Texture comparison in chips in various environments through mechanical property estimation

An Interactive Qualifying Project Report

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Abstract

Crispiness is an important factor when gauging the quality and freshness of a potato chip. In this study, the effects of pH and moisture content on the compressive and flexural properties of different types of chips were studied. In general, chips with surface ridges were found to have a lower compressive strength than the plain chips. It was determined that the breaking pattern of the chips during compression and flexural testing can be correlated with chip crispiness.

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Introduction

With potato chips earning $7.1764 Billion of revenue and tortilla chips generating an additional $5.5798 Billion in 2009 (1), Potato chips represent an enormous portion of the snack foods consumed in the United States and other western countries. Potato chips are such a popular snack that, according to the USDA, in 2007, 16 pounds of potato chips were consumed per capita in the United States. (2)

Plenty of research is done by Potato Chip manufacturers into the preservation of chips, but the goal of the research is to ensure that the product remains edible throughout its shelf life. This leaves an opportunity to gather unique data on the physical characteristics of chips that have been exposed to the air. Crunchiness is the most important aspect of a potato chip. Once a chip has lost its crunchiness, it is considered stale and inedible. The texture of the chips will deteriorate so quickly that most chips are discarded due to an unappetizing texture, only rarely do chips stay out long enough for them to become unsafe to eat. With potato chips generating such large revenues, the amount of chips wasted out of each bag becomes a topic of legitimate economic concern. The primary goal of our project was to scientifically model the process of a chip becoming stale.

In order to empirically define the crunchiness of a chip we performed compression tests on several different brands of chips. These chips were placed in controlled environments of low, normal, and high humidity. Additionally, we found the free water content and acid content as part of our efforts to define as many of the physical characteristics of potato chips as possible. The large quantity of data we have collected will help future efforts to improve on the ways chips are stored after the initial seal has been broken.

Background

The potato chip was famously invented on August 24, 1853 when a customer at the Moon's Lake House restaurant in Saratoga Springs, New York sent his French-fried potatoes back to the kitchen complaining that they were too thick and bland. The chef, George Crum, sliced the potatoes paper thin, hoping to rile the customer with a French-fried potato that could not be skewered with a fork. Crum's plan backfired and the newly invented chips were a hit.

To create potato chips, fresh potatoes are cleaned, peeled, and then cut into thin slices. This process can be done by hand, but is far more commonly done by a large machine in a factory. The slices are then fried in vegetable oil, allowed to cool, and salted. From this basic recipe there is plenty of room for variation. The cutting edge used in a factory can be replaced with a blade that will cut the potatoes into different shaped slices, like the ruffle shape. Additional seasoning can be added to the chips to create artificial flavors such as barbeque, and salt and vinegar. In the factory, discolored chips are sorted out by an electronic camera and discarded. The chips are then sorted into uniform quantities that are weighed before the chips are bagged.

Extruded potato chips, such as Pringles or Lay's Stax are made through a similar process. US Patent No. 5,104,673 details a method for making extruded starch snack foods. The key difference between extruded chips and standard potato chips is that extruded potato chips are not made of potato slices. "The process of this invention comprises the steps of mixing at least one ingredient having starch with water to form a composition"(Fazzolare, 1992, pg. 3). In the case of Pringles and Lay's Stax potato flakes are mixed with water, various starches and other ingredients of small quantity. The mixture must be heated as it is mixed to form "a machinable dough-like consistency"(Fazzolare, 1992, pg. 3). This mixture is flattened into a large sheet of dough "[with] thickness of about 1/32 of an inch"(Fazzolare, 1992, pg. 7). Out of this dough, a rotary cutter punches out oval shapes. These slices continue on while the excess dough is recycled back into the process. The oval shaped slices of dough are pressed into their unique arched shape to allow stacking. They are cooked into chips the same way potato chips made of potato slices are, they are fried in oil, salted, and flavored as needed. Equal quantities of these chips are sorted into tubes designed to maintain the freshness of the chips and to maximize the number of unbroken chips.

Additional information that can be found in US Patent No. 5,104,673 includes the mention of water content of completed chips. "For products according to this invention an acceptable total moisture content after baking and drying is between .5 and 6.0 percent by weight, typically less than about 3% by weight"(Fazzolare, 1992, pg. 8). The low water content is intentional and must be maintained throughout the handling and shipping of the product to help preserve the chips. For extruded potato chips, the free water content observed during testing should be close to this range.

US Patent No. 2,916,378 details the process for making corn chips. This patent describes an improvement on the previous methods of producing corn chips. "The new process also makes it practicable to produce a corn chip of the same essential shape and thickness as a potato chip, a matter not heretofore possible" (Kunce, 1959, pg. 1). The patent also mentions a reduction in fat and calorie content. "The instant chip has a drier, more dainty flavor, with no oily taste or feel that are predominant characteristics of extruded chips that are not pre-baked, with a result, the consumer can eat far more of the instant chip with no undesirable after effects..."(Kunce, 1959, pg. 2). The method described for creating corn chips that is very similar to the method used to create extruded potato chips, replacing the potato flakes with cornmeal in the initial mixture. In this patent the mixture is "worked between two oppositely rotating rollers against one of which a rotating cutting bar is operating"(Kunce, 1959, pg. 1). The corn mixture can also be rolled out into a thin sheet and cut to the desired shape to create another type of corn chip. This patent refers to a dehydration step before the chips are fried in oil. "In this process the moisture content of the chip is reduced from 50% to not more than 20%". This unique step is the key to the innovation of this patent. The chips are then fried "for a period of 30 seconds at a temperature of 370° F"(Kunce, 1959, pg. 4).The excess oil is removed and the chips are salted and flavored. In some cases oil is added once again to ensure that the flavoring powder sticks to the chip.

US Patent no. 2009/0169710 describes in detail a method for making low fat potato chips. In addition to describing the conventional method for creating potato chips, the patent describes several different previous attempts to make low fat potato chips and the reasons they were not successful. The first of these was US patent no. 4,749,579 which involved washing the potato slices in a salt or brine solution. After the chips were dried they were "pre-heated with infrared radiation prior to being sent to the fryer"[Copado, 2009, pg. 1]. This method proved to reduce fat content inconsistently, and the infrared laser needed to pre-heat the chips added to expenses. US patent no.

4,917,919 involved coating a potato chip with "an aqueous, polyvinylpyrrolidone" [Copado, 2009, pg. 2]. The issue with this method is that it left chips with a 4% moisture content by weight, "raising concerns of shelf stability"[Copado, 2009, pg. 2]. A third method, detailed in US Patent No. 4,537,786, involves thicker cut chips fried in oil for a shorter period of time. Hot air was then used to remove excess oil and finish cooking the chips. The problem with this method is that "hot air tends to accelerate oxidation of the oil reducing shelf life dramatically."[Copado, 2009, pg 2]

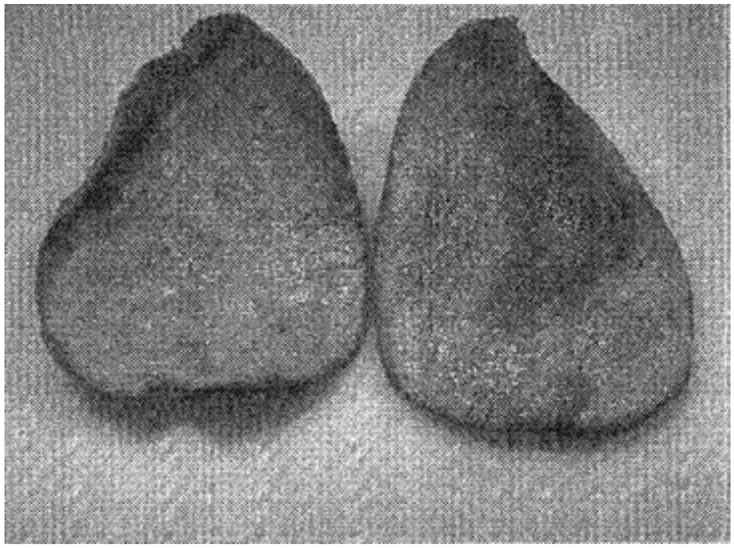
The innovation of this patent is the pretreatment step. In this method, the chips are marinated in a brine solution containing salt and acacia gum for approximately 9 to 14 seconds. This consistently reduces the fat content of potato chips without increasing the costs of production too severely. This patent displays the history of the research done to make potato chips with a lower fat content. In general the potato slices absorb fat from the oil as they are fried; all attempts to reduce the fat content of chips have been through minimizing this process. For a solution to be viable it must not increase the production costs, reduce the oil content to a point where the chip will be rejected for poor flavor, or leave the final moisture content such that the product's shelf life is reduced. While the production of potato chips is not an area of study in this project, this patent demonstrates the importance of the moisture content of potato chips. Chips with lower moisture content have a longer shelf life.

The ingredients of a brand of potato chips is an important point of reference when analyzing its physical properties. The ingredients are available on each bag and also available on the website of each brand. From the ingredients we can better classify the types of chips. Potato Chips are generally made of potatoes, vegetable oil, and salt. There is some variation in the vegetable oil used between brands. Extruded chips will identify their primary ingredient simply as dried potatoes, the other ingredients of the initial mixture are mentioned later as they represent a small percent of the chip's composition. Pita Chips supplement wheat flour in place of potatoes as the primary ingredient and corn chips use corn in place of potatoes. The exact ingredients of each brand of chip are available in appendix "?".

Modern potato chip bags are generally made of plastic. Plastic is the preferred material for potato chip packaging because it minimizes diffusion through the package, maximizing shelf life. The downside to using plastic is the distinct plastic off flavor that can be found in food products stored in plastic containers for an extended period of time. US Patent No. 2004/0043170 describes plastic packaging for potato chips and other products. The primary innovation of this patent is a reduction in plastic off flavor. "Plastic off flavor was surprisingly identified during the course of this development to be caused by a single short chain aldehyde, 8-Nonenal at extremely low levels within the product" [Zimmerman, 2004, par 0025]. The patent describes three circumstances that cause the plastic off flavor[Zimmerman, 2004, par 0026], each of them due to the production and diffusion of 8-Nonenal. If future expansion of this project involves the study of taste, experimentation to identify the presence of 8-Nonenal will be essential for quantifying the plastic off taste in chips.

US Patent No. 4,556,590 describes a flexible container for potato chips, cookies and other snack foods. The outermost layer of this package is a transparent sheet of nylon with an acrylic latex on the inner surface. This outer surface allows for effective printing on the package. The second layer is a coextruded laminate of pigmented polyethylene and an ethylene acrylic acid copolymer. Beneath the plastic layer is a metallic foil layer, the preferred material for this layer is aluminum. The inner wall of the package is a heat-sealable polyolefin. The resulting package is a flexible, printable container with minimal diffusion.

In addition to packaging, specific enzymes, such as Hexose Oxidase, can be used to preserve chips. US Patent No. 6,872,412 describes the effect of this enzyme in reducing or eliminating the Maillard reaction in a foodstuff. The examples mentioned in this patent include butterscotch, gratin, cakes, dairy products, pizza, mozzarella cheese, and potato chips. "We have found that the problems of excessive browning cause by Maillard reaction of foodstuffs with an enzyme capable of oxidising the reducing group of the sugar."[Søe, 2005, pg 3] The patent describes an experiment in which potato slices were divided into two groups, one group was treated with Hexose Oxidase and the other remained a control group. After the chips were fried in oil at 180°C for two minutes the chips treated with Hexose Oxidase remained lighter than the control group as displayed below.



US Patent No. 6,872,412 Figure 1
Left: Potato Chip pretreated with Hexose Oxidase. Right: Untreated Potato Chip

The physical properties of pre-treated potato slices were analyzed in volume 79, issue 4 of the Journal of Food Engineering. The physical properties tested included moisture and oil content, texture and color of the potato slices during frying at 120, 140, 160 and 180°C. This provides a frame of reference for free water content experiments. Although these tests were conducted on potato slices and not on finished potato chips, the relative range of temperatures used is similar. The range of temperatures used coincides with the observation that potato chips begin to char at 200°C. Unfortunately none of the values found for moisture content can be used as a reference because of the significant difference in moisture content found in potato chips before and after they are fried.

William Robinson wrote an article "Free and bound water determinations by the heat of fusion of ice method". This method was developed by Max Rubner and is useful in determining the "free" and "bound" water content of specimen. Free water content is defined as the water that can be withdrawn under a standard desiccating force and Bound water content is defined as the remaining water. The process involves freezing a sample to -20 C for several hours, then placing the sample in a calorimeter. The number of calories required to melt the ice crystals in the sample can be used along with mass data to determine water content. This method has a small range of error "Deviations from the mean were determined with 10 per cent gelatin in water… The average total water content was 8.344gm. per gm. of dry gelatin, with a deviation of +/- .001 gm; and the average bound water was found to be 1.210 gm. with a deviation of +/- .006 gm."[Robinson, 1931, pg 701]. This method may be preferable for a project focused more heavily on bound water content.

Compression testing equipment is commonly used in the field of Food Analysis to simulate the act of chewing. The Instron machine is a perfect substitute for the purposes of this project. The machine compresses a specimen and measures the stresses acting on the material over time. This is the perfect way to quantify the crunchiness of a potato chip. The machine can only compress so tightly before there is a risk of the machine damaging itself. Extruded potato chips such as Pringles and Lay's Stax are shaped in such a way that they are tall enough to use in the machine without risk, but other chips with no arch will need to be tested using a three point testing procedure detailed in the methodology section of this report.

Objectives

The intent of this project is to accomplish the following goals:

1. Assess the texture of different commercial chips
    a) *Use different methods on Instron machine to determine mechanical properties of “fresh” (out of the bag) chips*
    b) *Evaluate the surface of chips using imaging techniques*

2. Explore the effects of atmospheric conditions on the texture of chips
    a) *Create three closed, controlled atmospheres: one extremely humid, one extremely dry, and one at normal humidity*
    b) *Analyze texture at different amounts of time subjected to the atmospheres*

3. Correlate texture data to water content, acid content, and conductivity
    a) *Evaluate whether these correlate to variation in texture*
    b) *Elucidate practical uses for these findings*

Methodology

Packages of the following chip brands were obtained at a local grocery store for testing and analysis:

Pringles – Procter & Gamble
Lay's Stax – Frito Lay
Lay's Stax (Salt and Vinegar) – Frito Lay
Cape Cod – subsidiary of Snyder's-Lance, Inc.
Lay's Kettle – Frito Lay
Price Chopper Kettle – Price Chopper Supermarkets
Ruffles – Frito Lay
Wise Ridgies – Wise Snacks
Stacy's Pita – Stacy's Pita Chip Company
Fritos – Frito Lay
Doritos – Frito Lay
Santitas – Frito Lay

These brands were chosen as a representative sample spread over the most common types of chips. Several grocery stores were browsed in order to make a list of their commonly stocked chip types. Bags of different brands were chosen at random for each type. The number of samples obtained of each type was dependent on the number of brands the store carried of that variety. The samples include three extruded potato chips, three kettle potato chips, two rippled potato chips, two tortilla corn chips (nixtamalized, a process involving treating corn meal with an alkaline solution before using it as an ingredient), a corn chip, and a pita chip.

All chips were purchased within two months of packaging, older chips were avoided. Once purchased, the chips would undergo testing within 48hrs.

Opened bags were sealed with duct tape to minimize atmosphere exposure in case they were needed again, but all procedures were initiated within five to ten minutes after a bag's opening. The chips were discarded following the end of experimentation.

A literature review was done initially in order to discover industry-standard, useful tests (mechanical or otherwise) for the chips. It was decided that conductivity would be measured using a multimeter, and an Instron machine would be used to perform three-point or compressive tests on depending on the chip geometry conducive to one or the other. Water content, both free and bound, would be measured. Finally, a comparison of acid content would be established via pH testing.

Mechanical Testing:

The first portion of the mechanical testing was a three point bending test. This test is designed to have a single fracture occur which allows for calculation of maximum stress and strain the sample can handle. An important component to this test was to have the proper tool to place the sample on. An aluminum rod was machined for this purpose, making a hollow square with one side missing. The sample would be placed across this game and an Instron machine was with a metal bar clamped into the top portion. The Instron machine was set to provide a force of 1000N and a strain rate of 10mm/min or .0001667m/s. The video camera was placed on a raised platform to give a good view of the test in progress, as shown below.

Figure 2 Set up for three point stress test. a chip is placed across the gap of a piece of aluminum with the video camera pointed at the trial.

The three point test was conducted on 5 samples for nine different brands of chips. After the chips fractured, a set of calipers was used to measure the length of the fracture as well as take three measurements of the thickness to get an average value. Using the values for maximum force recorded, time before fracture, thickness, length of fracture, and distance between the supports the maximum stress and strain of the sample could be measured. The values calculated will be discussed more in the results section.

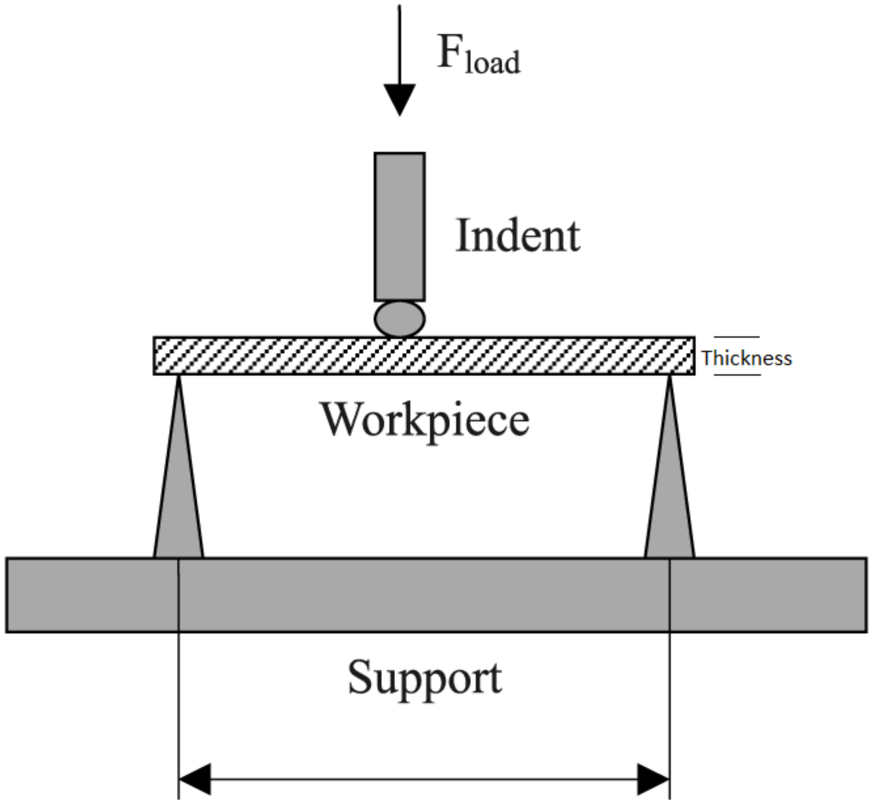


Figure 3 Set up of three point flexural test showing how thickness and distance between supports are measured.

The other mechanical test was a compressive test between two metal plates. Once again, these plates were attached to the Instron machine, using the 1000N force and a strain rate of 10mm/minute. For these test, only two types of chips, Lays Stax and Pringles, were tested. When the chips were initially opened, five samples of each were weighed and tested in the Instron machine. Once again, a video camera was placed on a platform to allow for a good recording of the trials.

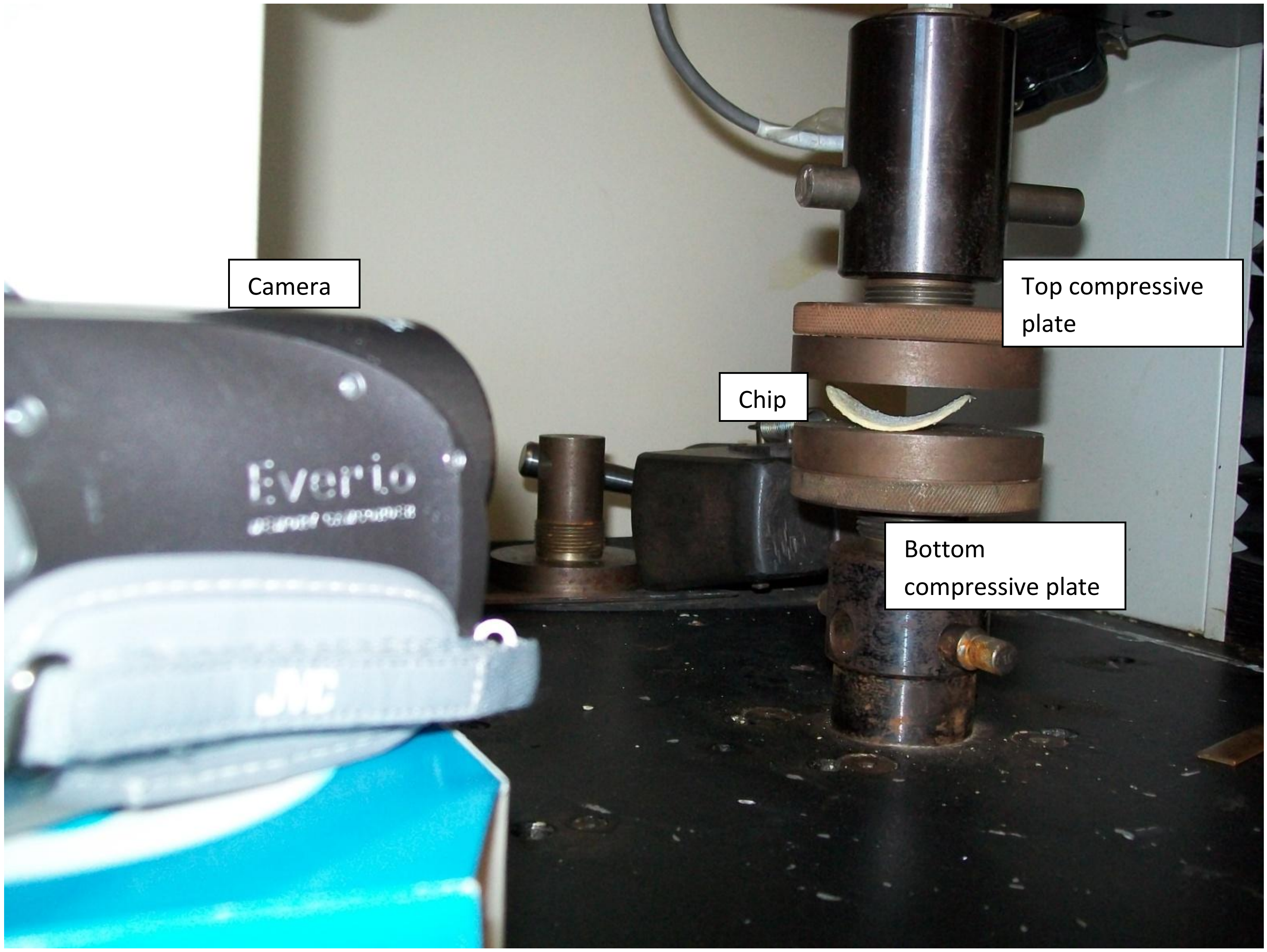


Figure 4 Compression test set up. The camera was placed on a platform for a better shot of the samples breaking.

The rest of the chips were split evenly into three sealable containers. These containers had been purchased at a nearby department store and sealed with a latch and rubber coating. One container had DrieRite Calcium Sulfate desiccant in the bottom of it to keep the air dry while another had a dish of water to keep the air humid. These containers also had a metal grate, raised with copper wire, added to keep the chips from making direct contact, a thermometer, and a hygrometer.

