CREATING AND ANALYZING AN 'IDEAL' WHITE

BREAD BASED ON CONSUMER PREFERENCES

An Interactive Qualifying Project Report

submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

Justin R. Bales   Brenden T. Gibbons   Raymond P. Short

Date: March 4, 2011

Professor Satya S. Shivkumar, Advisor

Table of Contents

Abstract

It is infrequent that one comes across certain bread that is appealing to a very large audience. The purpose of this investigation is to observe what consumers like most about bread and to create bread exhibiting these desired properties. Bread that displays features that are desired by a large population was created and validated by various testing methods. These findings may be further expanded and used to create a more widely accepted type of bread.

Original Research Article

This article was written for intended publication in the journal Cereal Foods World.

1.0 - Introduction

Since its invention, bread has been a staple of the human diet. It is so influential that even in today's times, a shortage of bread is synonymous with hard times. Because of bread's importance, it has become synonymous with both friendliness, with the Russian word for hospitality being a concatenation of the words for "bread" and "salt", and currency (as in the English "breadwinner", amongst others) [15]. Bread even plays an important religious significance, as a "staff of life." [12] For the near future, bread will continue to remain an integral part of much of the world's diet.

Bread is a "soft" solid [5], whose main components are its crumb and its crust. The main ingredients of a basic dough are flour, water, leavening (chemical or biological), and sodium chloride [4]. However, many other ingredients can be successfully integrated into bread dough. The multitude of possible options for constituent choice, combined with varying methods for preparing, baking, and storage give rise to a near infinite number of possible breads. To say that the process of producing bread is a complicated one is an understatement. Factors such as constituent choice, mixing and kneading methods, rising procedures, baking techniques, and storage duration all affect the overall outcome of the loaf

The staling of bread can be defined as the decrease in consumer acceptance caused by changes in the crumb and crust undue to microbiological action [2]. The percentage of consumer acceptability of white bread declines in relation to storage duration [8]. This is caused by a declination of bread's sensory qualities as the length of storage increases [20]. Since eighty percent of bakery sales are impulse purchases motivated by perceived freshness [19], the qualities of bread that indicate freshness are crucial to any acceptable loaf.

There are many methods for determining the staling of bread [18], be it simple visual inspection, taste testing, analyzing the amylose and amylopectin levels, magnetic resonance imaging (MRI) analysis, or monitoring the moisture content [1,14]. Electrical conductivity is the measure of a material's ability to conduct electrical current, and is often used to determine the moisture content of items [21]. Therefore, measuring the electrical conductivity of the crumb of bread may also be an accurate measure of its relative staleness.

There has been significant experimentation on both the mechanical and structural properties of bread [7,13,15,16,24], however little has been done to link these properties to consumer preference, especially in white bread. Little work has been done to assess what qualities average, non-trained consumers actually assign bread. Studies have been conducted using pre-determined qualities and trained assessors to rate bread quality, however because trained bread assessors and average consumers of bread verbally describe bread using a reasonably different vocabulary [9], the assessors' results may not agree with the sentiments of general consumers. As ten to thirty percent of bakery customers are unable to obtain their first choice bread [23], a universally acceptable recipe based on consumer preferences may help keep customers from leaving bakeries without making a purchase.

The purpose of this investigation was threefold. First, to derive a relationship between the electrical conductivity of the bread's crumb and its storage duration in order to obtain a novel, minimally invasive technique for measuring the staling of white bread. Second, to determine consumer preferences of white bread's texture based on simple, commonly used verbal descriptors. Third, to derive a loaf of white bread that fits the highest percentage of these preferences by controlling its quantifiable structural and mechanical properties.

2.0 – Objectives

- Discover the prevailing consumer preferences of bread.
- Design a bread that addresses these overall desired preferences.
- Relate the created bread to a series of breads that exhibit the extremes of certain characteristics.
- Validate and determine the created bread's relation with these characteristics.
- Determine if conductivity can be used as a determining factor in assessing a loaf's age during staling.
- Contribute this knowledge to the community about general preferences for bread consumption preferences.

3.0 - Materials

White breads were made by mixing dough consisting of King Arthur AP white flour (10-12% gluten), water, active dry yeast, salted butter, and salt, with a variation containing vital wheat gluten, as seen in Table 1. The dough was then kneaded for a certain time, specified by desired characteristics for each of the breads. The dough was then allowed to rise for one hour, then punched down and allowed to rise for another hour, as seen in Table 2. The breads were then baked using the Blodgett [3] convection ovens in the Campus Center kitchen at WPI.

Additionally, the baking times and temperatures were varied depending upon desired characteristics. The breads were then allowed to cool completely at room temperature for approximately two hours before storing in commercial plastic re-sealable freezer bags. Two loaves of each type were baked for each individual experiment.

3.1 - Conductivity and Water Loss Sampling Methods

Starting from completion of baking and again at an interval of twelve hours, one bagged and one open-air loaf was massed and then probed for conductivity measurements. Conductivity was attained by inserting the probes of a digital ohmmeter, seen in Figure 5 at a distance of 0.5 in from each other, and a depth of 0.9 in through the crust and into the crumb of the loaf, as seen in Figure 6. Ten measurements were taken per loaf and the average was calculated. This method was repeated twelve times, for a total experimental duration of 6.5 days (156 hours).

