0.176168
0.24029
0.304507
0.368828
0.43299
0.497272
0.561528
0.62565
0.689972
0.754268
0.81839
0.882607
0.946928
1.01105
1.075372
1.139628
1.20375
1.268072
1.332368
1.39645
1.460707
1.524908
1.58919
1.653407
1.717728
1.78185
1.846172

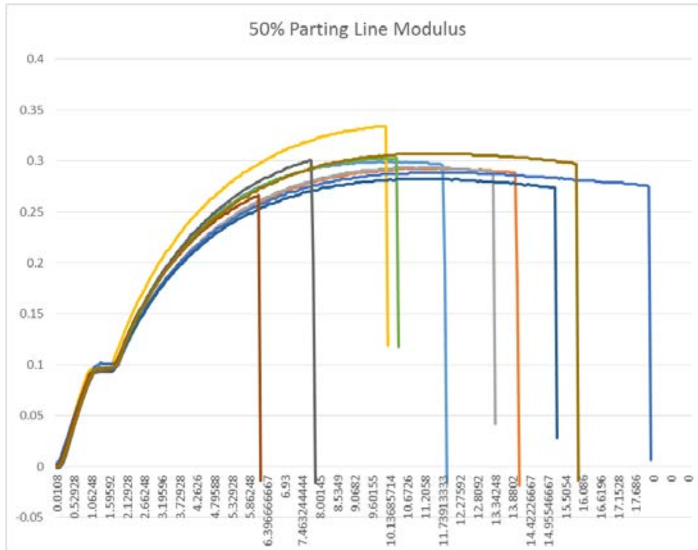

30% Parting Line Modulus
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
0
2.681188
5.378908
8.076708
10.774348
13.41483111
16.10127556
18.78738111
21.47409222
24.16023556
26.84693667
29.3780725
32.05065375
34.7225725
37.39444
39.79259714
42.44651857
45.09983857
47.75393143
50.40825286
53.06242571
55.71555286
58.36983857
61.02421714
63.67814
66.33174
68.98583857
71.63993143
74.29342286
76.94768714
79.60121
82.25549571
84.90924571
87.56318857
90.21666429
92.01801667
94.64795333
97.27799333
99.90736833

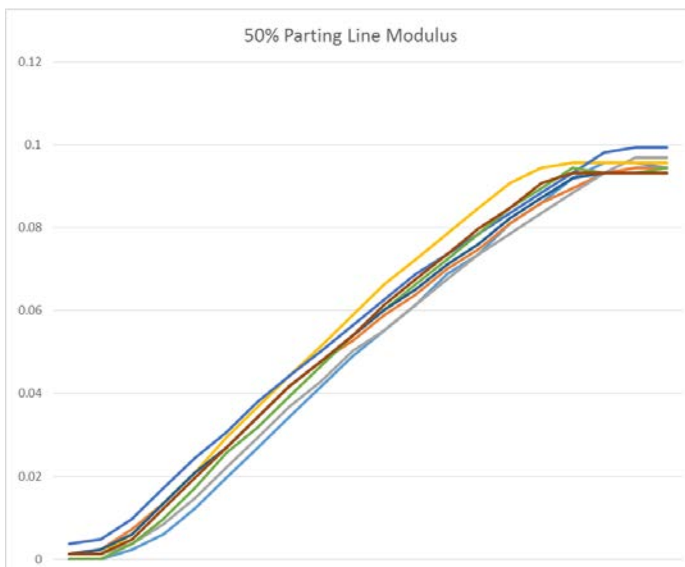

40% Parting Line Modulus


40% Parting Line Modulus


40% Side Wall Modulus
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0.04096
1.08956
2.15632
3.22296
4.2896
5.35632
6.42292
7.48956
8.55624
9.62276
10.68956
11.75991111
12.82653333
13.8981
14.956
16.02268571
17.0954
18.16186667
19.2286
20.29526667
21.36173333
22.42846667
23.48224
24.54872
25.61544
26.68192
27.7553
28.8218
29.8885
30.9551
32.0217
33.0885
34.16653333
35.2332
36.29986667
37.3668
38.456


40% Side Wall Modulus
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.04096
0.0896
0.15632
0.22308
0.2896
0.35632
0.423
0.48956
0.55632
0.62304
0.68956
0.75636
0.82296
0.8896
0.95632
1.023
1.08956
1.15632
1.22296
1.28956
1.35636
1.42308
1.4896
1.55632
1.62296
1.6896
1.75632
1.82296
1.88956
1.95636