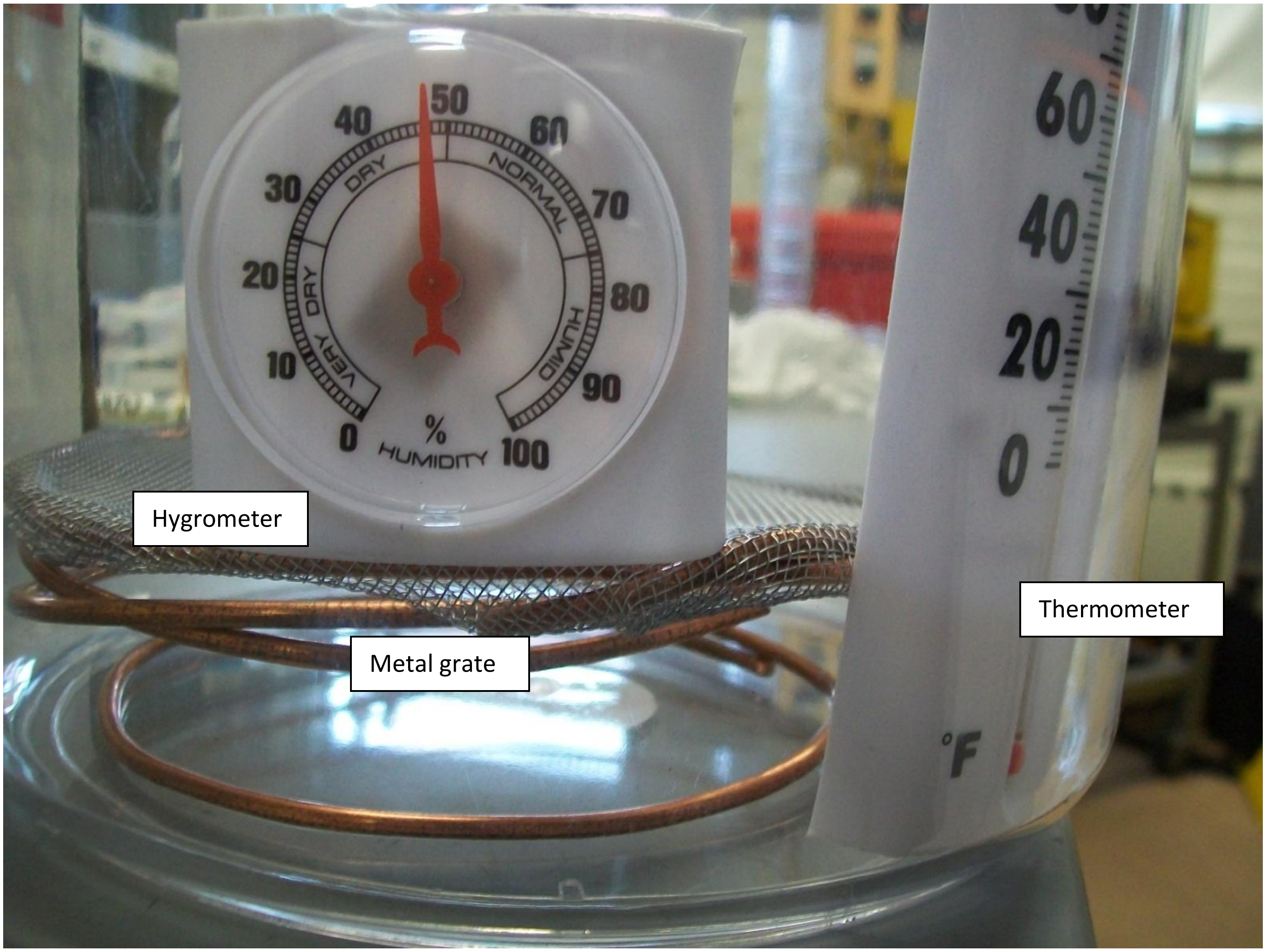


Figure 5 Sealable container with metal grating to hold the chip up. A thermometer and hygrometer were included to track the temperature and humidity in each container.

After multiple hours, varying from 3-17hrs, of the chips being in each environment, three samples were taken from each environment, weighed and tested in the Instron machine again. This was repeated to a maximum of 48hr in the containers.

Conductivity Testing

To measure conductivity across each chip, a MASTECH MAS830L multimeter was obtained. which has a maximum resistance measurement of 2 MΩ.

Figure 6 MASTECH MAS830L multimeter.

One chip (from each of the types listed below) was removed from its packaging. The multimeter was turned on and calibrated against known resistors.

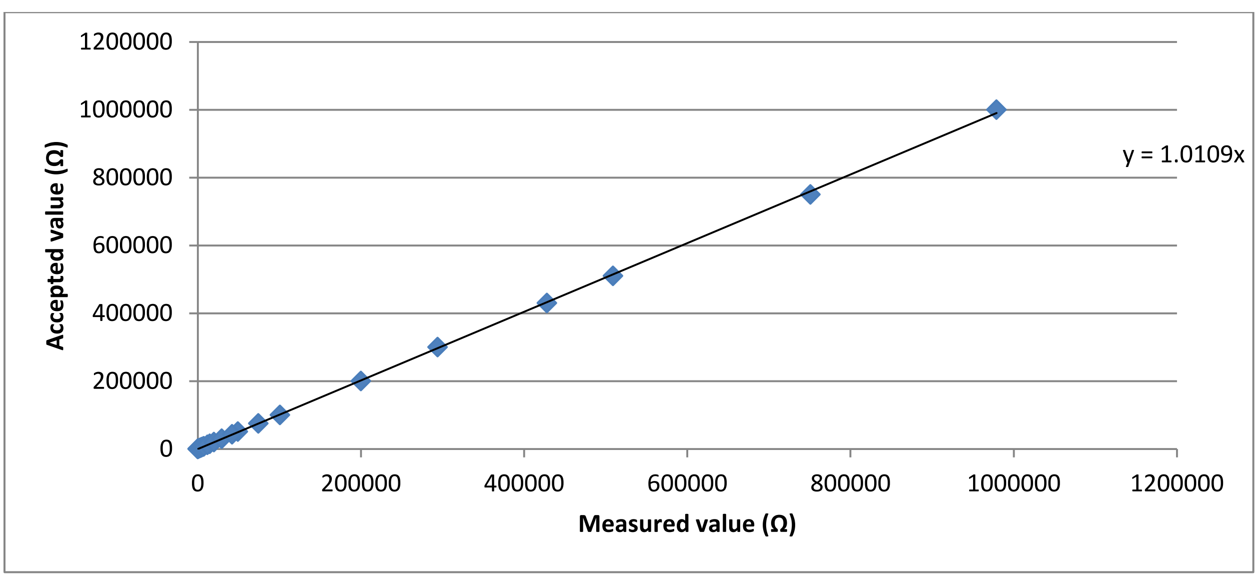


Figure 7 Calibration of the multimeter. Measured values were ploted with the accepted values of tested resistors. Following values given by the multimeter are inserted into the linear equation to account for error from the multimeter.

The two probing contacts were placed in various orientations 1 cm apart on the surface of the chip. Regardless of the position or orientation of the multimeter contacts on the surface of the chip, not a single electrical resistance value below 2 MΩ was observed for any chip tested.

Extruded: Pringles; Lay's Stax
Kettle: Cape Cod; Lay's Kettle; Price Chopper Kettle
Rippled: Ruffles; Ridgies
Corn (not nixtamalized): Fritos
Corn (nixtamalized): Doritos; Santitas

Resistance was measured with the same procedure for Pringles and Lay's Stax after being subjected to the aforementioned humid atmosphere for up to 48 hours. No value below 2 MΩ was obtained.

pH Testing:

One chip was taken from its container and placed in a mortar. It was ground thoroughly until the particles resisted further decrease in size. One gram of this particulate was weighed, then placed in an appropriately labeled beaker (100mL). Deionized water (50mL) was added, the time was recorded, and the mixture was stirred intermittently over the course of a 25+ minute soaking period.The emulsion caused by the oil content of the chip was allowed to settle. Any significant layer atop the mixture was decanted off and discarded to preserve the integrity of the ensuant pH probe. A portable pH probe (*insert brand name*) was inserted into the beaker, stirred, and the reading was allowed to stabilize. This pH reading and the time of measurement were recorded. The probe was removed, cleaned, and reinserted two more times to obtain a total of three pH values for the chip/water mixture.

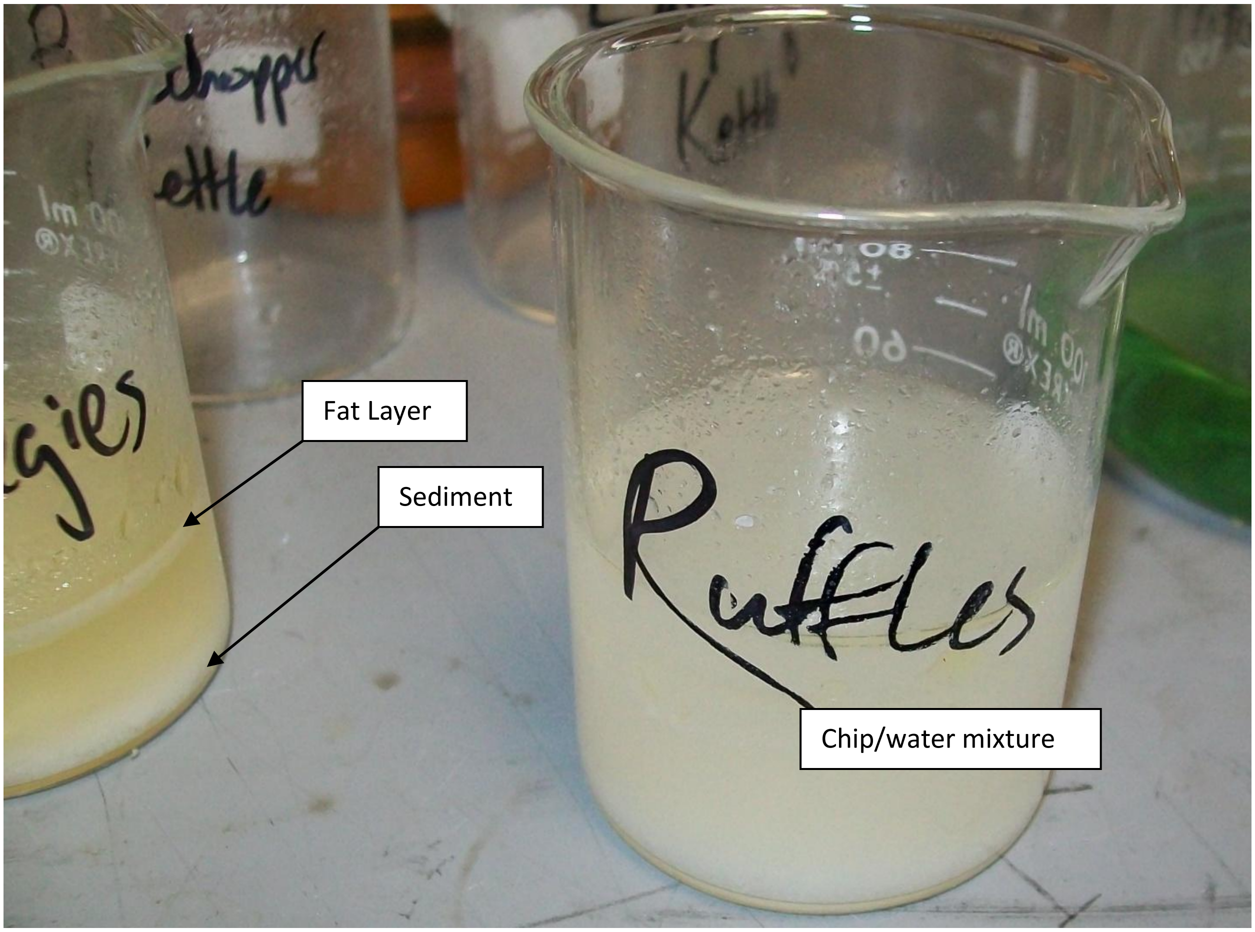


Figure 8 Example of chip/water mixture prior to pH measurement by portable probe. To the right is one rippled potato chip sample (Ruffles); notice the subtle white sediment at the bottom. Clearer separation can be seen in the cut-off beaker to the left, with a fat layer on top, an aqueous heterogeneous chip mixture in the middle, and a sedimentation layer at the bottom.

This process was followed for samples of the following types of chips:

Extruded: Pringles; Lay's Stax; Lay's Stax (Salt and Vinegar)
Kettle: Cape Cod; Lay's Kettle; Price Chopper Kettle
Rippled: Ruffles; Ridgies
Pita: Stacy's
Corn (not nixtamalized): Fritos
Corn (nixtamalized): Doritos; Santitas

Water content:

In order to find the free water content of the potato chips, chips were taken fresh from the bag found an average mass across 3-5 unbroken chips, then put them in the furnace at 100˚C. After 24hrs the chips were removed, allowed to cool, and then massed a second time. This gave us a water content of the chips fresh from the bag. We made the assumption that any variation in the mass of our chips stored in the environments of varied humidity over time would be due to a change in water content. This assumption allowed us to track the water content of the chips over time to compare with the compression testing data.

After the chips were massed the second time they were put into a second furnace at a temperature of 200˚C. These chips were only left in for a very short time because after 15-20 minutes the chips would begin to char. It was easy to identify the charring of the chips by the distinct smell of burnt food that would quickly fill the air. These chips were then weighed a third time to find a bound water content, water that would remain in the chip even after it was cooked at boiling temperature.

Results and Discussion

General chip observations:

Pringles:

This chip is a pale yellow-brown oval, with a hyperbolic paraboloid curve (looks somewhat like an oval saddle). Very uniform consistency throughout the chip. No obvious bubbles or significant areas of color variation. Packaged in a cylindrical cardboard canister with a foil-lined interior and a plastic lid. Very few chips were observed to have broken inside the packaging.

Lay's Stax:

Same color as Pringles. Shaped also like a saddle, but does not have the characteristic double curvature of a Pringle; it's more like an oval cut from a segment of cylindrical pipe. Same homogenous consistency, no obvious bubbles or significant areas of variation in color. Packaged in a plastic oblong-cylindrical canister with a plastic lid.

Lay's Stax (Salt and Vinegar):

Slightly lighter color than Lay's Stax. Surface powdery, smelled of vinegar. Same curvature and physical description as unflavored Stax and packaged in the same type of container.

Cape Cod:

Pale yellow-brown, with some dark brown spots up to a few millimeters across. Edges often darker than inner surface. Highly irregular shape; sometimes crumpled, sometimes flat, folded, or curved. Varying diameters from about 3 to 7 cm. Many bubbles, varying consistency across chip. Average thickness of 1.12 mm. Contained in plastic bag.

Lay's Kettle:

Same description as Cape Cod, but less browning around the edges. Average thickness of 1.26 mm. Contained in foil-lined plastic bag.

Price Chopper Kettle:

Same description as Lay's Kettle. Average thickness of 1.22 mm. Contained in foil-lined plastic bag.

Ruffles:

Darker yellow-brown. Ovular, with ~1 mm ridges down length. Often a slight curvature in plane orthogonal to the direction of the ridges (imagine an oval cut from the surface of a pipe which has ridges running down it lengthwise). A small number were folded over. Relatively homogenous consistency, few bubbles, some areas colored more darkly than others. Very greasy. Average thickness of 2.41 mm. Contained in foil-lined plastic bag.

Wise Ridgies:

Same description as Ruffles, but much flatter. Average thickness of 1.96 mm. Contained in foil-lined plastic bag.

Stacy's Pita:

Light brown, rough, and thick. Very dry, with uniform consistency throughout. Cut into square chips with irregular curvature; some were folded, others wavy, and some flat. Average thickness of 2.8 mm. Contained in foil-lined plastic bag.

Fritos:

Dark yellow with brown and black specks. Cut into small rectangular strips, similar irregularity in curvature to Stacy's, with many folded over. Some (but relatively little) bubbling observed. Average thickness of 1.69 mm. Contained in foil-lined plastic bag.

Doritos:

Striking orange color with black specks. Powdery from flavoring, smells like MSG and children's birthday parties. Triangular shape with irregular curvature; many were folded over. Lots of bubbles. Average thickness of 1.72 mm. Contained in foil-lined plastic bag.

Santitas:

Beige color with black specks. Triangular shape with irregular curvature resembling that of doritos. Very dry, lots of bubbles. Average thickness of 1.07 mm. Contained in plastic bag, no foil lining.

Three Point Flexural Testing:

From the data collected from the three point test, which may be viewed in Appendix A, graphs were made showing force verses time for each sample, these graphs may be viewed in appendix G. Using the calculated averages for maximum force and maximum strain, the following graph was compiled showing one test for each of the different chip brands.

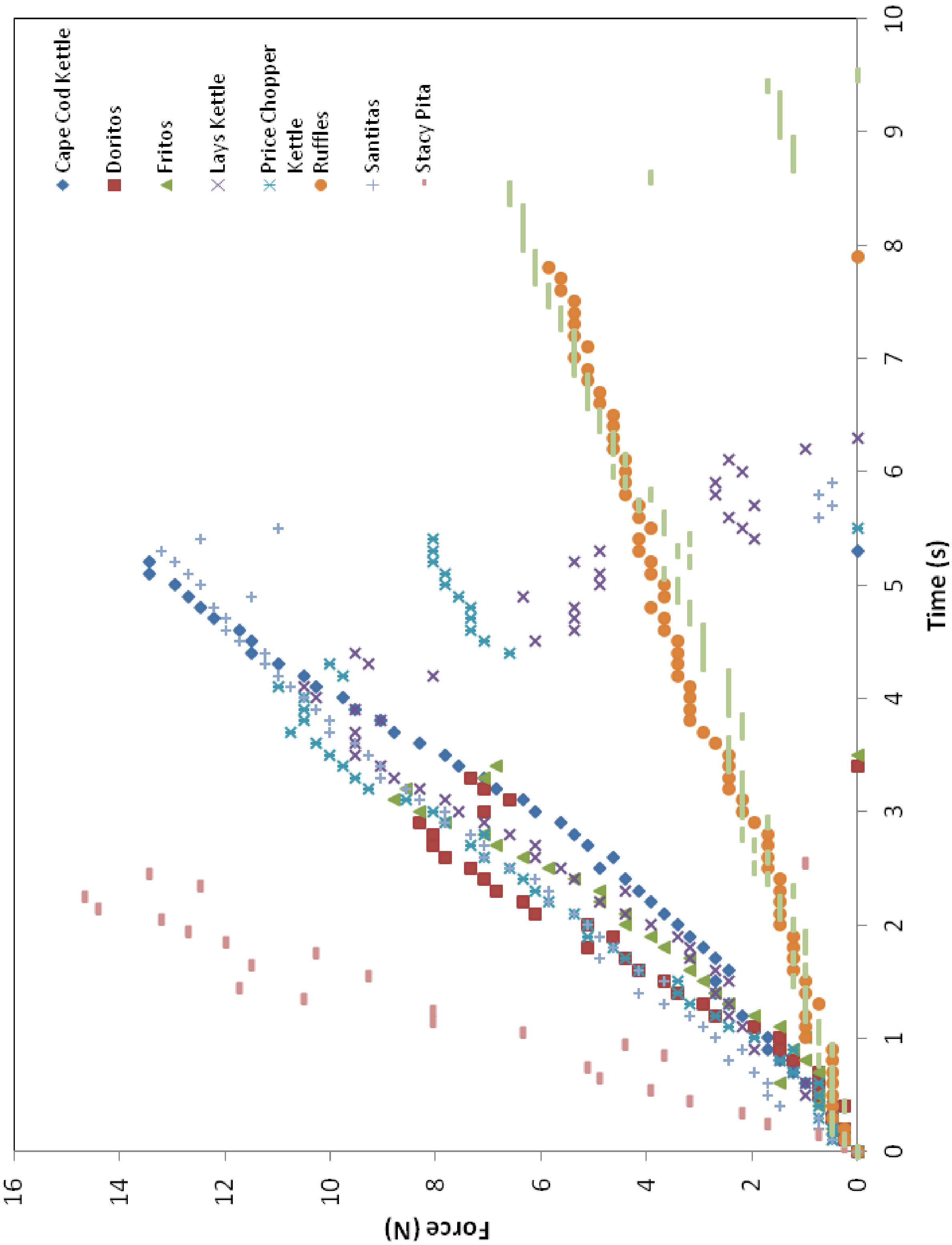


Figure 9 An average force verse time graph of the three point flexural test for each brand of chip tested.

From this graph a few interesting trends emerge. First, the slope and maximum breaking point for both of the ridged chips, Wise Ridgies and Ruffles, are nearly identical. Both have a much lower maximum breaking force than the rest of the samples. This lower breaking force is caused from the shape, the ridges cause straight line where the chip can easily fracture. The irregular shape, causing no straight lines, of other chips makes the force dispersed to other areas. This is the reason the kettle chips and tortilla chips have a higher breaking force. Finally, the pita chips are huge outliers in breaking force. Their average force of 18.12N is due to higher thickness.

Table 1 Average maximum breaking force for each chip type, based on five trials of the three point flexural test.

Chip Brand	Average Maximum Force (N)
Fritos	10.65
Santitas	13.14
Stacy Pita	18.12
Cape Cod Kettle	10.99
Doritos	10.65
Price Chopper Kettle	10.6
Lays Kettle	8.74
Wise Ridgies	7.47
Ruffles	6.98
Average	10.82

When thickness and fracture length are taken into consideration, this large force is shown to not be an outlier. When these variables are used in conjunction with the maximum force, the average maximum stress may be calculated.

Table 2 Calculated average stress for each chip brand. The table is sorted in decending order based on the average maximum stress.

Chip Brand	Average Maximum Stress (MPa)	Average Maximum Force (N)
Fritos	0.73	10.65
Santitas	0.42	13.14
Stacy Pita	0.37	18.12
Cape Cod Kettle	0.35	10.99
Doritos	0.28	10.65
Price Chopper Kettle	0.23	10.6
Lays Kettle	0.18	8.74
Wise Ridgies	0.07	7.47
Ruffles	0.05	6.98
Average	0.30	10.82

As this table 2 shows, the high value for the Pita Chip's breaking force combined with the high value of thickness calculate out to have an average maximum stress that is near the mean value of all the sample brands. The only outlier for average maximum stress are the Fritos, which is an extruded corn chip. Fritos are a very uniform chip, having very little air pockets inside its structure. This can explain why it has such a high maximum stress as the thickness measurement does not take air pockets into account.

Compressive Testing:

By using the different controlled environments set up in the sealable containers, the compressive properties could be observed while the samples absorbed water over time. The properties that were observed were maximum force, modulus of elasticity, time of trial, number of fractures, and the average time between each fracture.