3.1.1 - Preparation of Samples

A total of twenty six samples were created that were each 68 ± 0.5 g in weight (wet sample) in order to facilitate massing and probing an undamaged loaf for conductivity and mass data. The loaves were then split into two groups, with one remaining in open-air conditions and the other being placed in plastic re-sealable freezer bags.

3.2 - Tensile Testing Methods

Each sample was secured in screw side action grips [17] on both ends, ensuring that the middle section of each sample remained unmodified. The samples were then subjected to an extension rate of 12 mm/min on an Instron 5544 [11] until complete fracturing of the sample occurred, as seen in Figure 4. Data for load in Newtons and extension in millimeters was collected for each sample during testing.

3.2.1 - Preparation of Samples

Three slices of width 0.5 ± 0.05 in were taken from the middle section of each loaf. From the center of each slice, as seen in Figures 3, a tensile strength sample, shown in Figures 1 and 2, was cut with a Universal Laser Systems VersaLASER VLS4.60 [22] at settings power = 100%, speed = 3%, ppi = 700, z-axis = 0.500. A laser cutter was used instead of a traditional metal cutting device (i.e. knife or mold) to attempt to minimize cell deformation on the outer layer, which normally negatively affects the outcome of tensile tests. The preservation of the outer cell structure can be seen partially in Figure 4. The samples were then placed in the original re-sealable bags to prevent further staling.

4.0 – Results and Discussion

4.1 - Preference Survey

A survey, seen in Table 3, was distributed in order to collect qualitative information about consumer preferences in bread consumption. This survey consisted of fourteen questions, of which three were demographic-based. The survey was sent out to the entire Worcester Polytechnic Institute (WPI) community (undergraduate, graduate, faculty and staff) via email, as approved by the WPI Institutional Review Board. The online survey was hosted by SurveyMonkey.com, which provided collection and limited analysis of the data. Responses were collected over a span of four days, totaling to 1122 responses.

4.1.1 - Preference Survey Demographic

A total of 1122 responses were obtained from the consumer survey. When compared to the entire population of WPI of 4823, the number of responses represents 23% of all individuals. Tables 4 and 5 show the demographic of individuals who responded to the survey. The sample tended towards an age of early to mid-twenties, as the majority of responses were from undergraduates at WPI, making up nearly 70% of the sample population.

4.1.2 - Bread Characteristic Preference Profile

As can be seen in Table 6, shape was isolated from other characteristics, as the difference between the choices provided does not cause a significant change in other major characteristics. Although the shape of the bread may be significant in consumer preference, it was not a major influence from an analytical point of view.

The three qualities of chewiness of the crumb, texture of the crumb, and texture of the crust were analyzed in a different manner, as they were grouped differently and could not be adequately placed on a scale. These characteristics represented the greatest deal of significance in the ‘ideal’ bread profile, as they are mechanical characteristics that can best be quantitatively analyzed [7,13]. Of first note when looking through the results displayed in Table 7 are the factors that have non-polarized results, being those of crunchy versus chewy crust and light versus dense crumb. Due to this indifference, these characteristics were not a point of focus in the tailoring of the ‘ideal’ loaf and were mostly ignored. The more unbalanced results between thin and thick crust, 63.7% to 39.3%, and to an astounding amount moist versus dry crumb, 89.7% to 10.3%, were characteristics that were instead focused upon as main contributors to the definition of the 'ideal' loaf. The final aspect of taste was also a point of interest, with buttery (35.3%), plain (28.5%), and pungent/yeasty (16.3%) making up just over 80% of the responses. However, due to the limited extent of the testing at our disposal, and the fact that 80% of bakery purchases are due to impulse buys based on perceived freshness [19,23], the taste was no more than a qualitative consideration.

The data gathered, shown in Table 8, in which different choices fell on a scale were analyzed by assigning a numerical value to each division of that attribute and calculating a mean of the results. The mean could then be placed on the provided scale yielding a conclusion. The results for crust color and chewiness of the crumb carried little weight, as their mean values of 2.73 and 3.04, respectively, were very close to the exact midpoint of 3.00. Because of these results, it was decided to tailor the 'ideal' bread to have a crust that is of a slightly lighter nature and for the crumb to be somewhat chewy. The mean for porosity, being 1.39 compared to the midpoint of 1.50, was a mostly insignificant finding. The binary nature of the question and no strong tendency towards one side made the porosity of the bread a factor of little concern. The final scalable value of storage time, while important and interesting to note, is not one that can be controlled on the production side, and thus was also not a point of focus.

The overall results of the survey revealed that the 'ideal' loaf of bread has a light brown crust that is thin as well as both chewy and crunchy, with a crumb that is lighter, moist, moderately chewy, and uniform. The taste of the bread should also be slightly buttery with a hint of pungency. It was also specified that over 70% of respondents prefer to eat bread right after it is baked, with over 90% preferring to eat bread within a few hours of baking. Overall, the properties of bread that were preferred were those that best represented freshness, such as a moist crumb, and a rapid consumption time following baking. These results are in accordance with the findings of Gamboro et al, Scanlon, and South [7,8,16,19], and support the theory that perceived freshness is the primary factor for determining consumer acceptability of bread.