50% Parting Line Modulus
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0.0108
0.52928
1.06248
1.59592
2.12928
2.66248
3.19596
3.72928
4.2626
4.79588
5.32928
5.86248
6.396666667
6.93
7.463244444
8.00145
8.5349
9.0682
9.60155
10.13685714
10.6726
11.2058
11.73913333
12.27592
12.8092
13.34248
13.8802
14.42226667
14.95546667
15.5054
16.086
16.6196
17.1528
17.686
0
0
0


50% Parting Line Modulus
0.12
0.1
0.08
0.06
0.04
0.02
0


50% Side Wall Modulus
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
0.013437
0.046193
0.087249
0.129654
0.172334
0.215484
0.258633
0.301935
0.344773
0.387918
0.430751
0.473396
0.516382
0.559092
0.601268
0.644293
0.686149
0.727918
0.769812
0.810914
0.851345
0.892007
0.932334
0.972447
1.012487

APPENDIX B: WALL THICKNESS MEASUREMENTS

0%	Thickness	Width	Cross Sectional Area
1P	0.0455	0.524	0.023842
2P	0.046	0.592	0.027232
3P	0.0475	0.5785	0.027479
4P	0.05	0.569	0.02845
5P	0.0455	0.543	0.024707
6P	0.046	0.5485	0.025231
7P	0.0445	0.5425	0.024141
8P	0.047	0.5415	0.025451
9P	0.0435	0.529	0.023012

30%	Thickness	Width	Cross Sectional Area
1P	0.0355	0.508	0.018034
2P	0.037	0.513	0.018981
3P	0.0375	0.4935	0.018506
4P	0.04	0.5525	0.0221
5P	0.0385	0.5375	0.020694
6P	0.039	0.55	0.02145
7P	0.039	0.5545	0.021626
8P	0.0385	0.509	0.019597
9P	0.039	0.5445	0.021236
10P	0.042	0.5245	0.022029

0%	Thickness	Width	Cross Sectional Area
1S	0.0305	0.5155	0.015723
2S	0.038	0.5075	0.019285
3S	0.0375	0.545	0.020438
4S	0.0355	0.5275	0.018726
5S	0.037	0.515	0.019055
6S	0.036	0.575	0.0207
7S	0.037	0.566	0.020942
8S	0.0395	0.537	0.021212
9S	0.0365	0.558	0.020367
	0.036389		

30%	Thickness	Width	Cross Sectional Area
1S	0.027	0.5115	0.013811
2S	0.031	0.5565	0.017252
3S	0.0285	0.5685	0.016202
4S	0.0325	0.5285	0.017176
5S	0.0285	0.539	0.015362
6S	0.0295	0.5565	0.016417
7S	0.0295	0.541	0.01596
8S	0.0315	0.535	0.016853
9S	0.028	0.534	0.014952
10S	0.029	0.5445	0.015791

40%	Thickness	Width	Cross Sectional Area
1P	0.035	0.5665	0.019828
2P	0.036	0.551	0.019836
3P	0.036	0.5765	0.020754
4P	0.0455	0.567	0.025799
5P	0.0425	0.57	0.024225
6P	0.035	0.5555	0.019443
7P	0.0455	0.5805	0.026413
8P	0.0365	0.5455	0.019911
9P	0.036	0.579	0.020844
10P	0.037	0.5655	0.020924

50%	Thickness	Width	Cross Sectional Area
1P	0.0415	0.5365	0.022265
2P	0.0405	0.527	0.021344
3P	0.0405	0.5235	0.021202
4P	0.0445	0.526	0.023407
5P	0.036	0.56	0.02016
6P	0.04	0.537	0.02148
7P	0.037	0.548	0.020276
8P	0.0405	0.5295	0.021445
9P	0.042	0.549	0.023058
10P	0.0415	0.5705	0.023676

40%	Thickness	Width	Cross Sectional Area
1S	0.0285	0.5655	0.016117
2S	0.0285	0.5455	0.015547
3S	0.029	0.5625	0.016313
4S	0.033	0.5965	0.019685
5S	0.027	0.576	0.015552
6S	0.028	0.552	0.015456
7S	0.0415	0.5555	0.023053
8S	0.0285	0.5595	0.015946
9S	0.028	0.5815	0.016282
10S	0.027	0.577	0.015579