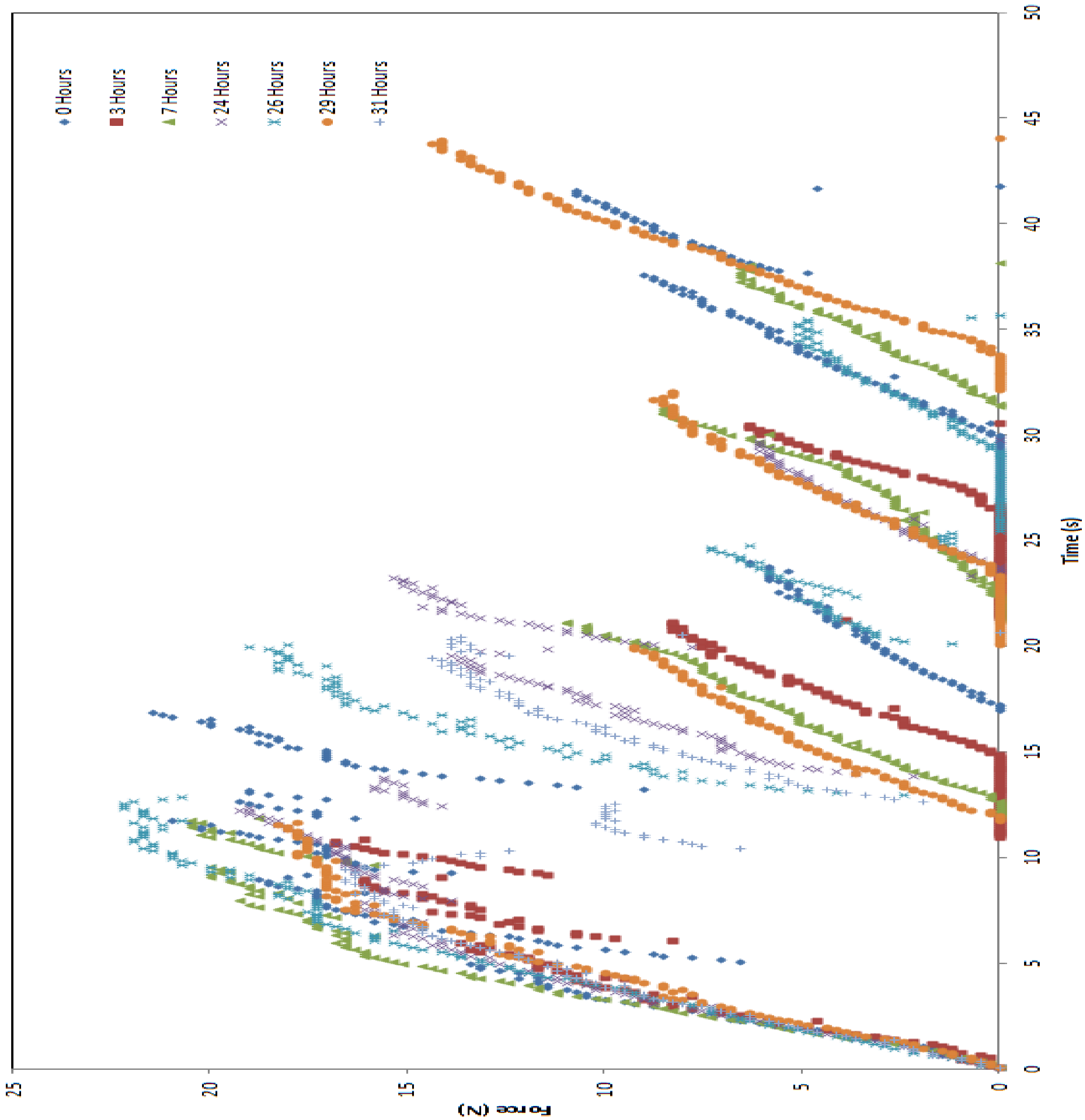


Figure 10 A typical force vs time graph obtained during testing of a Pringles chip kept in a humid environment. As the chips were exposed to moisture, their modulus of elasticity decreased dramatically.

As seen above, the chips would begin the tested with a high modulus and a low ductility. As the chips were kept in the humid environments longer, there would also be less snapping when fracture occurred. Specific values for modulus, maximum breaking force, and number of breaks can be found in Appendix L and M.

In order to check for reproducibility several tests were conducted under the same conditions. An example of three tests conducted after 29hrs in the dry environment is shown below.

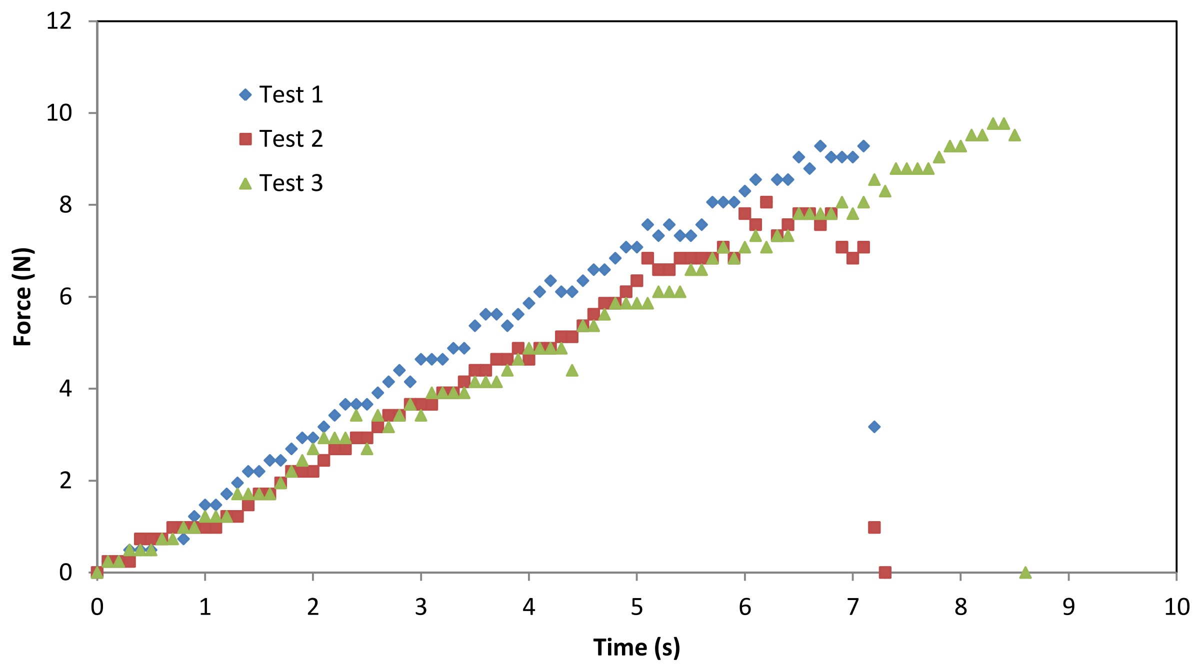


Figure 11 Three compressive tests of Lays Stax conducted after 29hrs in the dry environment. The similarity of each tests shows that our test was reproducible.

Maximum breaking force was always higher for the Pringles samples. This is due to the straight line which most Lays chips would fracture on.

Figure 12 Examples of broken Lays (Left) and Pringles (Right). Lays chips were likely to break down the center flat part of the chip. Pringles would break in a more random pattern.

In addition to having a lower maximum breaking force, the predictable break pattern caused by this flat line in Lays kept the number of fractures very low. At the time of opening, Pringles clearly showed a higher modulus, number of breaks, and maximum force needed for fracture.

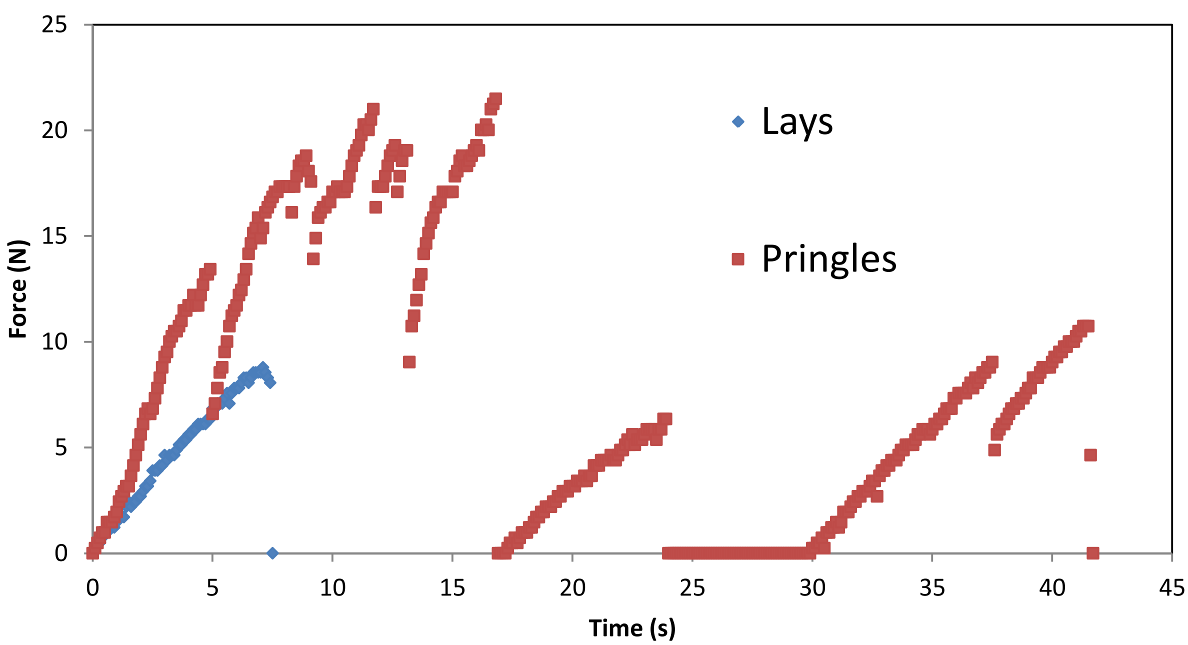


Figure 1 A comparison of the force verse time graphs right when the chips were taken out of packaging. This clearly shows the diffrence in maximum force, modulus, and number of breaks.

Over time, the chips placed in the wet environment degraded more than samples in the dried or normal air environment. This was shown most by the change in modulus over time.

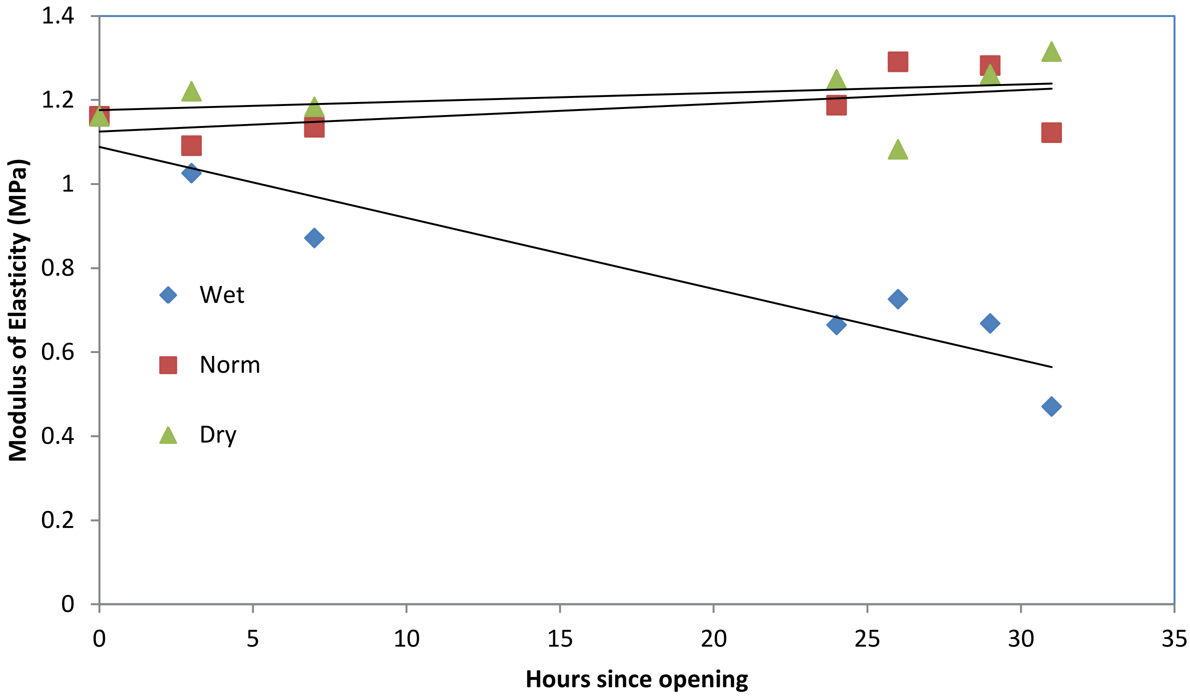


Figure 2 Changing modulus over time for Lays Stax chips. Samples in wet environment experienced more degradation over time.

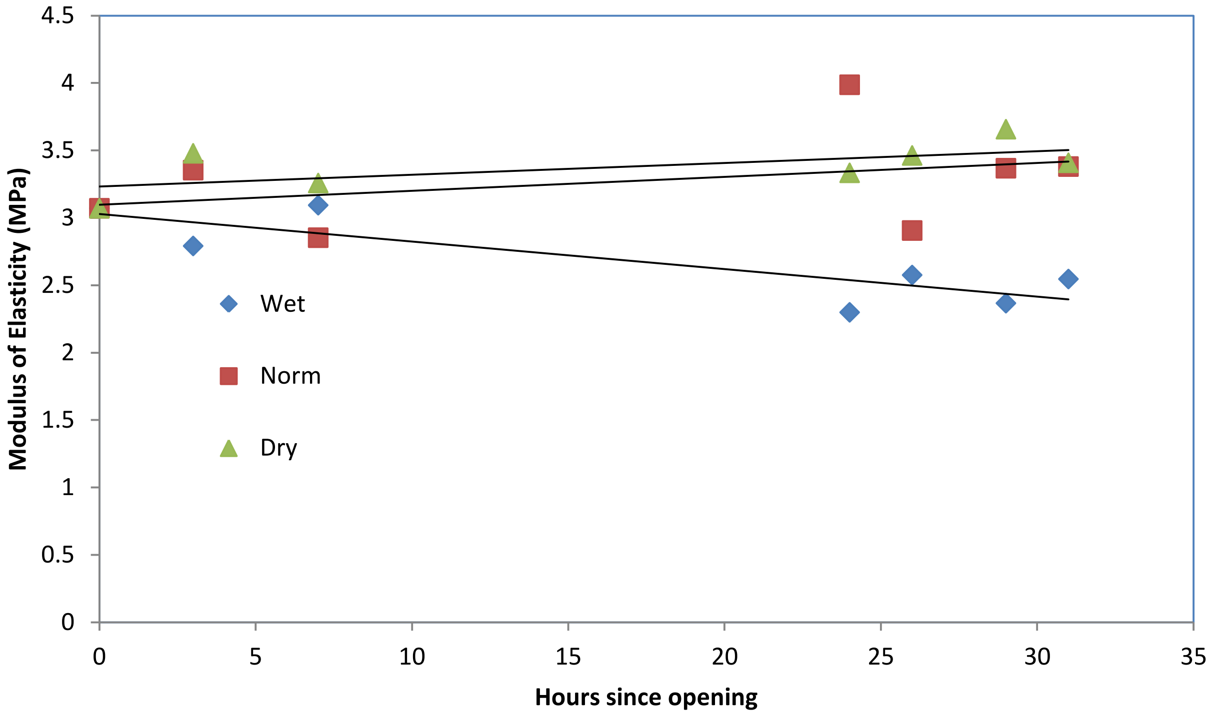


Figure 153 Changing modulus over time for Pringles chips. Samples in wet environment experienced more degrading over time.

These results show very well that high water content in a potato chip will severely lower its compressive properties. Although the moisture explains the decrease over time, the shape of the chip is an even larger factor for compressive properties. Lays Stax were on average, heavier than Pringles. However, even after 31hrs in a wet environment, Pringles still had better compressive properties.

Table 3 Average mass of Lays and Pringles chips in each environment. Lays chips always weighed more than Pringles.

		Average Mass (g)				
		Pringles			**Lays**	
Time	Wet	Norm	Dry	Wet	Norm	Dry
0	1.80	1.80	1.80	2.12	2.12	2.12
3	1.83	1.8	1.80	2.16	2.04	2.11

7	1.82	1.82	1.81	2.15	2.09	2.05
24	1.85	1.83	1.82	2.29	2.17	2.01
26	1.87	1.80	1.80	2.18	2.22	2.12
29	1.86	1.77	1.79	2.20	2.14	2.13
31	1.87	1.8	1.79	2.33	1.99	2.03

Conductivity Testing:

No usable results were obtained for the electrical resistance/conductivity of the potato and corn chips tested. All chips tested had electrical resistances of over 2 MΩ (the maximum of the multimeter used) across 1 cm.

pH Testing:

The chips were categorized according to chip type: extruded, kettle, ridged, pita, corn (nixtamalized) and corn (not nixtamalized). These groupings allowed comparison of pH between the types of chips, to see if they achieved similar results.

As can be observed from Table 1, most of the chip types correspond to similar pH results within their group. The extruded and pita chips are the most acidic, followed by rippled, then kettle. Fritos were the most basic (highest pH), and the nixtamalized (tortilla) chips scattered around the mid-range. These results were expected, given that chips of a given type are likely to be made with similar ingredients and in similar processes, and they will therefore probably have similar acidity.

Table 4: *Chips and their types, by ascending pH*

Type	Chip	pH (ascending)
Extruded	Stax S+V	5.18
Extruded	Pringle	5.81
Pita	Stacy's	5.88
Extruded	Stax	6.03
Nixtamalized	Dorito	6.22
Rippled	Ridgies	6.24
Rippled	Ruffles	6.26
Kettle	Lay's Kettle	6.32
Kettle	PC Kettle	6.33
Nixtamalized	Santitas	6.6
Kettle	Cape Cod	6.63
Corn	Fritos	6.72

Also, as evident in Figure 1, pH roughly ascends with the average maximum stress measured for each chip (for these stress values, see Appendix X). Stacy's Pita chips and Doritos are outliers, but this may be explained by the fact that Doritos is the only heavily flavored chip where both stress and pH was measured, and pita chips are unlike any of the other chips measured; they are made with baked bread. Consequently, a tentative correlation between basicity and mechanical stress can be made here.

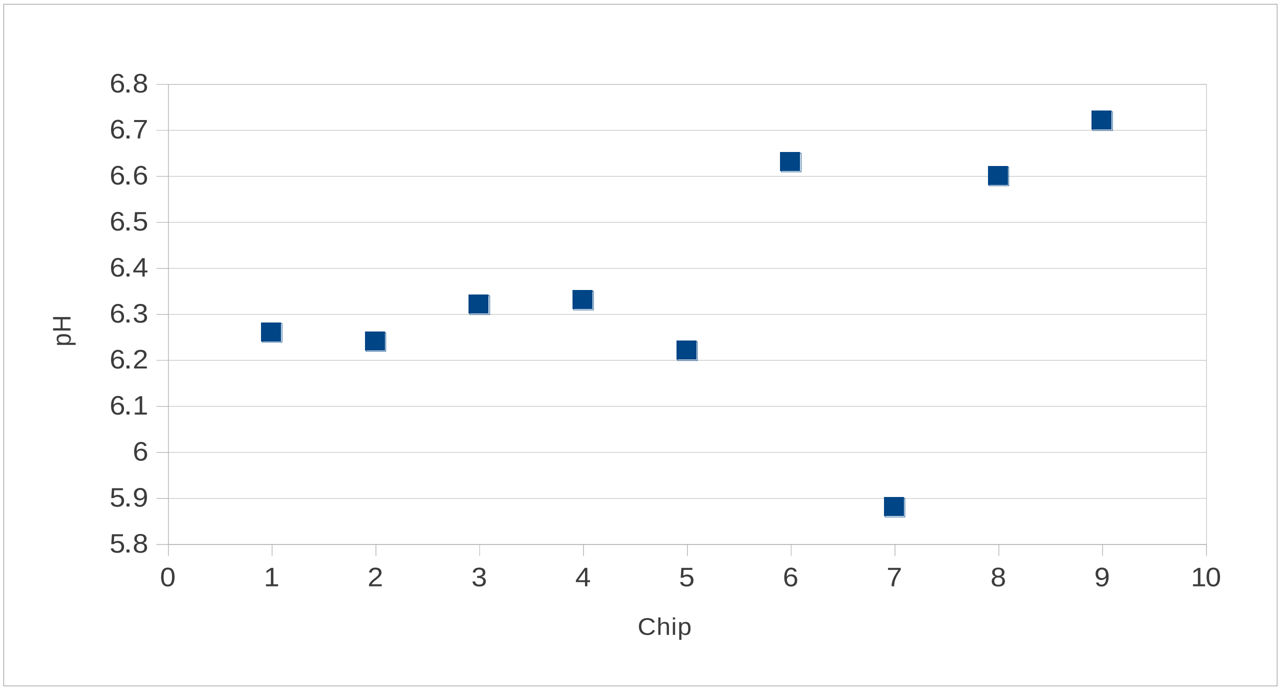


Figure 16: *Chip type (in order of ascending mechanical stress) vs. pH, where 1 = Ruffles; 2 = Wise Ridgies; 3 = Lay's Kettle; 4 = Price Chopper Kettle; 5 = Doritos; 6 = Cape Cod; 7 = Stacy's Pita; 8 = Santitas; 9 = Fritos*

The large difference in pH between the two nixtamalized chips, Doritos and Santitas, could result from a difference in their respective nixtamalization processes. Enzymes are mentioned in Doritos' ingredients, whereas it is lacking in Santitas. Classic nixtamalization is performed by treating the corn with an alkaline solution, but there is another commonly used industrial method of enzymatic nixtamalization which involves adding proteases to speed up the effect of the normal alkaline process. It is possible that the use of enzymes in one (Doritos) rather than the other (Santitas) requires a less alkaline (less basic) solution be used, thereby lowering its resultant pH. This would correspond to the data obtained for our two tortilla chips. However, this pH variation could also lie in an acidic compound present in the powdered flavoring of Doritos that is not present on Santitas.

What is clear from these data is that the strength of a chip positively correlates with pH, that less acidic chips are crunchier. If this is a desired texture, as is often advertised, a company may find that they can artificially raise pH in order to affect crunch without affecting flavor or other aspects of the chip.

This finding could also be useful in that raising the pH allows less breakage in-package en route to a distribution facility, store, or home. Some direct evidence for this comes from an observation that the Lay's Stax Salt and Vinegar had far more broken chips right out of the box than Pringles did; in fact, Pringles had few broken, if any. Correspondingly, Pringles has a much higher pH than the Stax Salt and Vinegar.

Water content:

	Initial Avg Mass (g)	Avg Mass after 24 hr (g)	% Loss
Fritos	.66	.59	10.61
Doritos	2.63	2.38	9.51
Kettle Chips (Price Chopper)	1.29	1.21	6.2
Ruffles	1.76	1.66	5.68
Lay's Stax	1.77	1.68	5.08
Pringles	1.85	1.75	5.41
Pita Chips	3.34	3.2	4.19
Cape Cod	2.02	1.97	2.48
Sanitas	3.06	2.985	2.45
Lay's Kettle Cooked	1.25	1.22	2.4
Ridgies (Wise)	2.2	2.16	1.82

This table shows the initial average mass of the chips at start, their mass after 24 hours at 100˚C and the percent mass lost. Assuming all mass lost is the result of water evaporating, this percent loss represents the percent of the chip's mass that is free water content.

	Avg Mass after 10-15 min at 200 C	% Loss from Avg Mass after 24 hr
Fritos	.58	1.69
Doritos	2.34	1.68
Kettle Chips (Price Chopper)	1.15	4.96

Ruffles	1.64	1.2
Lay's Stax	1.68	0
Pringles	1.74	.57
Pita Chips	3.19	.31
Cape Cod	1.95	1.02
Sanitas	2.95	1.17
Lay's Kettle Cooked	1.2	1.64
Ridgies (Wise)	2.13	1.39

This table displays the masses of the chips after they had been cooked at 200 C and the percent loss between these values and the masses of the chips after they were cooked at 100 C for 24 hr. This value represents the bound water content of the potato chips. These results are much lower than expected values for bound water content. The issue is that potato chips begin to char at 200 C very quickly. If the chips begin to change chemically due to heat, there is potential for a change in mass that is not due to the evaporation of water alone. In the future, to find bound water content, the chips should be cooked at 120 C, 140 C, 160 C, and 180 C in order to identify the maximum temperature at which the chips can cook for an extended period of time without charring. The chips should be heated to this temperature and weighed periodically to identify how long it takes for the mass of the chips to stabilize, this may be as long as 24 hours. This experiment can then be repeated with the newly found temperature and time for a more accurate bound water content.