4.2 - Electrical Conductivity as a Staling Indicator

Electrical conductivity was shown to be a reliable measure of the extent of staling in bread loaves. Figure 7 shows the changes in electrical conductivity of crumb during storage at approximately 21 °C. The electrical conductivity of the crumb of both the bagged and the unbagged loaves decreased significantly as a function of storage time. When fresh out of the oven, the bread crumb had an average conductivity of 0.3 reciprocal Siemens (S^{-1}) with a standard deviation (STD) of 0.04 S^{-1}. After 144 hours of storage, the final sample contained within a bag had an average conductivity of 1.7S^{-1} and a STD of 1.6 S^{-1}. At this time, the sample exposed to open air had an average conductivity of 14 S^{-1} with a STD of 3.6 S^{-1}. The high standard deviations are a byproduct of the inconsistent uniformity of bread crumb. Because of the low electrical conductivity (between 10^{13} and 10^{16} S^{-1}) of air, if large pockets open cells were present between the two ends of the conductivity probe during a particular measurement, the conductivity reading would be lower than expected. Conversely, if the probes were each touching one side of a dense crumb section, the conductivity reading would be higher than average. With both storage methods, the first 24 hours after baking demonstrated a near-linear, rapid loss of electrical conductivity with respect to storage duration, becoming more gradual as total duration increased. In the bread stored within a plastic bag, this could be attributed to a moisture gradient between crust and crumb that tended to equilibrate during storage [1], resulting in a decreasing crumb moisture content, and a corresponding diminution of electrical conductivity [6,10]. Figure 8 shows a very small percentage of mass lost by the loaves stored within bags, corresponding to the progression described above. The bread stored in open air continually lost mass at an almost linear rate, mostly due to evaporation. Regression curves and equations for mass lost in both bread stored in a bag and in open air are shown in Figure 8 and Table 10. This loss of moisture, combined with equilibrating moisture between the crumb and crust led to a more rapid and a larger decrease in electrical conductivity than the loaves stored in bags. All conductivity measurements had an accuracy of ±0.0005 S^{-1}.

In order to explore the relationship between bread crumb conductivity and hours elapsed since baking for bread loaves stored in bags and not stored in bags, regression equations were approximated for the corresponding data points. Table 99 shows these regression equations. The R^2 values, 0.99 and 0.95, respectively, for these equations indicate a high degree of confidence. Therefore, if the electrical conductivity of the loaf of bread is known immediately after baking, its age could be approximated using the regression equations presented in Table 9, where y represents conductivity in S^{-1}, and x represents the number of hours since baking, with reasonable accuracy.

4.3 - Tensile Testing

The graphs obtained from tensile testing of the crumb samples cut from the center of each loaf were analyzed to obtain stress, strain, and elastic modulus figures. The curves shown in Figures 9-12 show the relationship between load and extension for six samples from each of the four characteristic breads. An obvious aspect of these curves is the fact that among a single type of bread, and even in the same loaf, there is quite some spread of responses. This spread is often observed in tensile tests of bread, and can be observed in the works of Scanlon [12] and Zahgal [24].

Despite this tendency, many important aspects of each bread can be obtained from the figures. The chewy bread, Figure 9, has the overall highest maximum load and maximum extension. This is due not only to the higher gluten content of the bread due to adding extra gluten, but can also be attributed to the extended kneading time when preparing the dough. A large degree of variability in the initial linear sections is also noticeable, showing that among samples in the same loaf, the randomness of structure has a severe impact on strength readings.

The curves from testing samples from the not chewy bread in Figure 10 show the opposite of the chewy; the not chewy bread has the lowest overall maximum load and maximum extension. With a maximum extension of no more than 15 mm on average, the not chewy bread is the least resilient of the breads tested. This is because the not chewy bread was kneaded for only three minutes after mixing was completed, leading to a lower amount of created gluten strands. This led to a crumb that is more easily fractured by a lower force, providing the shorter curves seen. Also unlike the chewy bread, the initial linear sections of the not chewy samples are much more similar to each other, showing some tendency for the not chewy bread to be more uniform in its structural properties than the chewy loaves.

The thick crust bread in Figure 11 had some very interesting properties with its stress-strain curves. The initial section of all of the curves are almost identical in slope, unlike any of the other bread types tested. However, there is also much variance in the maximum load and maximum extension of the samples taken from this bread. This is likely due to an overall uniformity in mechanical structure throughout the loaves for the initial portions being similar, but isolated deformities in the individual samples that were selected caused the stark differences in the latter part of each curve.

Finally, the thin crust bread in Figure 12 exhibited the most widespread difference in results among the four types. While the first loaf (specimens 1-3) has curves that are somewhat similar, there is distinct spread in the curves from the second loaf (specimens 4-6). These vast differences between the two loaves can be explained most reasonably by a variance in local structure, such as placement of air pockets and perhaps internal layers remaining from the kneading and shaping of the dough prior to baking. The more similar results from the first loaf express a relatively low maximum load and a maximum extension that lies between the extensions for chewy and not chewy loaves.