50%	Thickness	Width	Cross Sectional Area
1S	0.03058	0.5375	0.016437
2S	0.0355	0.5285	0.018762
3S	0.0315	0.526	0.016569
4S	0.031	0.554	0.017174
5S	0.036	0.546	0.019656
6S	0.0305	0.547	0.016684
7S	0.039	0.58	0.02262
8S	0.03	0.5595	0.016785
9S	0.0305	0.55	0.016775
10S	0.035	0.584	0.02044

APPENDIX C: TENSILE ELONGATION MEASUREMENTS

	Load at Machine Peak Load (lbf)	Extension (in)		Load at Machine Peak Load (lbf)	Extension (in)
0%	**Parting Line**			**Side Wall**	
1P	63.89	9.73	**1S**	55.03	16.90
2P	66.30	16.95	**2S**	59.06	17.15
3P	64.96	16.92	**3S**	59.59	17.03
4P	65.77	17.00	**4S**	58.25	17.03
5P	58.79	16.93	**5S**	56.91	16.83
6P	62.81	16.90	**6S**	59.86	16.98
7P	64.96	16.79	**7S**	63.08	16.83
8P	64.16	16.75	**8S**	59.86	16.82
9P	62.28	16.85	**9S**	59.06	16.91
30%	**Parting Line**			**Side Wall**	
1P	54.76	1.69	**1S**	43.75	5.41
2P	54.22	2.15	**2S**	51.54	0.75
3P	53.15	2.53	**3S**	47.78	5.98
4P	58.79	0.49	**4S**	50.46	5.25
5P	57.98	0.95	**5S**	49.66	1.02
6P	59.06	1.03	**6S**	48.59	0.34
7P	61.20	1.75	**7S**	51.00	2.38
8P	56.91	2.02	**8S**	49.93	3.70
9P	59.86	2.67	**9S**	45.36	5.41
10P	60.93	1.67	**10S**	49.66	3.63
40%	**Parting Line**			**Side Wall**	
1P	58.52	0.79	**1S**	50.20	0.34
2P	57.44	0.51	**2S**	49.39	0.35
3P	59.59	0.61	**3S**	50.73	0.59
4P	58.52	0.85	**4S**	36.24	6.82
5P	61.47	0.51	**5S**	49.59	0.95
6P	57.71	0.65	**6S**	46.71	0.41
7P	54.49	0.30	**7S**	41.87	1.15
8P	58.79	0.28	**8S**	50.46	0.68
9P	61.20	0.49	**9S**	48.59	0.27
10P	59.86	0.55	**10S**	50.73	0.84
50%	**Parting Line**			**Side Wall**	
1P	65.50	0.30	**1S**	53.69	0.36
2P	64.16	0.35	**2S**	48.59	0.30
3P	64.16	0.34	**3S**	47.24	0.18
4P	73.02	0.25	**4S**	44.29	0.19
5P	63.08	0.46	**5S**	56.91	0.26
6P	66.30	0.26	**6S**	46.97	0.15
7P	61.74	0.38	**7S**	62.81	0.32
8P	58.25	0.16	**8S**	54.22	0.27
9P	65.77	0.20	**9S**	45.36	0.17
10P	67.38	0.40	**10S**	55.03	0.19

APPENDIX D: EXTRUSION BLOW MOLDING MACHINE SPECIFICATIONS

2005-Leshan- SCJ-75-55U+S2X1.10F HDPE Shuttle Blowmolder Model 75K2X 1.7
Serial #75-2005547M22D
Single Head-Dual Blow Station-75mm Screw Extruder, Hopper with Loader System, Digital Control, Chiller SC-010A, Low Pressure
Loader System, Digital Control, Low Pressure
Compressor 12.5 KG/1.8M3 with tank, Air Dehumidifier 30 KGS, Set of Gallon (125gr) and Set of Half, Gallon (65gr) Industrial Round Molds (4 Total)

APPENDIX E: DESCRIPTIVE COMPARITIVE STATISITCAL ANALYSIS DATA

	PL - 00	SW - 00	PL - 30	SW - 30	PL - 40	SW - 40	PL - 50	SW - 50
Max	0.05	0.0395	0.042	0.0325	0.0455	0.0415	0.0445	0.039
Min	0.0435	0.0305	0.0355	0.027	0.035	0.027	0.036	0.03
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]