	% Loss after 24 hr at 100 C	% Loss
Fritos	10.61	.72946
Doritos	9.51	.27586
Kettle Chips (Price Chopper)	6.2	.22953
Ruffles	5.68	.05097
Pita Chips	4.19	.37141
Cape Cod	2.48	.34761
Sanitas	2.45	.42087

Lay's Kettle Cooked	2.4	.17759
Ridgies (Wise)	1.82	.06677

Comparing the percent free water content of the various brands of potato chips with the average results for maximum stress of each chip yields no direct correlation, apart from the fact that Fritos brand corn chips had the highest free water content and maximum stress. From this comparison alone we cannot prove a relation between water content and maximum stress. The results of our high neutral and low humidity tests demonstrate clearly that dry chips are more brittle. From these results it is safe to conclude that free water content does have an effect on compressive strength, but this effect is insignificant compared to other factors.

Conclusion

During comparison of twelve different types of commonly consumed chips, several properties were determined to correlate with exposure to different atmospheres, acid content, and water content. Ripple chips had the lowest strength whereas corn chips had the strongest.

The strength of a potato chip plays a large factor in how intact the product is when it reaches consumers. Having a bag full of small pieces would usually be considered undesirable. The crunchiness of a chip can also be related to how brittle the chip is, a trait that is usually desired and advertised.

This crunchy texture, a tangible experience which is a direct artifact of mechanical strength, was found to be very negatively correlated with exposure to humid environments. The moisture absorbed makes the chips flexible and what is popularly described as "stale".

Proper sealing and packaging seems to be able to reduce or eliminate this staling factor for realistic periods of time (the amount of time someone would keep a bag of chips without eating it). The dry environment definitely gave the best retention of strength from being removed from the packaging, but the "normal" humidity sealed environment gave comparable results, which implies that as long as an opened bag is sealed properly by the consumer, a product can be kept fresh for extended periods of time without exposure to a desiccant or other atmospheric adulterants.

The crunchiness was also found to positively correlate with the pH of the chip; the less acidic the chip, the crunchier. This is a very useful finding for the chip manufacturing industry. It provides the opportunity to artificially raise or lower the pH of a chip, or use more pH-specific manufacturing processes, to achieve a certain strength or texture without affecting ingredients or taste. It also provides an opportunity to use the same procedures to keep a chip product from breaking in its packaging en route to a distribution facility, store, or consumer's hands.

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Appendix A - 3 point flexural test data

1. Cape Cod Kettle Chips
    - Test 1 - 3 point test\CapeCodKettle\1.txt
    - Test 2 - 3 point test\CapeCodKettle\2.txt
    - Test 3 - 3 point test\CapeCodKettle\3.txt
    - Test 4 - 3 point test\CapeCodKettle\4.txt
    - Test 5 - 3 point test\CapeCodKettle\5.txt
2. Doritos Chips
    - Test 1 - 3 point test\Doritos\1.txt
    - Test 2 - 3 point test\Doritos\2.txt
    - Test 3 - 3 point test\Doritos\3.txt
    - Test 4 - 3 point test\Doritos\4.txt
    - Test 5 - 3 point test\Doritos\5.txt
3. Fritos Chips
    - Test 1 - 3 point test\Fritos\1.txt
    - Test 2 - 3 point test\Fritos\2.txt
    - Test 3 - 3 point test\Fritos\3.txt
    - Test 4 - 3 point test\Fritos\4.txt
    - Test 5 - 3 point test\Fritos\5.txt
4. Lays Kettle Chips
    - Test 1 - 3 point test\LaysKettle\1.txt
    - Test 2 - 3 point test\LaysKettle\2.txt
    - Test 3 - 3 point test\LaysKettle\3.txt
    - Test 4 - 3 point test\LaysKettle\4.txt
    - Test 5 - 3 point test\LaysKettle\5.txt
5. Price Chopper Kettle Chips
    - Test 1 - 3 point test\PriceChopKettle\1.txt
    - Test 2 - 3 point test\PriceChopKettle\2.txt
    - Test 3 - 3 point test\PriceChopKettle\3.txt
    - Test 4 - 3 point test\PriceChopKettle\4.txt
    - Test 5 - 3 point test\PriceChopKettle\5.txt
6. Ruffles Chips
    - Test 1 - 3 point test\Ruffles\1.txt
    - Test 2 - 3 point test\Ruffles\2.txt
    - Test 3 - 3 point test\Ruffles\3.txt
    - Test 4 - 3 point test\Ruffles\4.txt
    - Test 5 - 3 point test\Ruffles\5.txt
7. Santitas Chips
    - Test 1 - 3 point test\Santitas\1.txt
    - Test 2 - 3 point test\Santitas\2.txt
    - Test 3 - 3 point test\Santitas\3.txt

- Test 4 - 3 point test\Santitas\4.txt
- Test 5 - 3 point test\Santitas\5.txt

8. Stacy's Pita Chips
    - Test 1 - 3 point test\StacyPita\1.txt
    - Test 2 - 3 point test\StacyPita\2.txt
    - Test 3 - 3 point test\StacyPita\3.txt
    - Test 4 - 3 point test\StacyPita\4.txt
    - Test 5 - 3 point test\StacyPita\5.txt
9. Wise Ridgies Chips
    - Test 1 - 3 point test\WiseRidges\1.txt
    - Test 2 - 3 point test\WiseRidges\2.txt
    - Test 3 - 3 point test\WiseRidges\3.txt
    - Test 4 - 3 point test\WiseRidges\4.txt
    - Test 5 - 3 point test\WiseRidges\5.txt

Appendix B - 3 point flexural test videos

10. Cape Cod Kettle Chips
    - Test 1 - 3 point test\CapeCodKettle\Test1.MOD
    - Test 2 - 3 point test\CapeCodKettle\Test2.MOD
    - Test 3 - 3 point test\CapeCodKettle\Test3.MOD
    - Test 4 - 3 point test\CapeCodKettle\Test4.MOD
    - Test 5 - 3 point test\CapeCodKettle\Test5.MOD
11. Doritos Chips
    - Test 1 - 3 point test\Doritos\Test1.MOD
    - Test 2 - 3 point test\Doritos\Test2.MOD
    - Test 3 - 3 point test\Doritos\Test3.MOD
    - Test 4 - 3 point test\Doritos\Test4.MOD
    - Test 5 - 3 point test\Doritos\Test5.MOD
12. Fritos Chips
    - Test 1 - 3 point test\Fritos\Test1.MOD
    - Test 2 - 3 point test\Fritos\Test2.MOD
    - Test 3 - 3 point test\Fritos\Test3.MOD
    - Test 4 - 3 point test\Fritos\Test4.MOD
    - Test 5 - 3 point test\Fritos\Test5.MOD
13. Lays Kettle Chips
    - Test 1 - 3 point test\LaysKettle\Test1.MOD
    - Test 2 - 3 point test\LaysKettle\Test2.MOD
    - Test 3 - 3 point test\LaysKettle\Test3.MOD
    - Test 4 - 3 point test\LaysKettle\Test4.MOD
    - Test 5 - 3 point test\LaysKettle\Test5.MOD
14. Price Chopper Kettle Chips
    - Test 1 - 3 point test\PriceChopKettle\Test1.MOD
    - Test 2 - 3 point test\PriceChopKettle\Test2.MOD
    - Test 3 - 3 point test\PriceChopKettle\Test3.MOD
    - Test 4 - 3 point test\PriceChopKettle\Test4.MOD
    - Test 5 - 3 point test\PriceChopKettle\Test5.MOD
15. Ruffles Chips
    - Test 1 - 3 point test\Ruffles\Test1.MOD
    - Test 2 - 3 point test\Ruffles\Test2.MOD
    - Test 3 - 3 point test\Ruffles\Test3.MOD
    - Test 4 - 3 point test\Ruffles\Test4.MOD
    - Test 5 - 3 point test\Ruffles\Test5.MOD
16. Santitas Chips
    - Test 1 - 3 point test\Santitas\Test1.MOD
    - Test 2 - 3 point test\Santitas\Test2.MOD
    - Test 3 - 3 point test\Santitas\Test3.MOD

- Test 4 - 3 point test\Santitas\Test4.MOD
- Test 5 - 3 point test\Santitas\Test5.MOD

17. Stacy's Pita Chips
    - Test 1 - 3 point test\StacyPita\Test1.MOD
    - Test 2 - 3 point test\StacyPita\Test2.MOD
    - Test 3 - 3 point test\StacyPita\Test3.MOD
    - Test 4 - 3 point test\StacyPita\Test4.MOD
    - Test 5 - 3 point test\StacyPita\Test5.MOD
18. Wise Ridgies Chips
    - Test 1 - 3 point test\WiseRidges\Test1.MOD
    - Test 2 - 3 point test\WiseRidges\Test2.MOD
    - Test 3 - 3 point test\WiseRidges\Test3.MOD
    - Test 4 - 3 point test\WiseRidges\Test4.MOD
    - Test 5 - 3 point test\WiseRidges\Test5.MOD

Appendix C - Pringles compressive test data

1. First Run
   - At time of opening
     - i) Test 1 - First Run\Time 0\test 53.txt
     - ii) Test 2 - First Run\Time 0\test 54.txt
     - iii) Test 3 - First Run\Time 0\test 55.txt
     - iv) Test 4 - First Run\Time 0\test 56.txt
     - v) Test 5 - First Run\Time 0\test 57.txt
   - 3 Hours in
     - i) Wet environment
       - (a) Test 1 - First Run\Time 3\test 58.txt
       - (b) Test 2 - First Run\Time 3\test 59.txt
       - (c) Test 3 - First Run\Time 3\test 60.txt
     - ii) Normal Air environment
       - (a) Test 1 - First Run\Time 3\test 61.txt
       - (b) Test 2 - First Run\Time 3\test 62.txt
       - (c) Test 3 - First Run\Time 3\test 63.txt
     - iii) Dry environment
       - (a) Test 1 - First Run\Time 3\test 64.txt
       - (b) Test 2 - First Run\Time 3\test 65.txt
       - (c) Test 3 - First Run\Time 3\test 66.txt
   - 7 Hours in
     - i) Wet environment
       - (a) Test 1 - First Run\Time 7\test 67.txt
       - (b) Test 2 - First Run\Time 7\test 68.txt
       - (c) Test 3 - First Run\Time 7\test 69.txt
     - ii) Normal Air environment
       - (a) Test 1 - First Run\Time 7\test 70.txt
       - (b) Test 2 - First Run\Time 7\test 71.txt
       - (c) Test 3 - First Run\Time 7\test 72.txt
     - iii) Dry environment
       - (a) Test 1 - First Run\Time 7\test 73.txt
       - (b) Test 2 - First Run\Time 7\test 74.txt
       - (c) Test 3 - First Run\Time 7\test 75.txt
   - 24 Hours in
     - i) Wet environment
       - (a) Test 1 - First Run\Time 24\test 76.txt
       - (b) Test 2 - First Run\Time 24\test 77.txt
       - (c) Test 3 - First Run\Time 24\test 78.txt
     - ii) Normal Air environment
       - (a) Test 1 - First Run\Time 24\test 79.txt
       - (b) Test 2 - First Run\Time 24\test 80.txt

(c) Test 3 - First Run\Time 24\test 81.txt

iii) Dry environment

(a) Test 1 - First Run\Time 24\test 82.txt

(b) Test 2 - First Run\Time 24\test 83.txt

(c) Test 3 - First Run\Time 24\test 84.txt

- 29 Hours in

i) Wet environment

(a) Test 1 - First Run\Time 29\test 85.txt

(b) Test 2 - First Run\Time 29\test 86.txt

(c) Test 3 - First Run\Time 29\test 87.txt

ii) Normal Air environment

(a) Test 1 - First Run\Time 29\test 88.txt

(b) Test 2 - First Run\Time 29\test 89.txt

(c) Test 3 - First Run\Time 29\test 90.txt

iii) Dry environment

(a) Test 1 - First Run\Time 29\test 91.txt

(b) Test 2 - First Run\Time 29\test 92.txt

(c) Test 3 - First Run\Time 29\test 93.txt

- 48 Hours in

i) Wet environment

(a) Test 1 - First Run\Time 48\test 94.txt

(b) Test 2 - First Run\Time 48\test 95.txt

(c) Test 3 - First Run\Time 48\test 96.txt

ii) Normal Air environment

(a) Test 1 - First Run\Time 48\test 97.txt

(b) Test 2 - First Run\Time 48\test 98.txt

(c) Test 3 - First Run\Time 48\test 99.txt

iii) Dry environment

(a) Test 1 - First Run\Time 48\test 100.txt

(b) Test 2 - First Run\Time 48\test 101.txt

(c) Test 3 - First Run\Time 48\test 102.txt

2. Second Run

- At time of opening

i) Test 1 - Second Run\time 0\P1.txt

ii) Test 2 - Second Run\time 0\P2.txt

iii) Test 3 - Second Run\time 0\P3.txt

iv) Test 4 - Second Run\time 0\P4.txt

v) Test 5 - Second Run\time 0\P5.txt

- 3 Hours in

i) Wet environment

(a) Test 1 - Second Run\time 3\PW1.txt

(b) Test 2 - Second Run\time 3\PW2.txt

(c) Test 3 - Second Run\time 3\PW3.txt

ii) Normal Air environment
   (a) Test 1 - Second Run\time 3\PN1.txt
   (b) Test 2 - Second Run\time 3\PN2.txt
   (c) Test 3 - Second Run\time 3\PN3.txt
iii) Dry environment
   (a) Test 1 - Second Run\time 3\PD1.txt
   (b) Test 2 - Second Run\time 3\PD2.txt
   (c) Test 3 - Second Run\time 3\PD3.txt

- 7 Hours in
  i) Wet environment
     (a) Test 1 - Second Run\Time 7\PW1.txt
     (b) Test 2 - Second Run\Time 7\PW2.txt
     (c) Test 3 - Second Run\Time 7\PW3.txt
     (d) Test 4 - Second Run\Time 7\PW4.txt
  ii) Normal Air environment
     (a) Test 1 - Second Run\Time 7\PN1.txt
     (b) Test 2 - Second Run\Time 7\PN2.txt
     (c) Test 3 - Second Run\Time 7\PN3.txt
  iii) Dry environment
     (a) Test 1 - Second Run\Time 7\PD1.txt
     (b) Test 2 - Second Run\Time 7\PD2.txt
     (c) Test 3 - Second Run\Time 7\PD3.txt
     (d) Test 4 - Second Run\Time 7\PD4.txt
- 24 Hours in
  i) Wet environment
     (a) Test 1 - Second Run\Time 24\PW1.txt
     (b) Test 2 - Second Run\Time 24\PW2.txt
     (c) Test 3 - Second Run\Time 24\PW3.txt
  ii) Normal Air environment
     (a) Test 1 - Second Run\Time 24\PN1.txt
     (b) Test 2 - Second Run\Time 24\PN2.txt
     (c) Test 3 - Second Run\Time 24\PN3.txt
  iii) Dry environment
     (a) Test 1 - Second Run\Time 24\PD1.txt
     (b) Test 2 - Second Run\Time 24\PD2.txt
     (c) Test 3 - Second Run\Time 24\PD3.txt
- 26 Hours in
  i) Wet environment
     (a) Test 1 - Second Run\Time 26\PW1.txt
     (b) Test 2 - Second Run\Time 26\PW2.txt
     (c) Test 3 - Second Run\Time 26\PW3.txt
  ii) Normal Air environment
     (a) Test 1 - Second Run\Time 26\PN1.txt

(b) Test 2 - Second Run\Time 26\PN2.txt
(c) Test 3 - Second Run\Time 26\PN3.txt

iii) Dry environment

(a) Test 1 - Second Run\Time 26\PD1.txt
(b) Test 2 - Second Run\Time 26\PD2.txt
(c) Test 3 - Second Run\Time 26\PD3.txt

- 29 Hours in

i) Wet environment

(a) Test 1 - Second Run\Time 29\PW1.txt
(b) Test 2 - Second Run\Time 29\PW2.txt
(c) Test 3 - Second Run\Time 29\PW3.txt

ii) Normal Air environment

(a) Test 1 - Second Run\Time 29\PN1.txt
(b) Test 2 - Second Run\Time 29\PN2.txt
(c) Test 3 - Second Run\Time 29\PN3.txt

iii) Dry environment

(a) Test 1 - Second Run\Time 29\PD1noV.txt
(b) Test 2 - Second Run\Time 29\PD2noV.txt
(c) Test 3 - Second Run\Time 29\PD3noV.txt

- 31 Hours in

i) Wet environment

(a) Test 1 - Second Run\Time 31\PW1.txt
(b) Test 2 - Second Run\Time 31\PW2.txt
(c) Test 3 - Second Run\Time 31\PW3.txt

ii) Normal Air environment

(a) Test 1 - Second Run\Time 31\PN1.txt
(b) Test 2 - Second Run\Time 31\PW2.txt
(c) Test 3 - Second Run\Time 31\PN3.txt

iii) Dry environment

(a) Test 1 - Second Run\Time 31\PD1.txt
(b) Test 2 - Second Run\Time 31\PD2.txt
(c) Test 3 - Second Run\Time 31\PD3.txt

Appendix D - Pringles compressive test video files

3. First Run
    - At time of opening
        i) Test 1 - First Run\Time 0\MOV035.MOD
        ii) Test 2 - First Run\Time 0\MOV036.MOD
        iii) Test 3 - First Run\Time 0\MOV037.MOD
        iv) Test 4 - First Run\Time 0\MOV038.MOD
        v) Test 5 - First Run\Time 0\MOV039.MOD
    - 3 Hours in
        i) Wet environment
            (a) Test 1 - First Run\Time 3\MOV03A.MOD
            (b) Test 2 - First Run\Time 3\MOV03B.MOD
            (c) Test 3 - First Run\Time 3\MOV03C.MOD
        ii) Normal Air environment
            (a) Test 1 - First Run\Time 3\MOV03D.MOD
            (b) Test 2 - First Run\Time 3\MOV03E.MOD
            (c) Test 3 - First Run\Time 3\MOV03F.MOD
        iii) Dry environment
            (a) Test 1 - First Run\Time 3\MOV040.MOD
            (b) Test 2 - First Run\Time 3\MOV041.MOD
            (c) Test 3 - First Run\Time 3\MOV042.MOD
    - 7 Hours in
        i) Wet environment
            (a) Test 1 - First Run\Time 7\MOV043.MOD
            (b) Test 2 - First Run\Time 7\MOV045.MOD
            (c) Test 3 - First Run\Time 7\MOV046.MOD
        ii) Normal Air environment
            (a) Test 1 - First Run\Time 7\MOV047.MOD
            (b) Test 2 - First Run\Time 7\MOV048.MOD
            (c) Test 3 - First Run\Time 7\MOV049.MOD
        iii) Dry environment
            (a) Test 1 - First Run\Time 7\MOV04A.MOD
            (b) Test 2 - First Run\Time 7\MOV04B.MOD
            (c) Test 3 - First Run\Time 7\MOV04C.MOD
    - 24 Hours in
        i) Wet environment
            (a) Test 1 - First Run\Time 24\MOV04D.MOD
            (b) Test 2 - First Run\Time 24\MOV04E.MOD
            (c) Test 3 - First Run\Time 24\MOV04F.MOD
        ii) Normal Air environment
            (a) Test 1 - First Run\Time 24\MOV050.MOD
            (b) Test 2 - First Run\Time 24\MOV051.MOD

(c) Test 3 - First Run\Time 24\MOV052.MOD

iii) Dry environment

(a) Test 1 - First Run\Time 24\MOV053.MOD

(b) Test 2 - First Run\Time 24\MOV054.MOD

(c) Test 3 - First Run\Time 24\MOV055.MOD

- 29 Hours in

i) Wet environment

(a) Test 1 - First Run\Time 29\MOV056.MOD

(b) Test 2 - First Run\Time 29\MOV057.MOD

(c) Test 3 - First Run\Time 29\MOV058.MOD

ii) Normal Air environment

(a) Test 1 - First Run\Time 29\MOV059.MOD

(b) Test 2 - First Run\Time 29\MOV05A.MOD

(c) Test 3 - First Run\Time 29\MOV05B.MOD

iii) Dry environment

(a) Test 1 - First Run\Time 29\MOV05C.MOD

(b) Test 2 - First Run\Time 29\MOV05D.MOD

(c) Test 3 - First Run\Time 29\MOV05E.MOD

- 48 Hours in

i) Wet environment

(a) Test 1 - First Run\Time 48\MOV05F.MOD

(b) Test 2 - First Run\Time 48\MOV060.MOD

(c) Test 3 - First Run\Time 48\MOV061.MOD

ii) Normal Air environment

(a) Test 1 - First Run\Time 48\MOV062.MOD

(b) Test 2 - First Run\Time 48\MOV063.MOD

(c) Test 3 - First Run\Time 48\MOV064.MOD

iii) Dry environment

(a) Test 1 - First Run\Time 48\MOV065.MOD

(b) Test 2 - First Run\Time 48\MOV066.MOD

(c) Test 3 - First Run\Time 48\MOV067.MOD

4. Second Run

- At time of opening

i) Test 1 - Second Run\time 0\Film\MOV06F.MOD

ii) Test 2 - Second Run\time 0\Film\MOV070.MOD

iii) Test 3 - Second Run\time 0\Film\MOV071.MOD

iv) Test 4 - Second Run\time 0\Film\MOV072.MOD

v) Test 5 - Second Run\time 0\Film\MOV073.MOD

- 3 Hours in

i) Wet environment

(a) Test 1 - Second Run\time 3\Film\MOV079.MOD

(b) Test 2 - Second Run\time 3\Film\MOV07A.MOD

(c) Test 3 - Second Run\time 3\Film\MOV07B.MOD

ii) Normal Air environment
    (a) Test 1 - Second Run\time 3\Film\MOV07F.MOD
    (b) Test 2 - Second Run\time 3\Film\MOV080.MOD
    (c) Test 3 - Second Run\time 3\Film\MOV080.MOD
iii) Dry environment
    (a) Test 1 - Second Run\time 3\Film\MOV085.MOD
    (b) Test 2 - Second Run\time 3\Film\MOV086.MOD
    (c) Test 3 - Second Run\time 3\Film\MOV087.MOD

- 7 Hours in
  i) Wet environment
    (a) Test 1 - Second Run\Time 7\Film\PringleWet1.MOD
    (b) Test 2 - Second Run\Time 7\Film\PringleWet2.MOD
    (c) Test 3 - Second Run\Time 7\Film\PringleWet3.MOD
    (d) Test 4 - Second Run\Time 7\Film\PringleWet4.MOD
  ii) Normal Air environment
    (a) Test 1 - Second Run\Time 7\Film\PringleNorm1.MOD
    (b) Test 2 - Second Run\Time 7\Film\PringleNorm2.MOD
    (c) Test 3 - Second Run\Time 7\Film\PringleNorm3.MOD
  iii) Dry environment
    (a) Test 1 - Second Run\Time 7\Film\PringleDry1.MOD
    (b) Test 2 - Second Run\Time 7\Film\PringleDry2.MOD
    (c) Test 3 - Second Run\Time 7\Film\PringleDry3.MOD
    (d) Test 4 - Second Run\Time 7\Film\PringleDry4.MOD
- 24 Hours in
  i) Wet environment
    (a) Test 1 - Second Run\Time 24\Film\MOV00E.MOD
    (b) Test 2 - Second Run\Time 24\Film\MOV00F.MOD
    (c) Test 3 - Second Run\Time 24\Film\MOV010.MOD
  ii) Normal Air environment
    (a) Test 1 - Second Run\Time 24\Film\MOV014.MOD
    (b) Test 2 - Second Run\Time 24\Film\MOV015.MOD
    (c) Test 3 - Second Run\Time 24\Film\MOV016.MOD
  iii) Dry environment
    (a) Test 1 - Second Run\Time 24\Film\MOV01A.MOD
    (b) Test 2 - Second Run\Time 24\Film\MOV01B.MOD
    (c) Test 3 - Second Run\Time 24\Film\MOV01C.MOD
- 26 Hours in
  i) Wet environment
    (a) Test 1 - Second Run\Time 26\Film\MOV020.MOD
    (b) Test 2 - Second Run\Time 26\Film\MOV021.MOD
    (c) Test 3 - Second Run\Time 26\Film\MOV022.MOD
  ii) Normal Air environment
    (a) Test 1 - Second Run\Time 26\Film\MOV026.MOD