For the purposes of simplicity and generalization, one curve has been selected from each of the loaves to be analyzed, shown in Figure 13. The chosen curves best represent the average of their respective loaf's properties. As can be seen in Figures 9-13, the initial portion each of the stress-strain curves is nearly linear, so it can be assumed that the bread is an elastic substance [15,16] and thus has an elastic modulus that may be calculated from this region.

4.3.1 - Validation of Bases for Comparison

Of the four characteristic breads that were created and tested, the thick crust bread had the largest elastic modulus value at an average of 23 kPa, while the chewy bread had the lowest at 19 kPa, as seen in Table 11. While values of this magnitude may seem somewhat high, the large amount of gluten in the flour (10-12%) and addition of gluten in the chewy bread make these figures much more reasonable and likely. This result for the chewy bread was as expected; the larger number of gluten strands and thus higher concentration of starch increased the elasticity of the crumb, increasing the amount of deformation that could occur per unit force [15]. The larger modulus for the thick crust bread showed the opposite, where the starch was less prevalent and the crumb was more brittle than that of the chewy bread. While the not chewy bread did not have the highest modulus value, it was very close to the highest with an average value of 23 kPa.

In a similar comparison of maximum extension, there was a much clearer distinction of the not chewy bread as being the most brittle. The average extension from an original length of 36 mm for the not chewy bread was 14 mm, whereas the chewy samples exhibited an average extension of 24 mm. The remaining breads of thick and thin crust had average extensions of 17 and 18 mm, respectively. As can be seen by the vast difference in extension, the chewy bread is the most resilient to pulling forces while the not chewy bread is the most susceptible.

In addition, the maximum load prior to fracturing is an influential factor. For the chewy bread, the maximum load was the highest at 0.64 N, while the not chewy and thin crust breads were the lowest at 0.55 and 0.54 N respectively. This difference in maximum load exhibits the overall strength of the gluten strands in the bread [15], of which there is an abundance of in the chewy bread and a deficit of in the thin crust and not chewy breads.

4.3.2 - Validation of Qualities of the 'Ideal' Loaf

After performing the multitude of trials to achieve what was interpreted as the most ideal loaf of bread as per the results of the preference survey, a loaf was arrived at that exhibited the characteristics listed before, namely for these tests, having a medium amount of chewiness in the crust and crumb. This overall characteristic of being moderately chewy can be shown by comparing the ideal bread to the existing characteristic loaves, as shown in Figure 14.

In a comparison of elastic modulus, the value of 20 kPa for the ideal loaf falls closer to the side of the chewy and thin breads, but is still in between the values of the characteristic loaves. When comparing the maximum extension for the ideal bread, its value of 20 mm lies almost directly between those for the chewy and not chewy breads, being 24 and 14 mm respectively. For the final influential measurement of maximum load, the ideal bread has a value of 0.57 N, being closer to the not chewy bread than the chewy bread. In the analysis of these values, it can be seen that the ideal bread does indeed have a moderate chewiness. It is very near the average for max extension, favors chewy for elastic modulus, and favors not chewy for the maximum load.

5.0 - Conclusions

Electrical conductivity testing was found to be an accurate method of determining a bread loaf's relative staleness. The ability to take a loaf of bread, knowing only a relative conductivity of it from shortly after baking, and determine approximately how long it has been staling for is a very helpful ability. This is accented by the fact that the testing procedure used is minimally invasive, so most, if not all of the loaf that is tested may be consumed in whatever desired manner.

The survey that was distributed proved to obtain an advantageous perspective on the general public with respect to their desired traits of bread. Though a portion of the answers that were obtained, such as those people who prefer wheat or whole-grain breads instead of our topic of white bread, were of little use to this investigation, the information can be used by others. This information can prove to be indispensible when tailoring products to certain audiences. Through the entire survey of 1122 individuals, it was found that the most accepted bread was white bread that had a thin light brown crust. a crumb that is moist ,moderately chewy, and generally uniform. The generally accepted taste for white bread was also found to be a buttery flavor.

The following majority preference percentages for the thin, moist crumb, and buttery flavor were 63.7% 89.7% and 35.3% respectively.

Through tensile analysis of various characteristic breads, it was found that the derived 'ideal' white bread loaf followed guidelines and characteristics set by the consumer preference survey. Through multiple tests of other breads that exhibited characteristics such as a thick crust with an elastic modulus of 23KPa, or a chewy crust and crumb with modulus of 19 kPa, a place was determined for the 'ideal' loaf rated at 20 kPa. Its primary testable characteristic under tensile testing of overall chewiness was determined to be between the extremes of not chewy and chewy. This directly reflects the results of the survey, where the chewiness of the bread was desired to be slightly more towards chewy than not chewy, when placed on a gradient between the two extremes.

Overall, the acquisition of a bread that applies to so many desired characteristics is a very important achievement in the commercial world. These discoveries may help further advances in breads that appeal to a large audience, as well as a better understanding of consumer preferences in breads. The results from conductivity testing of whole loaves is also a very promising test to obtain the relative freshness of a bread, and can be enhanced to produce even better results.

6.0 - References

[1] Baik, Moo-Yeol, and Pavinee Chinachoti. "Moisture Redistribution and Phase Transitions During Bread Staling." *Cereal Chemistry* 77.4 (2000): 484-88. Print.
[2] Betchel, W. G. "A Review of Bread Staling Research." *Cereal Chemistry* 31.176 (1955). Print.
[3] "Blodgett Full Size Convection Ovens." *Building Quality Products Since 1848*. Web. 20 Feb. 2011. <http://www.blodgett.com/convection_full.htm>.
[4] Brown, J. "Advances in Breadmaking Technology." *Advances in Baking Technology*. By Basil S. Kamel and Clyde E. Stauffer. London: Blackie Academic & Professional, 1993. 38-87. Print.
[5] Clark, A. H., R. K. Richardson, S. B. Ross-Murphy, and J. M. Stubbs. "Structural and Mechanical Properties of Agar/gelatin Co-gels. Small-deformation Studies." *Macromolecules* 16.8 (1983): 1367-374. Print.
[6] Giovanelli, Gabriella, Claudio Peri, and Valeria Borri. "Effects of Baking Temperature on Crumb-Staling Kinetics." *Cereal Chemistry* 74.6 (1997): 710-14. Print.
[7] GÅmbaro, A., P. Varela, A. GimÉnez, A. Aldrovandi, S. M. Fiszman, and G. Hough. "Textural Quality of White Pan Bread by Sensory and Instrumental Measurements." *Journal of Texture Studies* 33 (2002): 401-13. Print.
[8] Gámbaro, A., S. Fiszman, A. Giménez, P. Varela, and A. Salvador. "Consumer Acceptability Compared with Sensory and Instrumental Measures of White Pan Bread: Sensory Shelf-life Estimation by Survival Analysis." *Journal of Food Science* (2004). Print.
[9] Hersleth, Margrethe. "Perception of Bread: A Comparison of Consumers and Trained Assessors." *Journal of Food Science* 70.2 (2005): S95. Print.
[10] Humphreys, Marion. Toasting Device. Patent 2387586. 23 Oct. 1945. Print.
[11] *Instron Home*. Instron. Web. 20 Feb. 2011. <http://www.instron.us/wa/home/default_en.aspx>.
[12] Kahn, E. J. *The Staffs of Life*. Boston: Little, Brown, 1984. 166-202. Print.
[13] Liu, Z., and M. Scanlon. "Predicting Mechanical Properties of Bread Crumb." *Food and Bioproducts Processing* 81.3 (2003): 224-38. Print.
[14] Maleki, M. "Effects of Loaf Volume, Moisture Content, and Protein Quality on the Softness and Staling Rate of Bread." *Cereal Chemistry* 57.2 (1980): 138. Print.
[15] Scanlon, M. G. "Bread Properties and Crumb Structure." *Food Research International* 34.10 (2001): 841. Print.
[16] Scanlon, M. G. "Mechanical Properties of Bread Crumb Prepared from Flours of Different Dough Strength." *Journal of Cereal Science* 32.3 (2000): 235-43. Print.
[17] "Screw Side Action Grips." *Screw Side Action Grips*. Instron. Web. 20 Feb. 2011. <http://www.instron.us/wa/acc_catalog/detail.aspx?aid=4781>.
[18] Sidhu, J. "Comparison of Methods for the Assessment of the Extent of Staling in Bread." *Food Chemistry* 58.1-2 (1997): 161-67. Print.
[19] South, G. "Bread Bakes a Dynamic Image." *Supermarketing* 4 (1989): 43-45. Print.
[20] Stollman, U., and B. Lundgren. "Texture Changes in White Bread: Effects of Processing and Storage." *Cereal Chemistry* 64.4 (1987): 230-36. Print.

[21] Sun, Z. J. "The Effect of Soil Electrical Conductivity on Moisture Determination Using Time-domain Reflectometry in Sandy Soil." *Canadian Journal of Soil Science* 80.1 (2000): 13. Print.

[22] "VersaLASER Laser Marking Platform, Affordable Laser Engraving, ULS Engraving Laser Manufacturer." *Universal Laser Systems - Laser Cutting Engraving Marking Equipment, Machines, and Software*. Web. 20 Feb. 2011. <http://www.ulsinc.com/english/laser_systems/product_line/VersaLaser_platform.html>.

[23] Woensel, Tom Van, Karel Van Donselaar, Rob Broekmeulen, and Jan Fransoo. "Consumer Responses to Shelf Out-of-stocks of Perishable Products." *International Journal of Physical Distribution & Logistics Management* 37.9 (2007): 704-18. Print.

[24] Zghal, M. C. "Cellular Structure of Bread Crumb and Its Influence on Mechanical Properties." *Journal of Cereal Science* 36.2 (2002): 167. Print.

Table 1: Ingredient list for breads created for experimentation.

Ingredient	g/100 g wet basis
Wheat Flour	56.9 *
Water	35.5
Dry Active Yeast	1.4
Salted Butter	4.8
Salt	1.4
Vital Wheat Gluten	0.0 *

* 47.4g wheat flour and 9.5g vital wheat gluten in high-gluten version

Table 2: Kneading and baking information for characteristic and ideal bread types.