(b) Test 2 - Second Run\Time 26\Film\MOV027.MOD
(c) Test 3 - Second Run\Time 26\Film\MOV028.MOD

iii) Dry environment
(a) Test 1 - Second Run\Time 26\Film\MOV02C.MOD
(b) Test 2 - Second Run\Time 26\Film\MOV02D.MOD
(c) Test 3 - Second Run\Time 26\Film\MOV02E.MOD

- 29 Hours in

i) Wet environment
(a) Test 1 - Second Run\Time 29\Film\MOV032.MOD
(b) Test 2 - Second Run\Time 29\Film\MOV033.MOD
(c) Test 3 - Second Run\Time 29\Film\MOV034.MOD

ii) Normal Air environment
(a) Test 1 - Second Run\Time 29\Film\MOV038.MOD
(b) Test 2 - Second Run\Time 29\Film\MOV039.MOD
(c) Test 3 - Second Run\Time 29\Film\MOV03A.MOD

- 31 Hours in

i) Wet environment
(a) Test 1 - Second Run\Time 31\Film\MOV03E.MOD
(b) Test 2 - Second Run\Time 31\Film\MOV03F.MOD
(c) Test 3 - Second Run\Time 31\Film\MOV040.MOD

ii) Normal Air environment
(a) Test 1 - Second Run\Time 31\Film\MOV044.MOD
(b) Test 2 - Second Run\Time 31\Film\MOV045.MOD
(c) Test 3 - Second Run\Time 31\Film\MOV046.MOD

iii) Dry environment
(a) Test 1 - Second Run\Time 31\Film\MOV04A.MOD
(b) Test 2 - Second Run\Time 31\Film\MOV04B.MOD
(c) Test 3 - Second Run\Time 31\Film\MOV04C.MOD

Appendix E - Lays Stax compressive test data

5. Only Run
   - At time of opening
     i) Test 1 - Second Run\time 0\L1.txt
     ii) Test 2 - Second Run\time 0\L2.txt
     iii) Test 3 - Second Run\time 0\L3.txt
     iv) Test 4 - Second Run\time 0\L4.txt
     v) Test 5 - Second Run\time 0\L5.txt
   - 3 Hours in
     i) Wet environment
        (a) Test 1 - Second Run\time 3\LW1.txt
        (b) Test 2 - Second Run\time 3\LW2.txt
        (c) Test 3 - Second Run\time 3\LW3.txt
     ii) Normal Air environment
        (a) Test 1 - Second Run\time 3\LN1.txt
        (b) Test 2 - Second Run\time 3\LN2.txt
        (c) Test 3 - Second Run\time 3\LN3.txt
     iii) Dry environment
        (a) Test 1 - Second Run\time 3\LD1.txt
        (b) Test 2 - Second Run\time 3\LD2.txt
        (c) Test 3 - Second Run\time 3\LD3.txt
   - 7 Hours in
     i) Wet environment
        (a) Test 1 - Second Run\Time 7\LW1.txt
        (b) Test 2 - Second Run\Time 7\LW2.txt
        (c) Test 3 - Second Run\Time 7\LW3.txt
     ii) Normal Air environment
        (a) Test 1 - Second Run\Time 7\LN1.txt
        (b) Test 2 - Second Run\Time 7\LN2.txt
        (c) Test 3 - Second Run\Time 7\LN3.txt
     iii) Dry environment
        (a) Test 1 - Second Run\Time 7\LD1.txt
        (b) Test 2 - Second Run\Time 7\LD2.txt
        (c) Test 3 - Second Run\Time 7\LD3.txt
   - 24 Hours in
     i) Wet environment
        (a) Test 1 - Second Run\Time 24\LW1.txt
        (b) Test 2 - Second Run\Time 24\LW2.txt
        (c) Test 3 - Second Run\Time 24\LW3.txt
     ii) Normal Air environment
        (a) Test 1 - Second Run\Time 24\LN1.txt
        (b) Test 2 - Second Run\Time 24\LN2.txt

(c) Test 3 - Second Run\Time 24\LN3.txt

iii) Dry environment

(a) Test 1 - Second Run\Time 24\LD1.txt

(b) Test 2 - Second Run\Time 24\LD2.txt

(c) Test 3 - Second Run\Time 24\LD3.txt

- 26 Hours in

i) Wet environment

(a) Test 1 - Second Run\Time 26\LW1.txt

(b) Test 2 - Second Run\Time 26\LW2.txt

(c) Test 3 - Second Run\Time 26\LW3.txt

ii) Normal Air environment

(a) Test 1 - Second Run\Time 26\LN1.txt

(b) Test 2 - Second Run\Time 26\LN2.txt

(c) Test 3 - Second Run\Time 26\LN3.txt

iii) Dry environment

(a) Test 1 - Second Run\Time 26\LD1.txt

(b) Test 2 - Second Run\Time 26\LD2.txt

(c) Test 3 - Second Run\Time 26\LD3.txt

- 29 Hours in

i) Wet environment

(a) Test 1 - Second Run\Time 29\LW1.txt

(b) Test 2 - Second Run\Time 29\LW2.txt

(c) Test 3 - Second Run\Time 29\LW3.txt

ii) Normal Air environment

(a) Test 1 - Second Run\Time 29\LN1.txt

(b) Test 2 - Second Run\Time 29\LN2.txt

(c) Test 3 - Second Run\Time 29\LN3.txt

iii) Dry environment

(a) Test 1 - Second Run\Time 29\LD1noV.txt

(b) Test 2 - Second Run\Time 29\LD2noV.txt

(c) Test 3 - Second Run\Time 29\LD3noV.txt

- 31 Hours in

i) Wet environment

(a) Test 1 - Second Run\Time 31\LW1.txt

(b) Test 2 - Second Run\Time 31\LW2.txt

(c) Test 3 - Second Run\Time 31\LW3.txt

ii) Normal Air environment

(a) Test 1 - Second Run\Time 31\LN1.txt

(b) Test 2 - Second Run\Time 31\LN2.txt

(c) Test 3 - Second Run\Time 31\LN3.txt

iii) Dry environment

(a) Test 1 - Second Run\Time 31\LD1.txt

(b) Test 2 - Second Run\Time 31\LD2.txt

(c) Test 3 - Second Run\Time 31\LD3.txt

Appendix F - Lays Stax compressive test video files

6. First Run
    - At time of opening
        i) Test 1 - Second Run\time 0\Film\MOV074.MOD
        ii) Test 2 - Second Run\time 0\Film\MOV075.MOD
        iii) Test 3 - Second Run\time 0\Film\MOV076.MOD
        iv) Test 4 - Second Run\time 0\Film\MOV077.MOD
        v) Test 5 - Second Run\time 0\Film\MOV078.MOD
    - 3 Hours in
        i) Wet environment
            (a) Test 1 - Second Run\time 3\Film\MOV07C.MOD
            (b) Test 2 - Second Run\time 3\Film\MOV07D.MOD
            (c) Test 3 - Second Run\time 3\Film\MOV07E.MOD
        ii) Normal Air environment
            (a) Test 1 - Second Run\time 3\Film\MOV082.MOD
            (b) Test 2 - Second Run\time 3\Film\MOV083.MOD
            (c) Test 3 - Second Run\time 3\Film\MOV084.MOD
        iii) Dry environment
            (a) Test 1 - Second Run\time 3\Film\MOV088.MOD
            (b) Test 2 - Second Run\time 3\Film\MOV089.MOD
            (c) Test 3 - Second Run\time 3\Film\MOV08A.MOD
    - 7 Hours in
        i) Wet environment
            (a) Test 1 - Second Run\Time 7\Film\LaysWet1.MOD
            (b) Test 2 - Second Run\Time 7\Film\LaysWet2.MOD
            (c) Test 3 - Second Run\Time 7\Film\LaysWet3.MOD
        ii) Normal Air environment
            (a) Test 1 - Second Run\Time 7\Film\LaysNorm1.MOD
            (b) Test 2 - Second Run\Time 7\Film\LaysNorm2.MOD
            (c) Test 3 - Second Run\Time 7\Film\LaysNorm3.MOD
        iii) Dry environment
            (a) Test 1 - Second Run\Time 7\Film\LaysDry1.MOD
            (b) Test 2 - Second Run\Time 7\Film\LaysDry2.MOD
            (c) Test 3 - Second Run\Time 7\Film\LaysDry3.MOD
    - 24 Hours in
        i) Wet environment
            (a) Test 1 - Second Run\Time 24\Film\MOV011.MOD
            (b) Test 2 - Second Run\Time 24\Film\MOV012.MOD
            (c) Test 3 - Second Run\Time 24\Film\MOV013.MOD
        ii) Normal Air environment
            (a) Test 1 - Second Run\Time 24\Film\MOV017.MOD
            (b) Test 2 - Second Run\Time 24\Film\MOV018.MOD

(c) Test 3 - Second Run\Time 24\Film\MOV019.MOD

iii) Dry environment

(a) Test 1 - Second Run\Time 24\Film\MOV01D.MOD

(b) Test 2 - Second Run\Time 24\Film\MOV01E.MOD

(c) Test 3 - Second Run\Time 24\Film\MOV01F.MOD

- 26 Hours in

i) Wet environment

(a) Test 1 - Second Run\Time 26\Film\MOV023.MOD

(b) Test 2 - Second Run\Time 26\Film\MOV024.MOD

(c) Test 3 - Second Run\Time 26\Film\MOV025.MOD

ii) Normal Air environment

(a) Test 1 - Second Run\Time 26\Film\MOV029.MOD

(b) Test 2 - Second Run\Time 26\Film\MOV02A.MOD

(c) Test 3 - Second Run\Time 26\Film\MOV02B.MOD

iii) Dry environment

(a) Test 1 - Second Run\Time 26\Film\MOV02F.MOD

(b) Test 2 - Second Run\Time 26\Film\MOV030.MOD

(c) Test 3 - Second Run\Time 26\Film\MOV031.MOD

- 29 Hours in

i) Wet environment

(a) Test 1 - Second Run\Time 29\Film\MOV035.MOD

(b) Test 2 - Second Run\Time 29\Film\MOV036.MOD

(c) Test 3 - Second Run\Time 29\Film\MOV037.MOD

ii) Normal Air environment

(a) Test 1 - Second Run\Time 29\Film\MOV03B.MOD

(b) Test 2 - Second Run\Time 29\Film\MOV03C.MOD

(c) Test 3 - Second Run\Time 29\Film\MOV03D.MOD

- 31 Hours in

i) Wet environment

(a) Test 1 - Second Run\Time 31\Film\MOV041.MOD

(b) Test 2 - Second Run\Time 31\Film\MOV042.MOD

(c) Test 3 - Second Run\Time 31\Film\MOV043.MOD

ii) Normal Air environment

(a) Test 1 - Second Run\Time 31\Film\MOV047.MOD

(b) Test 2 - Second Run\Time 31\Film\MOV048.MOD

(c) Test 3 - Second Run\Time 31\Film\MOV049.MOD

iii) Dry environment

(a) Test 1 - Second Run\Time 31\Film\MOV04D.MOD

(b) Test 2 - Second Run\Time 31\Film\MOV04E.MOD

(c) Test 3 - Second Run\Time 31\Film\MOV04F.MOD

(d)

Appendix G - Three point flexural test graphs.

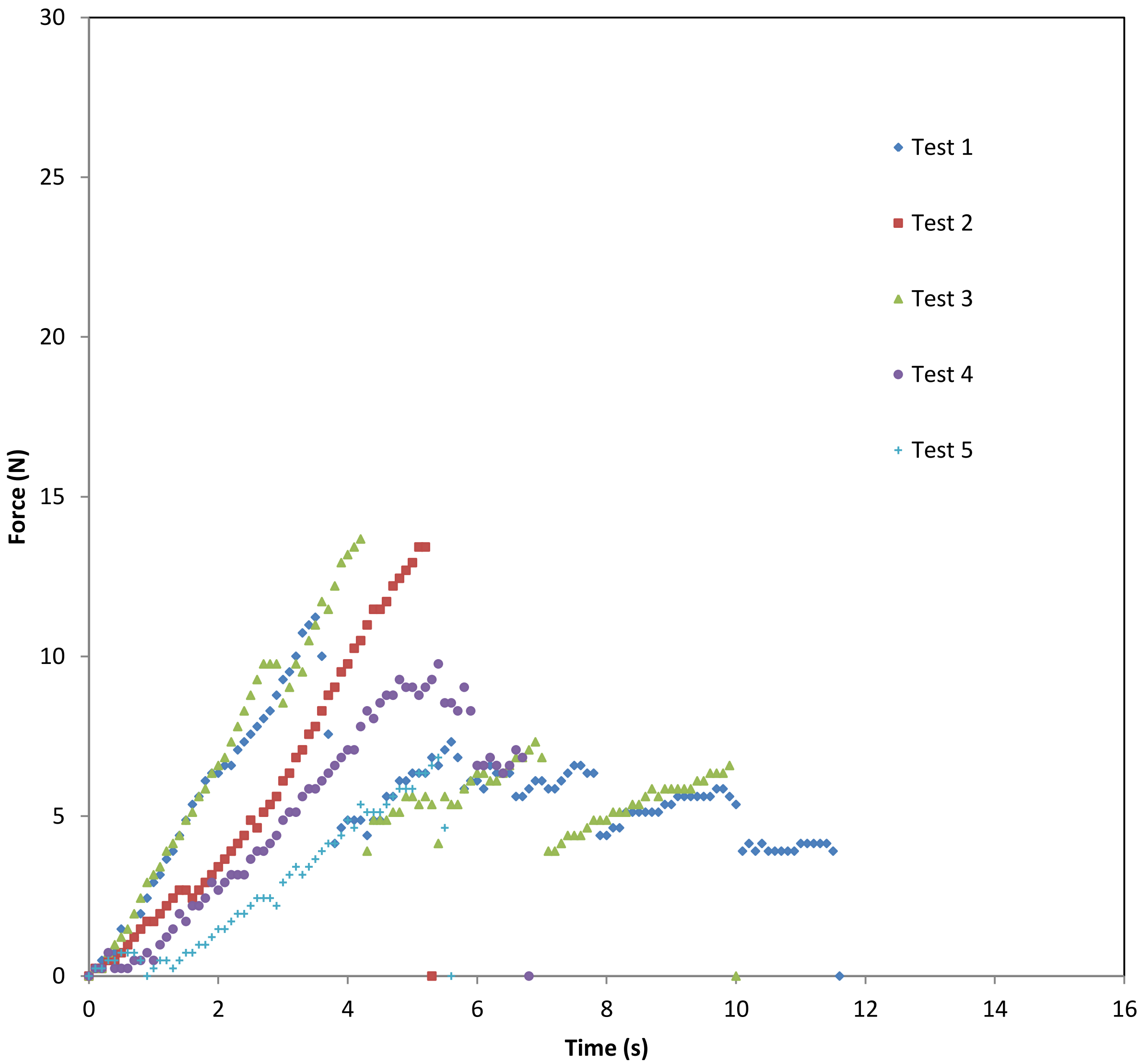

Figure 4 Force verse time graph for the five 3 point flexural test for Cape Cod Kettle chips.

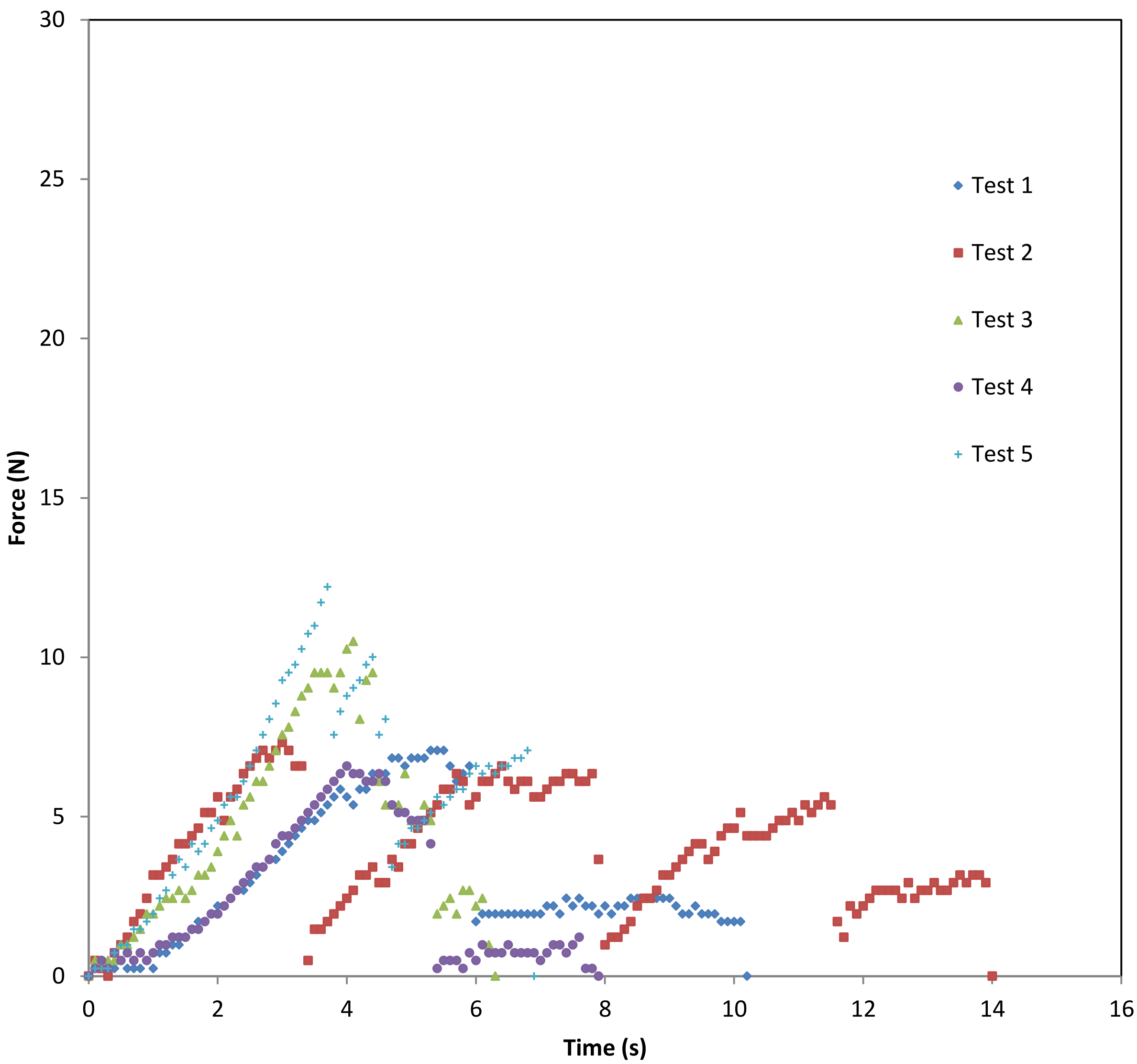

Figure 5 Force verse time graph for the five 3 point flexural test for Lays Kettle chips.

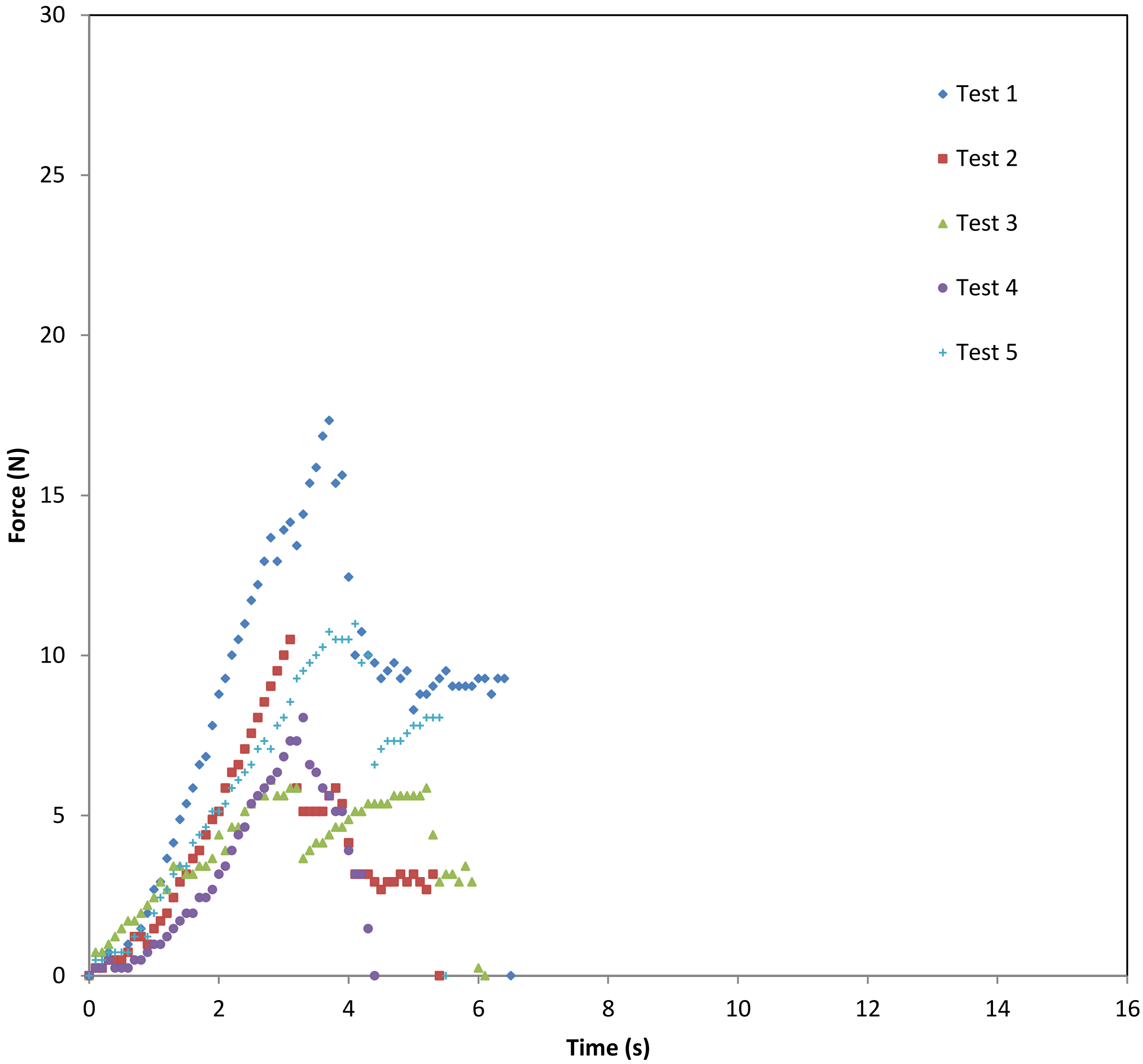

Figure 6 Force verse time graph for the five 3 point flexural test for Price Chopper Kettle chips.