Bread Type	Kneading Time (min)	Baking Temperature °C (°F)	Baking Time (min)
Thin	10	232 (450)	15
Thick	10	177 (350)	30
Chewy	15	204 (400)	20
Not Chewy	3	204 (400)	20
'Ideal'	7	218 (425)	14

Table 3: Survey that was distributed across the WPI community.

Question	Answer 1	Answer 2	Answer 3	Answer 4	Answer 5
Please select your gender:	Male	Female			
What is your affiliation with WPI?	Under-graduate	Graduate	Faculty	Staff	Other
What is your age?	Text Field				
Where do you typically buy your favorite bread?	Super-market	Conveni-ence Store	Local Bakery	Online Retailer	Home-made
What kind of bread do you eat most often?	White	Wheat	Whole Grain	Rye/Pum-pernickel	
I normally buy bread that is:	Sliced	Whole-loaf			
I prefer loaves of bread to be shaped like:	Oblong Dome	Circular Dome	Long and Thin	Other	
I like the crumb of my bread to be:	Uniform	Non-uniform			
I prefer a crust that is:	Thick and crunchy	Thin and crunchy	Thick and chewy	Thin and chewy	
I prefer a crust that is:	1 (light brown)	2	3	4	5 (dark brown)
I prefer bread to have a crumb that is:	Dense and moist	Light and moist	Dense and crumbly	Light and crumbly	
I prefer white bread to taste:	Buttery	Pungent and yeasty	Plain	Salty	Sweet
I prefer my bread to be:	Fresh from the oven	A few hours old	A few days old	More than a week old	
I prefer the crumb of the bread to be:	1 (not chewy)	2	3	4	5 (very chewy)

Table 4: Consumer profile for gender and affiliation derived from survey results.

Gender	# Responses	% Responses
Male	583	51.9
Female	539	48.1
Affiliation		
Undergraduate	748	69.8
Graduate	107	9.5
Faculty	74	6.6
Staff	168	14.9
Other	25	2.2

Table 5: Consumer profile for age derived from survey results.

Age	Years
Average	27.1
Standard Deviation	12.45
Male Avg.	24.7
Male SD	11.0
Female Avg.	27.8
Female SD	13.0

Table 6: Preferences on loaf shape derived from survey results.

Shape	% Responses
Oblong dome	62.0
Circular dome	7.9
Long thin	23.8
Other	6.3

Table 7: Preference for texture and flavor-based characteristics derived from survey responses.

Characteristic	% Responses
Thin Crust[a]	63.7
Thick Crust[a]	36.3
Crunchy Crust[b]	52.5
Chewy Crust[b]	47.5
Dense Crumb[c]	47.5
Light Crumb[c]	52.5
Moist Crumb[d]	89.7
Dry Crumb[d]	10.3
Buttery Flavor[e]	35.3
Pungent/Yeasty Flavor[e]	16.3
Plain Flavor[e]	28.5
Salty Flavor[e]	7.6
Sweet Flavor[e]	12.3

Entries with the same superscript are meant to combine to a total of 100%. In the cases of a-d, the two options are mutually exclusive, occasionally resulting in a preference of one over another.

Table 8: Results for characteristic properties of bread derived from survey results.

Characteristic	Mean	SD	%Confidence
Color[a]	2.73	0.96	0.029
Chewiness of Crumb[b]	3.04	0.95	0.028
Time[c]	1.38	0.67	0.020
Porosity[d]	1.39	0.49	0.015

[a] Scale ascending from lightest (1) to darkest (5), [b] Scale ascending from not chewy (1) to very chewy (5), [c] Scale ascending from fresh from the oven (1) to a few hours (2) to a few days (3) to more than a week (4), [d] Choice between uniform (1) and non-uniform (2)

Table 9: Regression equations for the relationships illustrated in Figure 7.

Storage Method	Regression Equation	R^2
In Bag	$y = 0.0098x+0.3264$	0.99
Out of Bag	$y = 0.3088e^{0.0236x}$	0.95

Table 10: Regression equations for the relationships illustrated in 8.

Storage Method	Regression Equation	R^2
In Bag	$y = -0.0085x + 99.646$	0.99
Out of Bag	$y = -7.625\ln(x) + 119.78$	0.99

Table 11: Elastic modulus, max load, and max extension values for various bread samples.

Type	Elastic Modulus (Pa)	Max Load (N)	Max Extension (mm)
Chewy 1	20787	0.6697	26.83
Chewy 2	17455	0.6201	20.64
Chewy Avg.	19121	0.6449	23.74
Not Chewy 1	20235	0.6487	13.09
Not Chewy 2	25036	0.4484	14.96
Not Chewy Avg.	22636	0.5486	14.02
Thin 1	14751	0.4495	19.98
Thin 2	24449	0.6312	17.00
Thin Avg.	19600	0.5404	18.49
Thick 1	24020	0.6690	19.77
Thick 2	22729	0.5391	15.22
Thick Avg.	23375	0.6041	17.49
Ideal	19772	0.5701	19.75

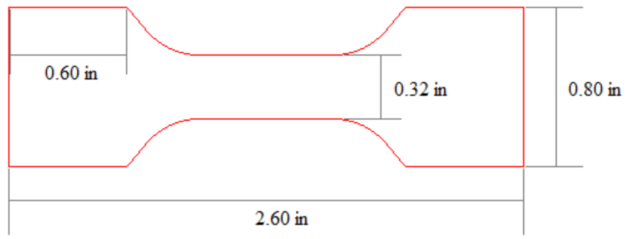

Figure 1: Mock-up of template used to cut out tensile specimen.

Figure 2: Sample tensile specimen cut out of 0.25 in thick acrylic.

Figure 3: Tensile specimen cut out of a slice of bread, but not removed. Effect from the heat of the laser can be seen in the cut and some of the surrounding area.

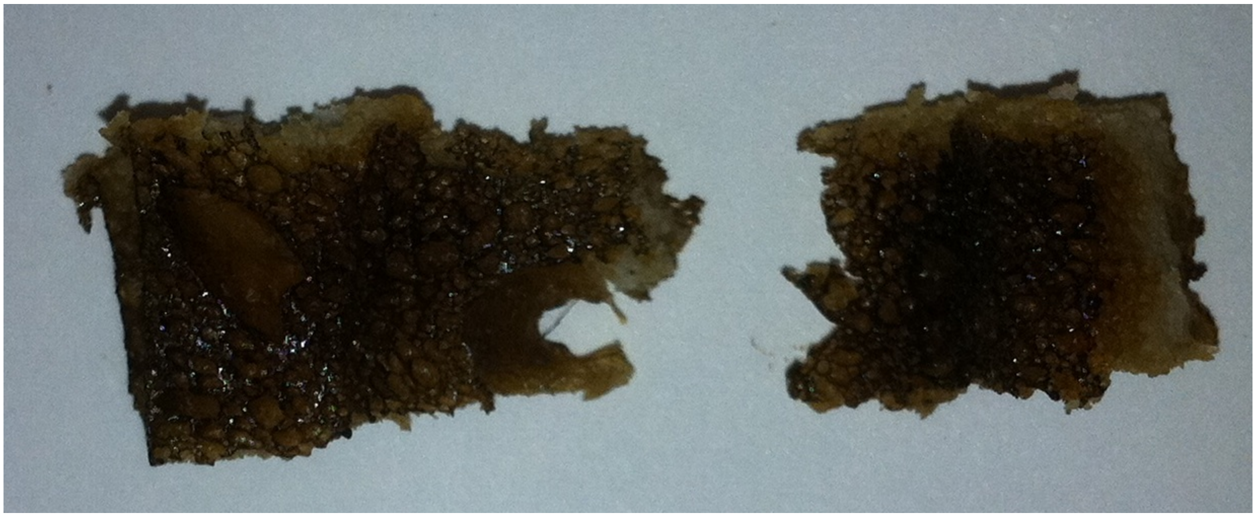

Figure 4: Fractured bread specimen showing one form of fracture. The browning caused by the heat of the laser used for cutting can also be seen, as the edge is much darker than the original color and has a shiny quality to it.