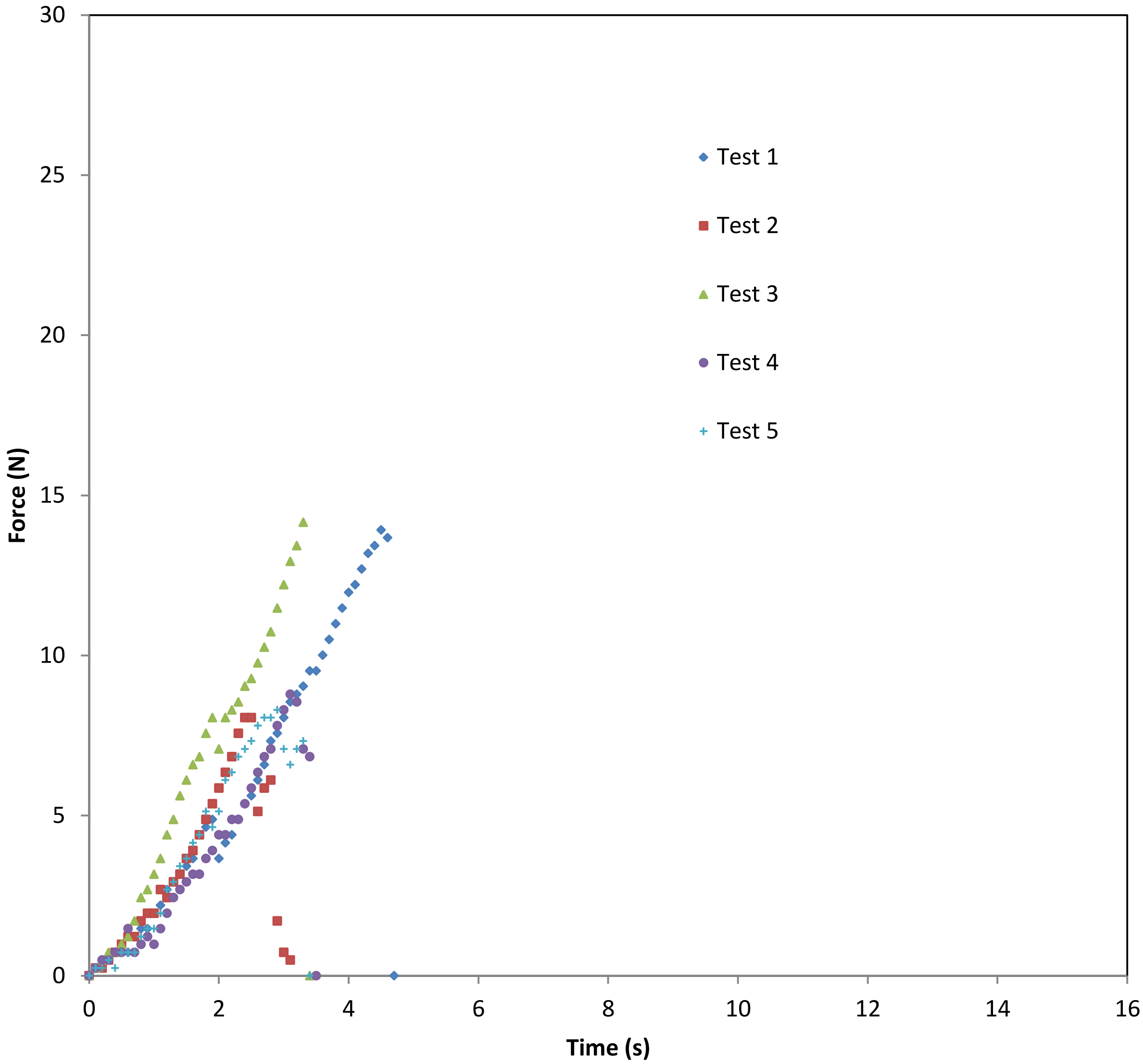

Figure 7 Force verse time graph for the five 3 point flexural test for Fritos chips.

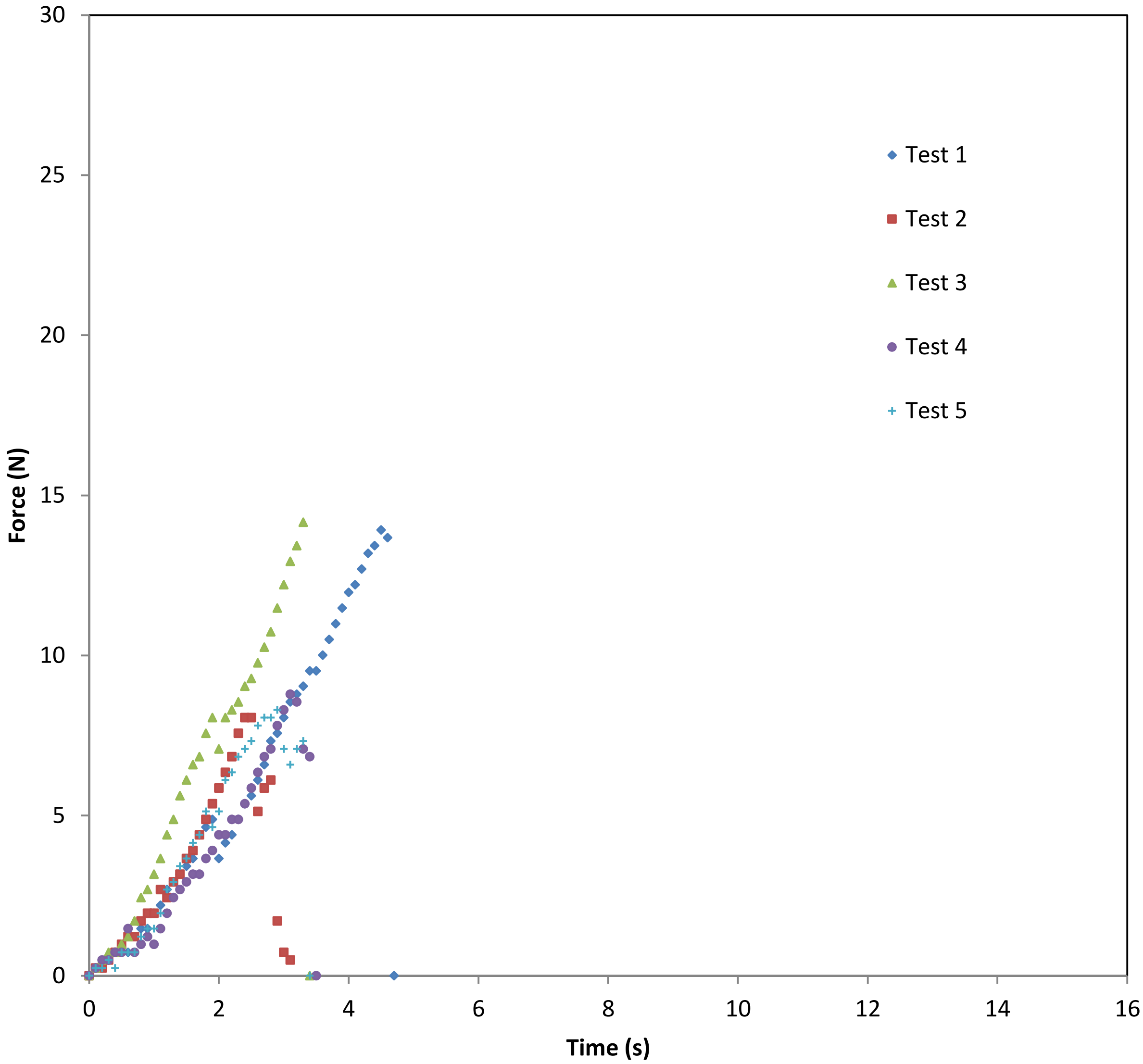

Figure 8 Force verse time graph for the five 3 point flexural test for Doritos chips.

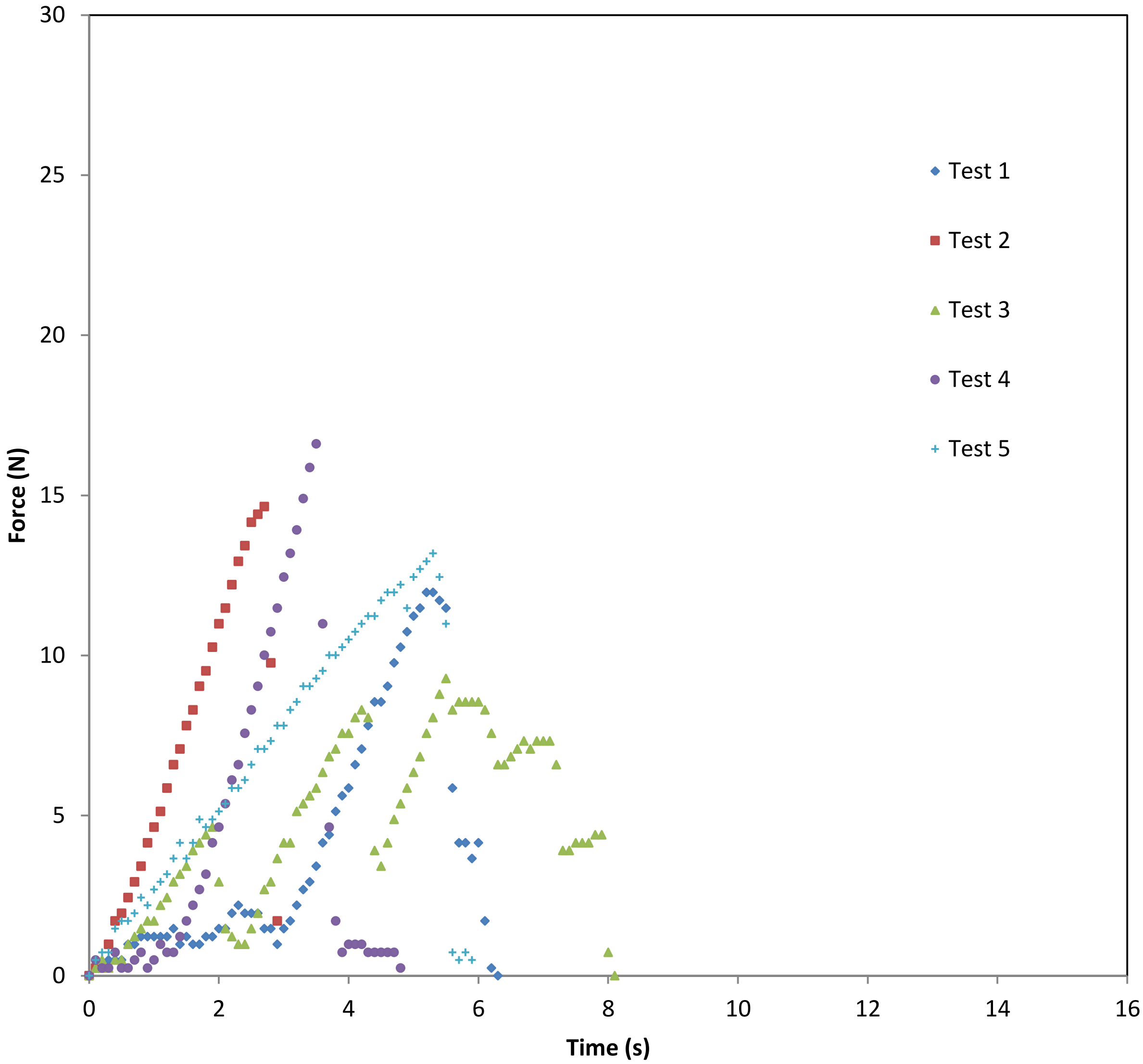

Figure 9 Force verse time graph for the five 3 point flexural test for Santitas Tortilla chips.

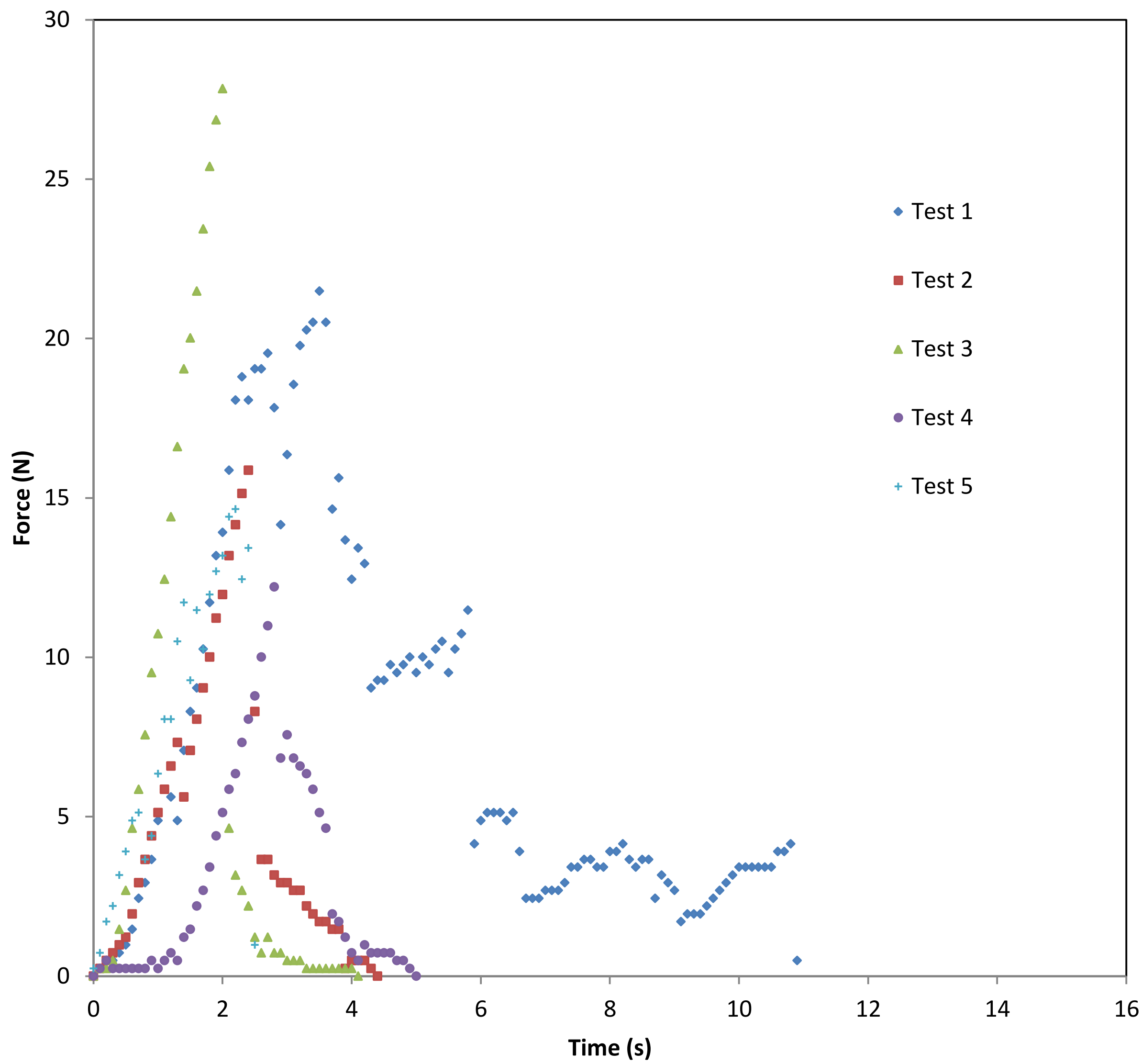

Figure 10 Force verse time graph for the five 3 point flexural test for Stacy's Pita chips.

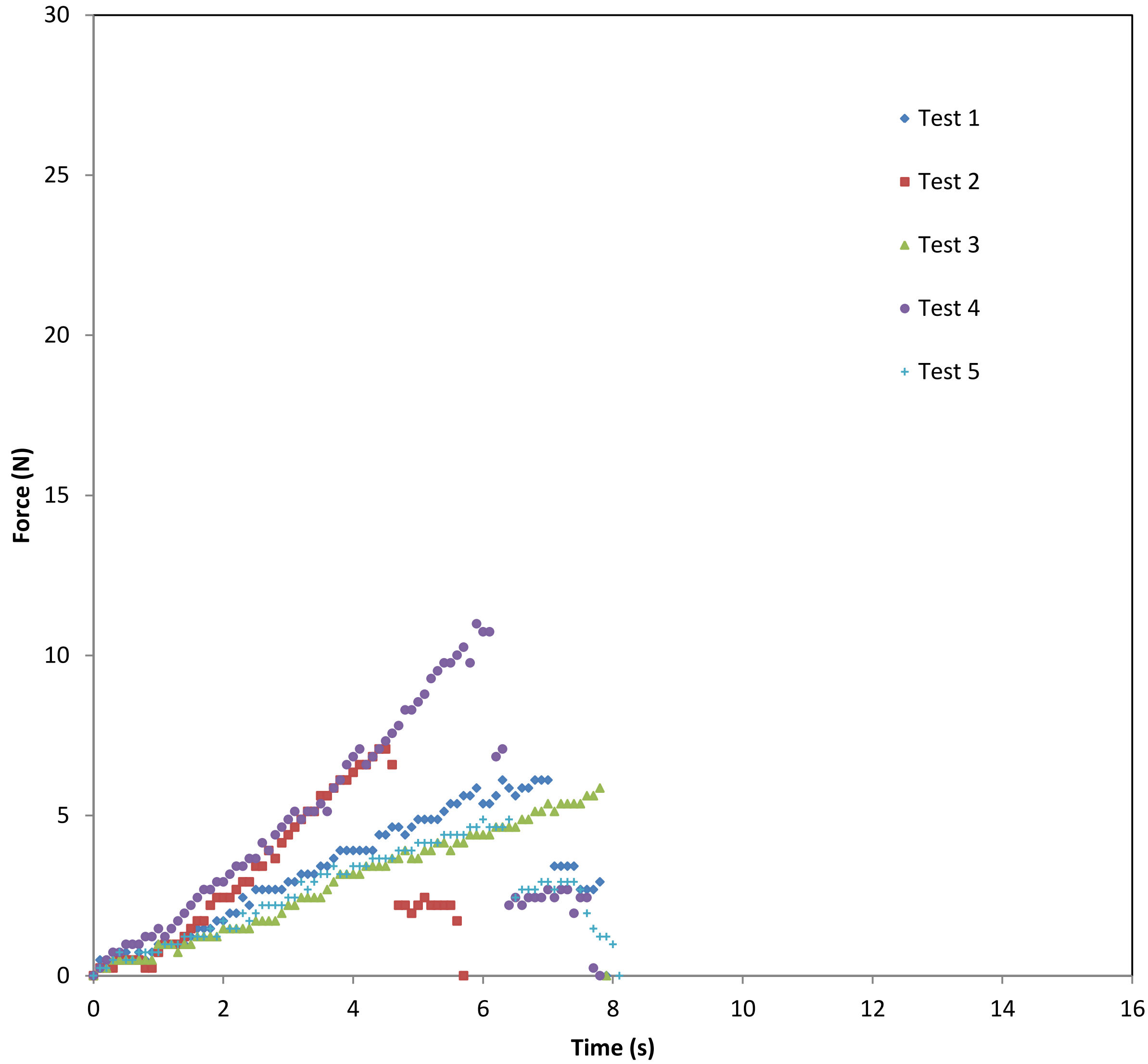

Figure 11 Force verse time graph for the five 3 point flexural test for Ruffles chips.

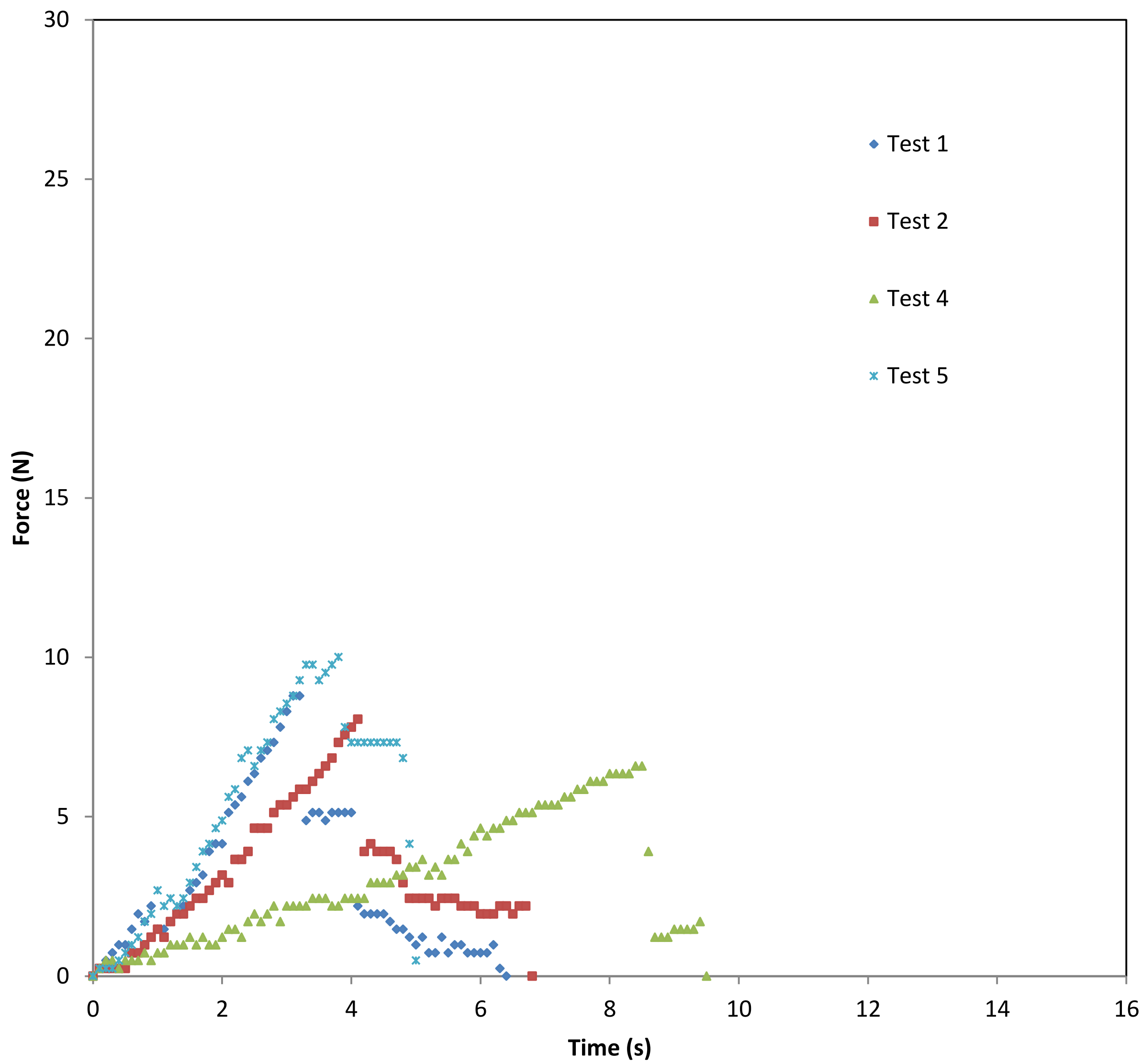

Figure 12 Force verse time graph for the four 3 point flexural test for Wise Ridgies chips. One trial was removed due to errors in data collection.

Appendix H - Three point flexural test data tables.
P - Maximum force achieved (N)
L - Distance between the bottom supports, constant 19.15mm
b - Thickness of sample (mm)
d - Length or fracture (mm)
t - Time of trial (s)
D - Maximum distance flexed, is equal to t/6. (mm)

Cape Cod Kettle Chips								
Test Number	P (N)	L (mm)	b (mm)	d (mm)	t (s)	D (mm)	Stress	Strain
1	11.23	19.15	1.22	36.18	3.8	0.63	0.20	0.37
2	13.43	19.15	1.17	37.85	5.2	0.87	0.23	0.54
3	13.68	19.15	1.18	39.95	4.2	0.7	0.21	0.46
4	9.77	19.15	0.9	28	5.4	0.9	0.40	0.41
5	6.84	19.15	1.13	15.75	5.4	0.9	0.70	0.23
Average	10.99	19.15	1.12	31.55	4.8	0.8	0.35	0.40
Standard Deviation	2.83	0	0.13	9.92	0.75	0.12	0.21	0.11

Lays Kettle Chips								
Test Number	P (N)	L (mm)	b (mm)	d (mm)	t (s)	D (mm)	Stress	Strain
1	7.08	19.15	1.43	34.6	5.5	0.92	0.12	0.52
2	7.33	19.15	1.1	33.3	3	0.5	0.17	0.27
3	10.5	19.15	1.23	41	4.1	0.68	0.15	0.46
4	6.59	19.15	0.9	31	4	0.67	0.22	0.34
5	12.21	19.15	1.62	30.55	3.7	0.62	0.23	0.31
Average	8.74	19.15	1.26	34.09	4.06	0.68	0.18	0.38
Standard Deviation	2.48	0	0.28	4.20	0.91	0.15	0.05	0.10

Price Chopper Kettle Chips								
Test Number	P (N)	L (mm)	b (mm)	d (mm)	t (s)	D (mm)	Stress	Strain
1	17.34	19.15	1.08	38.85	3.7	0.62	0.30	0.39
2	10.5	19.15	1.35	31.6	3.1	0.52	0.22	0.27
3	6.11	19.15	1.08	33	2.8	0.47	0.15	0.25
4	8.06	19.15	1	36	3.3	0.55	0.18	0.32
5	10.99	19.15	1.6	26	4.1	0.68	0.29	0.29
Average	10.6	19.15	1.22	33.09	3.4	0.57	0.23	0.31

Standard Deviation	4.25	0	0.25	4.85	0.51	0.08	0.07	0.06

Fritos Chips								
Test Number	P (N)	L (mm)	b (mm)	d (mm)	t (s)	D (mm)	Stress	Strain
1	13.92	19.15	1.93	15.05	4.6	0.77	0.91	0.19
2	8.06	19.15	1.58	14.25	2.5	0.42	0.72	0.10
3	14.16	19.15	1.92	19.65	3.3	0.55	0.55	0.18
4	8.79	19.15	1.42	15.1	3.2	0.53	0.78	0.13
5	8.3	19.15	1.58	14.85	2.9	0.48	0.68	0.12
Average	10.65	19.15	1.69	15.78	3.3	0.55	0.73	0.14
Standard Deviation	3.11	0	0.23	2.19	0.79	0.13	0.13	0.04

Doritos Chips								
Test Number	P	L	b	d	t	D	Stress	Strain
1	13.92	19.15	2.17	22.4	4.7	0.78	0.37	0.29
2	8.06	19.15	1.62	19.3	3.1	0.52	0.38	0.16
3	14.16	19.15	1.33	37.6	3.4	0.57	0.22	0.35
4	8.79	19.15	2.2	22.55	3.5	0.58	0.23	0.22
5	8.3	19.15	1.27	31.85	3.4	0.57	0.19	0.30
Average	10.646	19.15	1.72	26.74	3.62	0.60	0.28	0.26
Standard Deviation	3.11	0	0.45	7.68	0.62	0.10	0.09	0.07

Santitas Tortilla Chips								
Test Number	P (N)	L (mm)	b (mm)	d (mm)	t (s)	D (mm)	Stress	Strain
1	11.97	19.15	1.03	27.45	5.5	0.92	0.44	0.41
2	14.65	19.15	1.08	25.45	2.7	0.45	0.60	0.19
3	9.28	19.15	1.05	35.8	4.2	0.7	0.20	0.41
4	16.61	19.15	1.22	27.8	3.5	0.58	0.51	0.27
5	13.19	19.15	0.95	33.4	5.3	0.88	0.36	0.48
Average	13.14	19.15	1.07	29.98	4.24	0.71	0.42	0.35
Standard Deviation	2.77	0	0.10	4.39	1.19	0.20	0.15	0.12

Stacy's Pita Chips								
Test Number	P (N)	L (mm)	b (mm)	d (mm)	t (s)	D (mm)	Stress	Strain
1	21.49	19.15	3.02	29.4	2.6	0.43	0.24	0.21
2	15.87	19.15	2.23	30.6	2.4	0.4	0.22	0.20
3	27.84	19.15	3.05	21.9	2	0.33	0.55	0.12
4	12.21	19.15	2.78	16.2	2.8	0.47	0.48	0.12
5	13.19	19.15	2.92	18.6	2.4	0.4	0.38	0.12
Average	18.12	19.15	2.8	23.34	2.44	0.41	0.37	0.15
Standard Deviation	6.52	0	0.33	6.42	0.30	0.05	0.15	0.05

Ruffles Chips								
Test Number	P (N)	L (mm)	b (mm)	d (mm)	t (s)	D (mm)	Stress	Strain
1	6.11	19.15	2.43	48	7	1.17	0.03	0.92
2	7.08	19.15	2.45	31.25	4.6	0.77	0.09	0.39
3	5.86	19.15	2.3	43	7.8	1.3	0.04	0.91
4	10.99	19.15	2.45	43.15	5.9	0.98	0.07	0.69
5	4.88	19.15	2.4	44.32	6.4	1.07	0.03	0.77
Average	6.98	19.15	2.41	41.94	6.34	1.06	0.050	0.74
Standard Deviation	2.37	0	0.06	6.31	1.20	0.20	0.02	0.22

Wise Ridgies								
Test Number	P (N)	L (mm)	b (mm)	d (mm)	t (s)	D (mm)	Stress	Strain
1	8.79	19.15	2.4	36.45	3.1	0.52	0.08	0.31
2	8.06	19.15	1.8	41.7	4.1	0.68	0.07	0.47
3	3.91	19.15	2.02	41.65	10.2	1.7	0.03	1.16
4	6.59	19.15	1.82	41.55	8.4	1.4	0.06	0.95
5	10.01	19.15	1.78	42.75	3.8	0.63	0.09	0.44
Average	7.472	19.15	1.96	40.82	5.92	0.99	0.07	0.67
Standard Deviation	2.34	0	0.26	2.49	3.17	0.53	0.02	0.37

Appendix I - An average Pringles compressive trial.

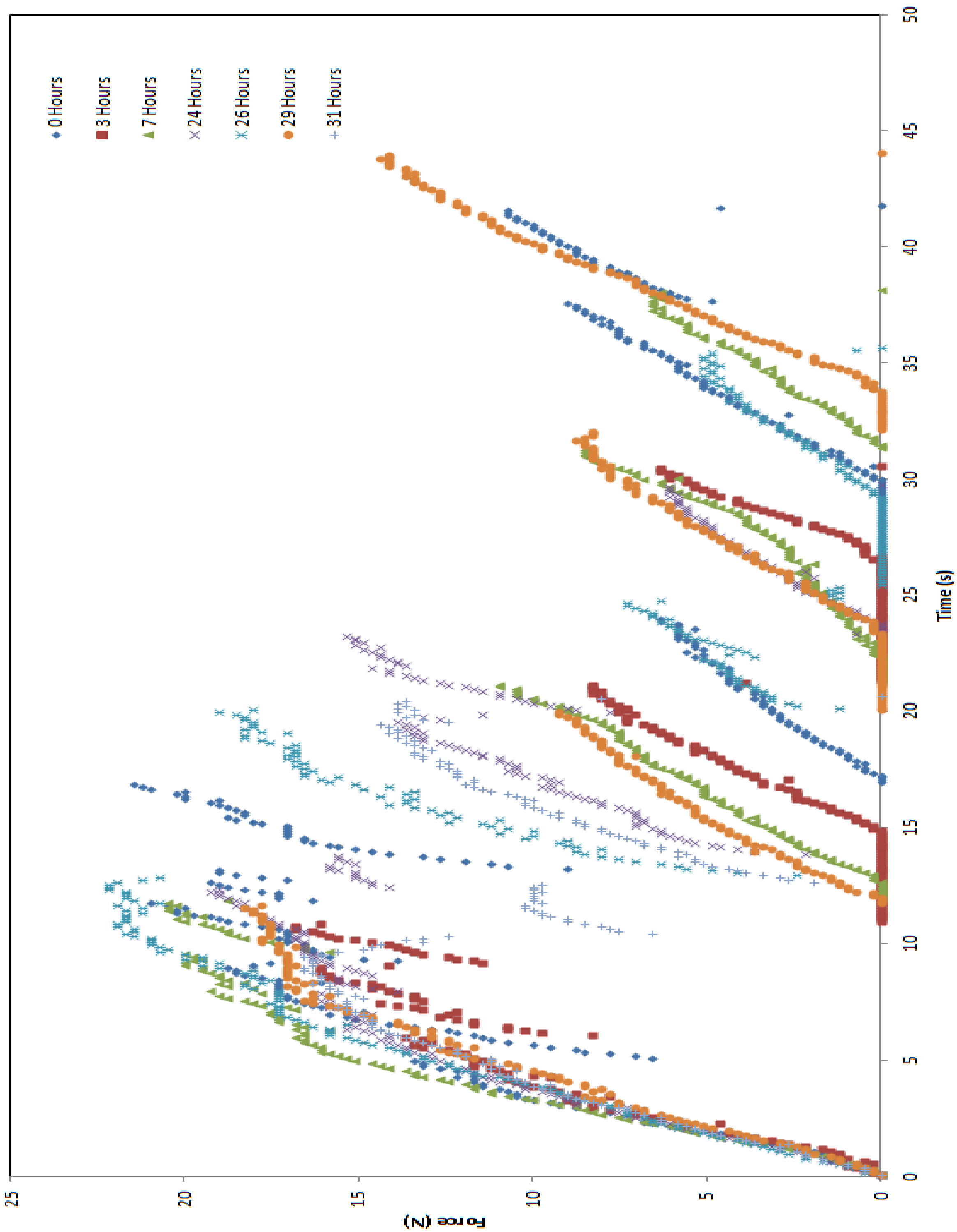

Figure 13 Average compressive trial for Pringle chips placed in the humid environment.

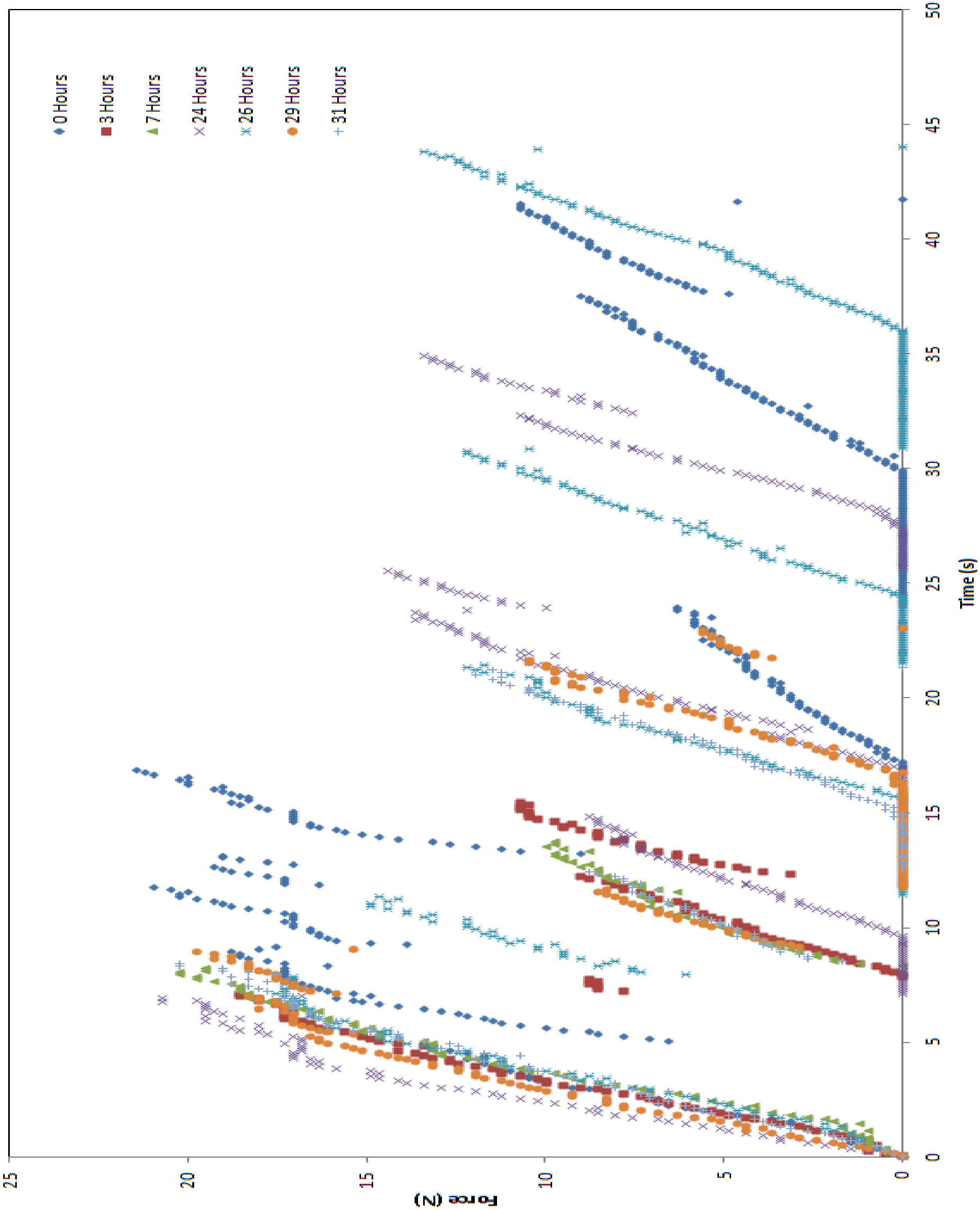

Figure 14 Average compressive trial for Pringle chips placed in the normal air environment.

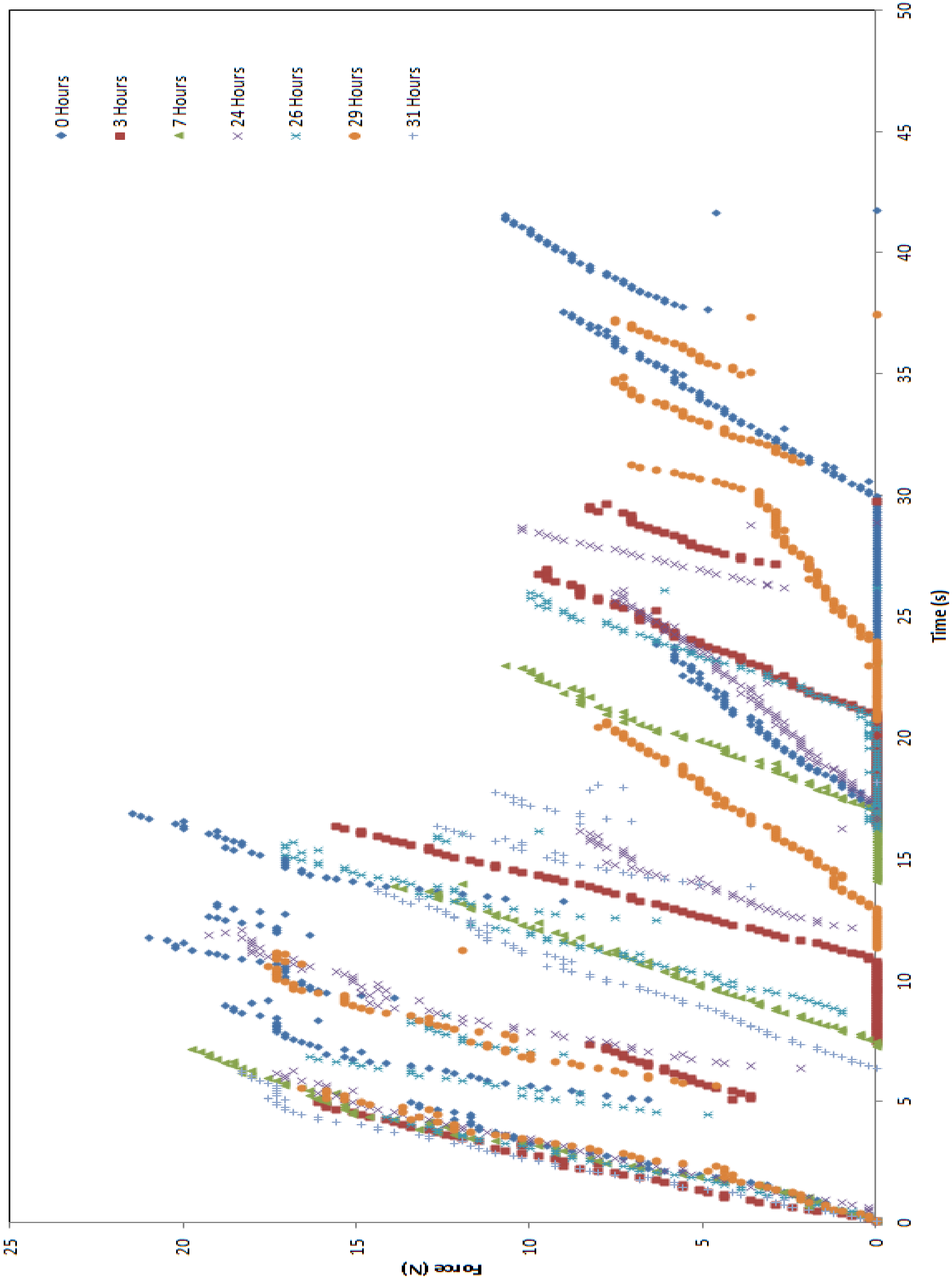

Figure 15 Average compressive trial for Pringle chips placed in the dry environment.

Appendix J - An average Lays compressive trial.

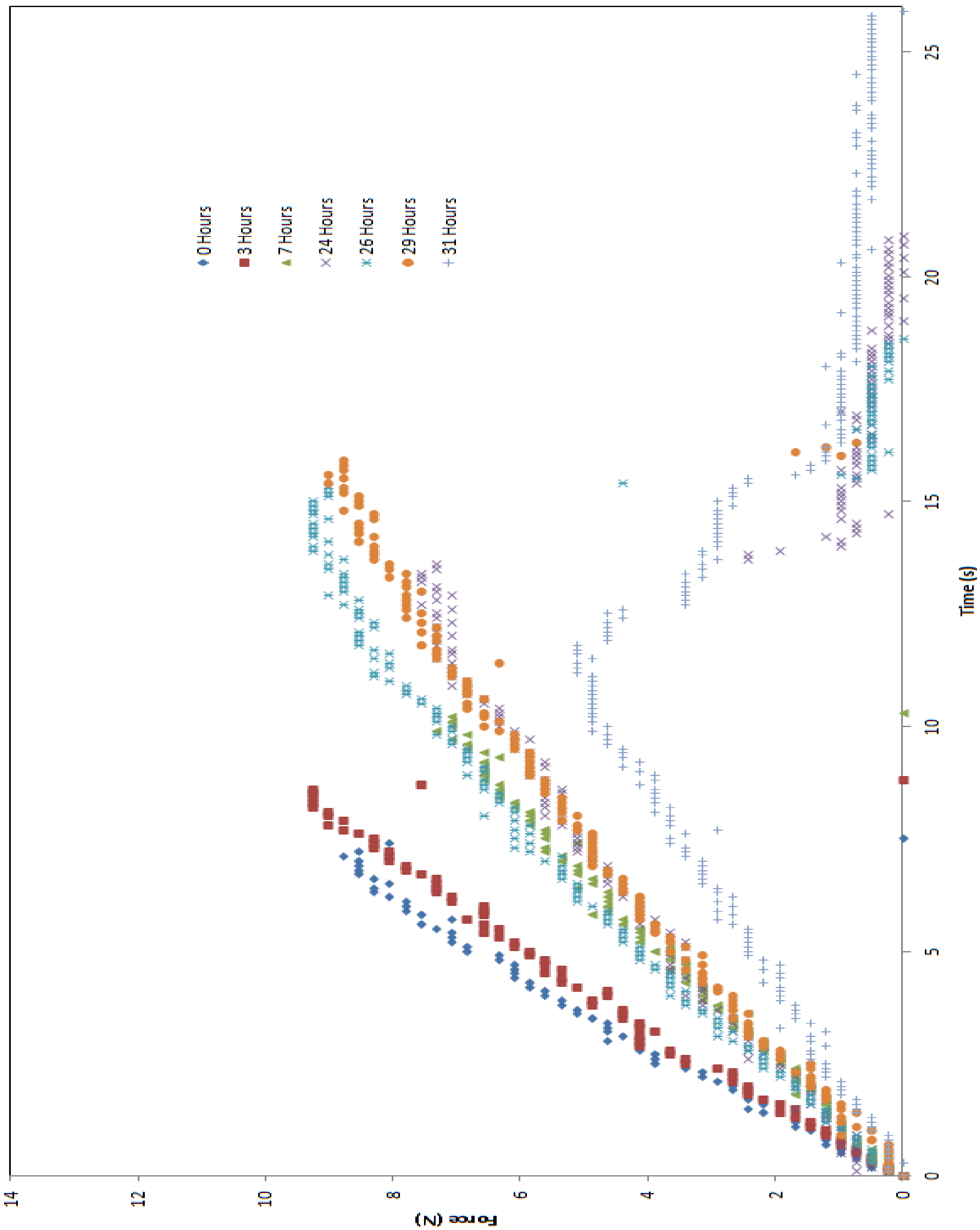

Figure 16 Average compressive trial for Lays chips placed in the humid environment.

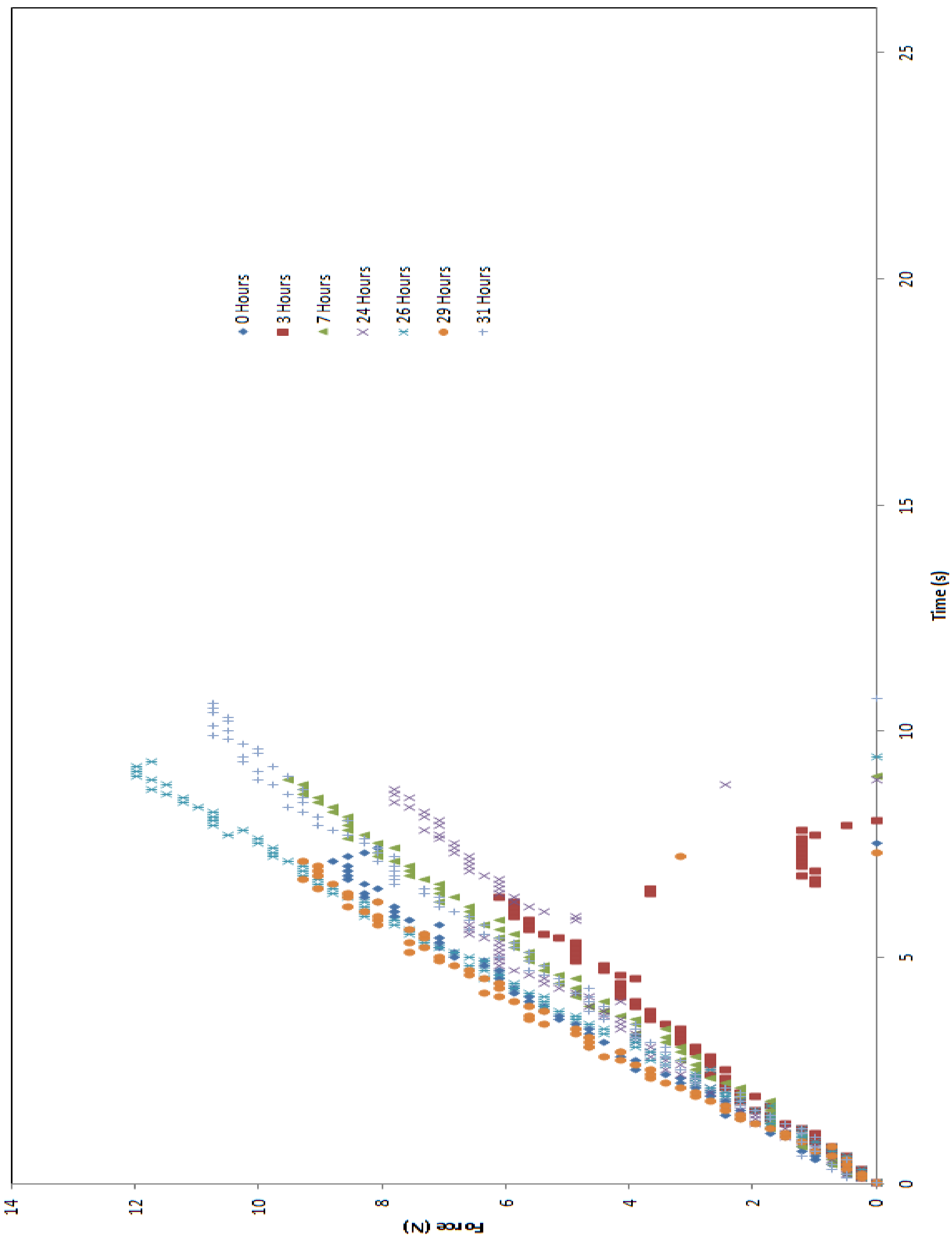

Figure 17 Average compressive trial for Lays chips placed in the normal air environment.

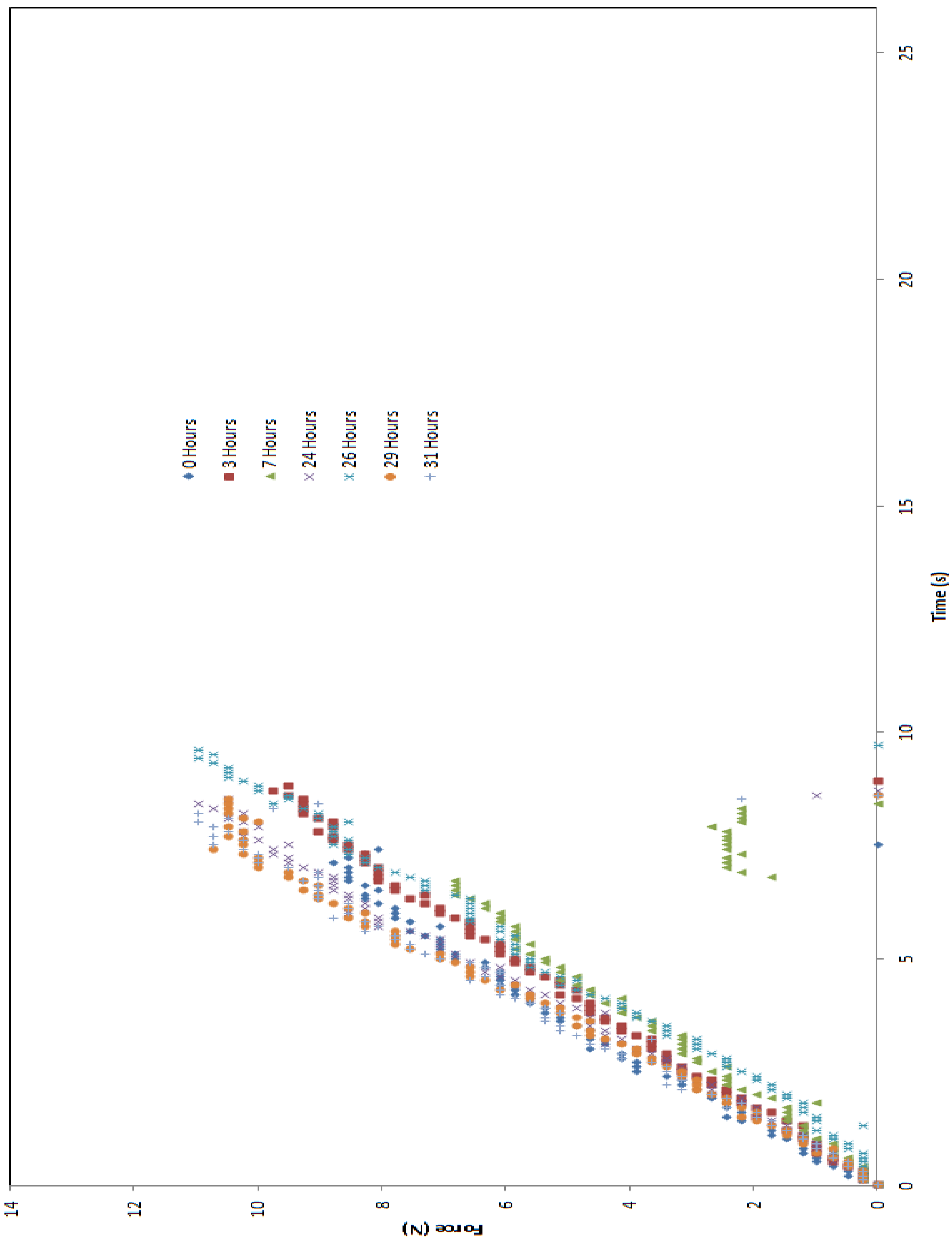

Figure 18 Average compressive trial for Lays chips placed in the dry environment.

Appendix K - Ingredients of chips used.

Pringles: Dried Potatoes, Vegetable Oil (Contains one or more of the following: Corn Oil, Cottonseed Oil, Soybean Oil, and/or Sunflower Oil), Rice Flour, Wheat Starch, Maltodextrin, Salt and Dextrose.

Lay's Stax: Dried Potatoes, Vegetable Oil (Cottonseed, Sunflower, and/or Corn Oil), Unmodified Potato Starch, Rice Flour, and Less than 2% or the following: mono- and diglycerides, Salt, Sugar, Dextrose and Soy Lecithin

Doritos: Whole Corn, Vegetable Oil, Maltodextrin, less than 2% of the following: Wheat Flour, Salt, Cheddar Cheese, Whey, Monosodium Glutamate, Buttermilk, Romano Cheese, Whey Protein Concentrate, Onion Powder, Partially Hydrogenated soybean and Cottonseed Oil, Corn Flour, Natural and Artificial Flavor, Dextrose, Tomato Powder, Lactose, Spices, Artificial Color (including Yellow 6, Yellow 5, Red 40), Lactic Acid, Citric Acid, Sugar, Garlic Powder, Skim Milk, Whey Protein Isolate, Corn Syrup Solids, Red and Green Bell Pepper Powder, Sodium Caseinate, Disodium Inosinate, and Disodium Guanylate.

Fritos original corn chips: Corn, Corn Oil, and Salt.

Stacy's Pita Chips: Enriched Wheat Flour (wheat flour, Niacin, Reduced Iron, Thiamin mononitrate, Riboflavin, Folic Acid), Sunflower Oil (rosemary extract, Ascorbic Acid), Sea Salt, Whole Wheat Flour, and less than 2% of the following: Organic Cane Sugar, Oat Fiber, Active Yeast, Compressed Yeast, Inactive Yeast, and Malted Barley Flour.

Ruffles: Potatoes, Vegetable Oil (sunflower, Corn and/or Canola Oil), and Salt.

Lay's Kettle Cooked: Potatoes, Vegetable Oil (Sunflower, Corn and/or Canola Oil), and Sea Salt.

Cape Cod Potato Chips: Potatoes, Canola Oil, Salt.

Wise Ridgies: Potatoes, Vegetable Oil (Corn, Cottonseed, Sunflower, Soybean or Canola Oil), Salt.

Santitas: Whole White Corn, Vegetable Oil (Corn, Sunflower, Canola, and/or Soybean Oil), and Salt.

Appendix L - Pringles compressive data tables.

First run -

Number of Breaks									
Time	Wet			Norm			Dry		
0	9	7	3	10	6				
3	7	6	5	7	9	6	1	3	6
7	6	7	7	8	3	5	2	5	5
24	3	6	5	6	5	5	6	4	4
29	3	4	2	4	10	5	3	7	7
48	2	1	2	3	2	12	3	6	3

Time of Trial									
Time	Wet			Norm			Dry		
0	42.72	36.4	10.1	51.3	36.2				
3	51.3	47.5	48.5	42.7	53.7	33.8	12.7	24.2	49.5
7	56.8	57.11	65.31	49.7	15.8	29.2	11.8	34.7	22.5
24	28.3	47.5	41.51	33.3	32.6	25.7	31.9	29.2	21.7
29	45.1	67.11	34.5	17.6	56.42	32.4	17.1	48.51	27
48	61.21	66.32	67.31	16.6	11.6	60.9	20.5	35.9	28.6

Maximum Force (N)									
Time	Wet			Norm			Dry		
0	12.94	15.63	10.74	13.19	13.43				
3	12.21	17.58	15.38	15.38	15.63	13.68	17.83	15.14	17.83
7	14.65	14.65	12.94	11.72	12.94	11.97	13.43	12.21	13.19
24	11.48	15.63	15.63	12.21	16.12	14.41	11.48	11.48	14.16
29	13.68	12.45	15.63	12.7	14.65	11.72	8.79	12.7	11.97
48	7.57	10.99	9.77	10.99	10.26	14.16	13.92	12.21	16.36

Average Time/Break									
Time	Wet			Norm			Dry		
0	4.75	5.2	3.37	5.13	6.03				
3	7.33	7.92	9.7	6.1	5.97	5.63	12.7	8.07	8.25
7	9.47	8.16	9.33	6.21	5.27	5.84	5.9	6.94	4.5
24	9.43	7.92	8.30	5.55	6.52	5.14	5.32	7.3	5.425
29	15.03	16.78	17.25	4.4	5.64	6.48	5.7	6.93	3.86
48	30.61	66.32	33.66	5.53	5.8	5.08	6.83	5.98	9.53

Modulus									
Time	Wet			Norm			Dry		
0	1.52	2.11	1.82	1.40	1.53				
3	1.02	1.15	1.25	1.49	1.43	2	1.46	1.43	1.59
7	1.30	1.20	1.07	1.28	0.10	1.25	1.40	1.63	2.93
24	1.24	1.18	1.27	1.22	1.44	1.22	1.43	1.41	1.39
29	0.68	0.80	0.62	1.32	1.47	1.22	1.38	1.40	1.44
48	0.36	0.22	0.23	1.38	1.35	1.32	1.39	1.57	1.67

Average for Each container			Standard Deviations		
Wet	Normal	Dry	Wet	Normal	Dry
Number of Breaks					
7	7	7	2.74	2.74	2.74
6	7.33	3.33	1	1.53	2.52
6.67	5.33	4	0.58	2.52	1.73
4.67	5.33	4.67	1.53	0.58	1.15
3	6.33	5.67	1	3.21	2.31
1.67	5.67	4	0.58	5.51	1.73
Time of Trial					
Wet	Normal	Dry	Wet	Normal	Dry
35.34	35.34	35.34	15.40	15.40	15.40
49.10	43.40	28.80	1.97	9.97	18.83
59.74	31.57	23.00	4.83	17.07	11.46
39.10	30.53	27.60	9.82	4.20	5.28
48.90	35.47	30.87	16.63	19.59	16.06
64.95	29.70	28.33	3.27	27.14	7.70
Maximum Force (N)					
Wet	Normal	Dry	Wet	Normal	Dry
13.19	13.19	13.19	1.74	1.74	1.74
15.06	14.90	16.93	2.70	1.06	1.55
14.08	12.21	12.94	0.99	0.64	0.65
14.25	14.25	12.37	2.40	1.96	1.55
13.92	13.02	11.15	1.60	1.49	2.08
9.44	11.80	14.16	1.73	2.07	2.09
Average Time/Break					
Wet	Normal	Dry	Wet	Normal	Dry
4.90			0.97	0.97	0.97
8.32	5.90	9.67	1.23	0.24	2.62
8.99	5.77	5.78	0.72	0.48	1.22

8.55	5.74	6.01	0.79	0.71	1.12
16.35	5.51	5.50	1.17	1.05	1.55
43.53	5.47	7.45	19.80	0.37	1.85
Modulus					
Wet	Normal	Dry	Wet	Normal	Dry
1.67	1.67	1.67	0.29	0.29	0.29
1.14	1.64	1.49	0.11	0.31	0.09
1.19	0.88	1.99	0.11	0.67	0.83
1.23	1.29	1.41	0.05	0.12	0.02
0.70	1.34	1.40	0.09	0.13	0.03
0.27	1.35	1.55	0.08	0.03	0.14

Second run -

Number of Breaks									
Time	Wet			Norm			Dry		
0	10	3	7	8	6				
3	5	7	5	5	4	4	4	5	5
7	3	5	3	1	2	5	3	4	1
24	5	5	4	6	5	6	9	5	4
26	7	4	1	4	5	4	6	1	7
29	4	6	4	5	3	7	6	6	5
31	3	2	3	6	3	2	4	4	3
Time of Trial									
Time	Wet			Norm			Dry		
0	54.9	19.6	23.7	41.7	24.2				
3	28.1	51.9	30.5	11.6	15.4	24	16.7	29.7	39
7	20.4	38.1	25.3	2.8	13.8	36.3	23	21.3	6.2
24	29.7	49.2	29.4	35	29.9	26.7	40.6	28.8	29.5
26	57.11	35.6	8	22.7	44	15.9	32.4	6.7	26.1
29	44	55.4	40	23	22	21	37.4	18.5	37.24
31	25.3	21.7	20.6	27.6	21.3	18.7	18.1	30.8	11.8
Maximum Force (N)									
Time	Wet			Norm			Dry		
0	18.07	18.56	14.16	21.49	20.27				
3	16.61	18.07	15.87	17.09	18.56	20.51	19.29	16.12	17.83
7	29.79	20.51	21.25	0	20.27	19.05	19.73	17.58	16.85
24	19.29	16.61	14.9	20.76	18.32	21.98	17.58	19.29	19.05
26	18.32	22.22	16.85	23.44	17.58	13.68	23.44	17.09	17.09
29	18.32	18.07	18.8	19.87	17.58	16.85	17.58	18.8	13.67
31	17.34	15.14	16.61	16.36	20.27	20.76	18.32	17.09	16.85
Average Time/Break									

Time	Wet			Norm			Dry		
0	5.49	6.53	3.39	5.21	4.03				
3	5.62	7.41	6.1	2.32	3.85	6	4.175	5.94	7.8
7	6.8	7.62	8.43	2.8	6.9	7.26	7.67	5.33	6.2
24	5.94	9.84	7.35	5.83	5.98	4.45	4.51	5.76	7.38
26	8.16	8.9	8	5.68	8.8	3.98	5.4	6.7	3.73
29	11	9.23	10	4.6	7.33	3	6.23	3.08	7.45
31	8.43	10.85	6.87	4.6	7.1	9.35	4.525	7.7	3.93
Modulus									
Time	Wet			Norm			Dry		
0	3.08	2.89	3.13	2.81	3.45				
3	3.39	2.59	2.40	3.71	3.08	3.275	3.69	3.38	3.36
7	3.01	3.09	3.18	2.44	2.74	3.37	3.45	3.22	3.11
24	2.53	2.27	2.09	4.29	3.54	4.13	3.62	3.10	3.28
26	2.52	2.65	2.55	3.58	2.88	2.25	3.75	3.26	3.38
29	2.52	2.09	2.49	3.42	3.7	2.98	3.17	4.55	3.26
31	2.49	2.8	2.35	3.55	2.78	3.81	3.83	3.02	3.38

Average for Each container			Standard Deviations		
Wet	Normal	Dry	Wet	Normal	Dry
Number of Breaks					
6.80	6.80	6.80	2.59	2.59	2.59
5.67	4.33	4.67	1.15	0.58	0.58
5.67	2.67	3.33	1.15	2.08	1.53
4.67	5.67	6.00	0.58	0.58	2.65
4.00	4.33	4.67	3.00	0.58	3.21
4.67	5.00	5.67	1.15	2.00	0.58
2.67	3.67	3.67	0.58	2.08	0.58
Time of Trial					
Wet	Normal	Dry	Wet	Normal	Dry
32.82	32.82	32.82	14.99	14.99	14.99
36.83	17.00	28.47	13.10	6.35	11.20
31.30	17.63	15.45	9.14	17.08	9.25
36.10	30.53	32.97	11.35	4.19	6.62
33.57	27.53	21.73	24.62	14.66	13.39
46.47	22.00	31.05	7.99	1.00	10.87
22.53	22.53	20.23	2.46	4.58	9.68
Maximum Force (N)					
Wet	Normal	Dry	Wet	Normal	Dry
18.51	18.51	18.51	2.79	2.79	2.79
16.85	18.72	17.75	1.12	1.72	1.59
21.98	19.66	18.97	5.16	11.37	1.50

16.93	20.35	18.64	2.21	1.86	0.93
19.13	18.23	19.21	2.78	4.91	3.67
18.40	18.10	16.68	0.37	1.58	2.68
16.36	19.13	17.42	1.12	2.41	0.79
Average Time/Break					
Wet	Normal	Dry	Wet	Normal	Dry
4.93	4.93	4.93	1.24	1.24	1.24
6.38	4.06	5.97	0.93	1.85	1.81
7.44	5.65	6.21	0.82	2.48	1.18
7.71	5.42	5.88	1.97	0.84	1.44
8.35	6.15	5.28	0.48	2.45	1.49
10.08	4.98	5.59	0.89	2.19	2.25
8.72	7.02	5.39	2.01	2.38	2.03
Modulus					
Wet	Normal	Dry	Wet	Normal	Dry
3.07	3.07	3.07	0.25	0.25	0.25
2.79	3.35	3.48	0.52	0.32	0.19
3.09	2.85	3.26	0.09	0.47	0.17
2.30	3.99	3.33	0.22	0.40	0.27
2.58	2.91	3.46	0.07	0.66	0.26
2.37	3.37	3.66	0.24	0.36	0.77
2.55	3.38	3.41	0.23	0.53	0.41

Appendix M - Lays Stax compressive data tables.

			Number of Breaks						
Time	Wet			Norm			Dry		
0	1	1	3	1	1				
3	1	1	1	2	1	1	1	1	1
7	1	1	1	2	1	1	1	2	2
24	1	1	1	1	1	1	1	1	2
26	1	1	1	1	1	1	1	1	1
29	2	1	1	1	1	1	1	1	1
31	1	1	2	1	1	2	1	1	2
			Time of Trial						
Time	Wet			Norm			Dry		
0	7.5	8.3	18.6	8.5	8.2				
3	8.8	10.1	8	8	7.5	8.9	8.4	8.9	9.1
7	8.9	7.4	10.3	8	9	8	7.9	8.4	8.6
24	20.9	14.5	12.7	8.9	9.8	10.1	8.7	7.5	11.5
26	18.6	16.4	22	8.4	9.4	9.6	9.7	8	12.4
29	45.7	24.6	16.3	7.3	7.3	8.6	7.1	8.7	8.6
31	42.5	25.9	34.1	10.7	9.3	17.5	8.6	8.8	7.3
			Maximum Force (N)						
Time	Wet			Norm			Dry		
0	8.79	5.37	7.8	8.79	8.79				
3	9.28	9.04	7.57	6.11	3.91	11.48	10.26	9.77	10.5
7	7.81	5.37	7.33	8.55	9.52	4.15	8.28	6.84	5.62
24	7.57	9.04	4.64	7.81	8.06	7.33	10.99	8.06	8.55
26	9.28	9.52	7.81	10.01	11.97	10.74	10.98	9.77	7.08
29	9.28	7.33	9.04	9.28	8.06	9.77	9.04	8.06	10.74
31	5.13	5.13	5.86	10.74	10.5	10.99	10.99	9.77	7.33
			Average Time/Break						
Time	Wet			Norm			Dry		
0	7.5	8.3	6.2	8.5	8.2				
3	8.8	10.1	8	4	7.5	8.9	8.4	8.9	9.1
7	8.9	7.4	10.3	4	9	8	7.9	4.2	4.3
24	20.9	14.5	12.7	8.9	9.8	10.1	8.7	7.5	5.75
26	18.6	16.4	22	8.4	9.4	9.6	9.7	8	12.4
29	22.85	24.6	16.3	7.3	7.3	8.6	7.1	8.7	8.6
31	42.5	25.9	17.05	10.7	9.3	8.75	8.6	8.8	3.65
			Modulus						
Time	Wet			Norm			Dry		
0	1.30	0.93	1.04	1.32	1.22				

3	1.12	0.95	1.01	0.99	0.84	1.44	1.27	1.20	1.19
7	0.90	0.94	0.78	1.19	1.07	1.14	1.29	1.13	1.13
24	0.60	0.76	0.63	1.27	1.18	1.11	1.33	1.26	1.15
26	0.78	0.76	0.64	1.37	1.37	1.13	1.14	1.41	0.69
29	0.64	0.67	0.70	1.39	1.27	1.19	1.34	1.03	1.41
31	0.42	0.49	0.50	1.15	1.19	1.03	1.39	1.27	1.29

Average for Each container			Standard Deviation		
Wet	Normal	Dry	Wet	Normal	Dry
Number of Breaks					
1.4	1.4	1.4	0.89	0.89	0.89
1	1.33	1	0	0.58	0
1	1.33	1.86	0	0.58	0.58
1	1	1.33	0	0	0.58
1	1	1	0	0	0
1.33	1	1	0.58	0	0
1.33	1.33	1.33	0.58	0.58	0.58
Time of Trial					
Wet	Normal	Dry	Wet	Normal	Dry
10.22	10.22	10.22	4.70	4.70	4.70
8.97	8.13	8.8	1.06	0.71	0.36
8.87	8.33	8.3	1.45	0.58	0.36
16.03	9.6	9.23	4.31	0.62	2.05
19	9.13	10.03	2.82	0.64	2.22
28.87	7.73	8.13	15.16	0.75	0.90
34.17	12.5	8.23	8.30	4.39	0.81
Maximum Force (N)					
Wet	Normal	Dry	Wet	Normal	Dry
7.91	7.91	7.91	1.48	1.48	1.48
8.63	7.17	10.18	0.93	3.89	0.37
6.84	7.41	6.91	1.29	2.86	1.33
7.08	7.73	9.2	2.24	0.37	1.57
8.87	10.91	9.28	0.93	0.99	2.00
8.55	9.04	9.28	1.06	0.88	1.36
5.37	10.74	9.36	0.42	0.25	1.86
Average Time/Break					
Wet	Normal	Dry	Wet	Normal	Dry
7.74	7.74	7.74	0.94	0.94	0.94
8.97	6.8	8.8	1.06	2.52	0.36
8.87	7	5.47	1.45	2.65	2.11
16.03	9.6	7.32	4.31	0.62	1.48
19	9.13	10.03	2.82	0.64	2.22

21.25	7.73	8.13	4.38	0.75	0.90
28.48	9.58	7.02	12.92	1.01	2.92
Modulus					
Wet	Normal	Dry	Wet	Normal	Dry
1.16	1.16	1.16	0.17	0.17	0.17
1.03	1.09	1.22	0.08	0.31	0.04
0.87	1.13	1.18	0.08	0.06	0.09
0.66	1.19	1.25	0.09	0.08	0.09
0.73	1.29	1.08	0.08	0.14	0.36
0.67	1.28	1.26	0.03	0.10	0.20
0.47	1.12	1.32	0.05	0.08	0.06