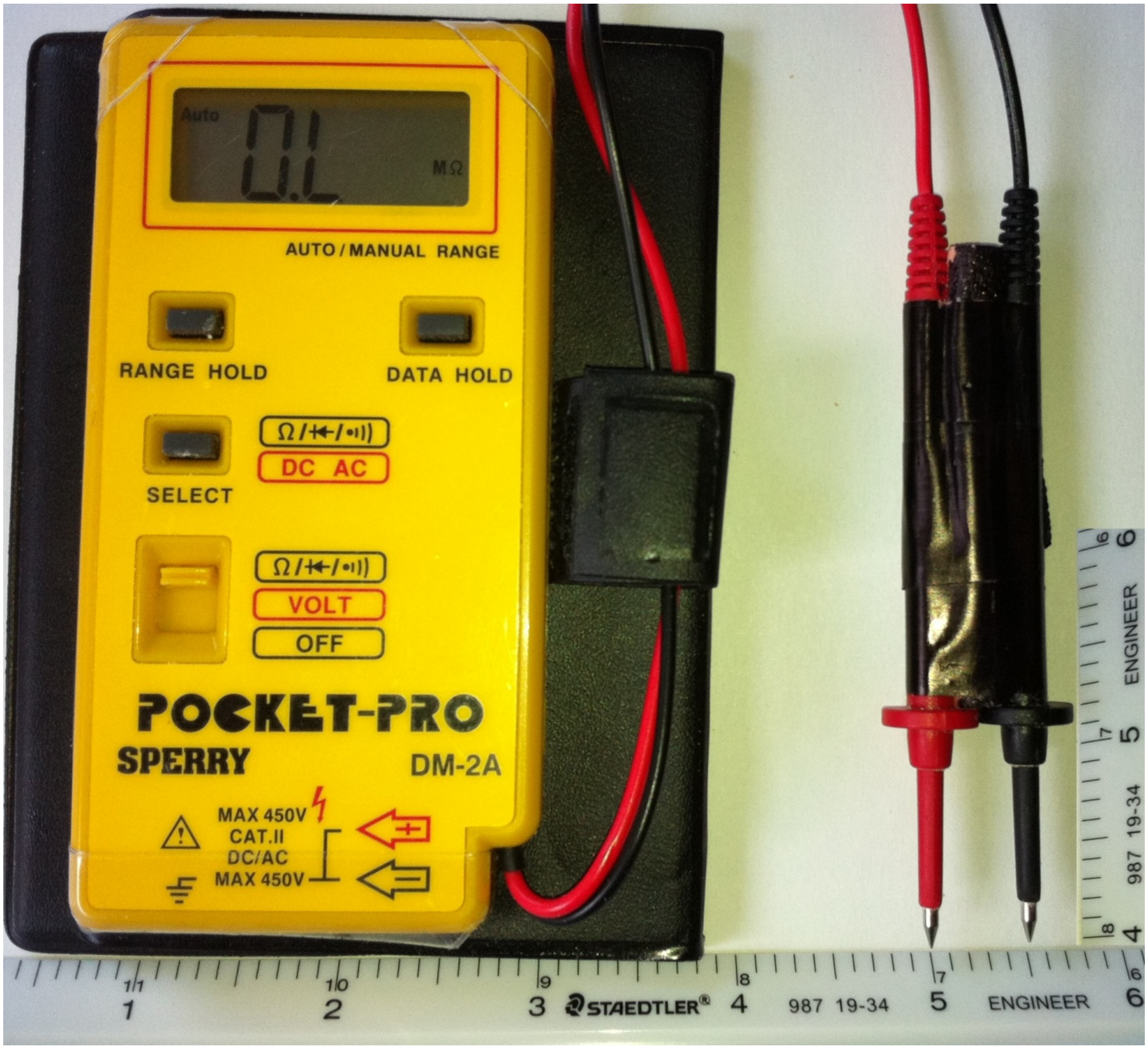

Figure 5: Picture of ohmmeter assembly. The two probes are secured together to inhibit any movement while being used for measurements. Distance between probes was measured at 0.5 in and depth of entry was measured at 0.9 in.

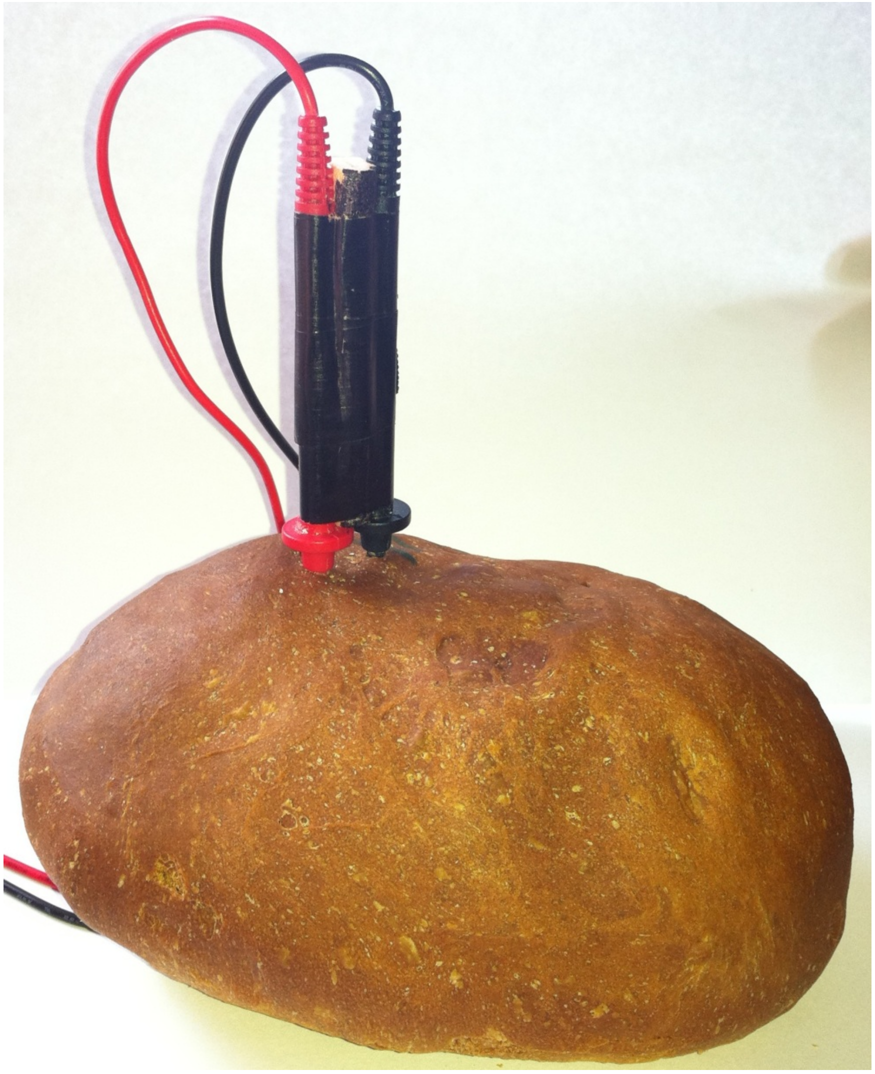

Figure 6: Sample image of testing the conductivity of a full loaf of bread. The probe apparatus was inserted in a manner to obtain the best access to the crumb of the bread.

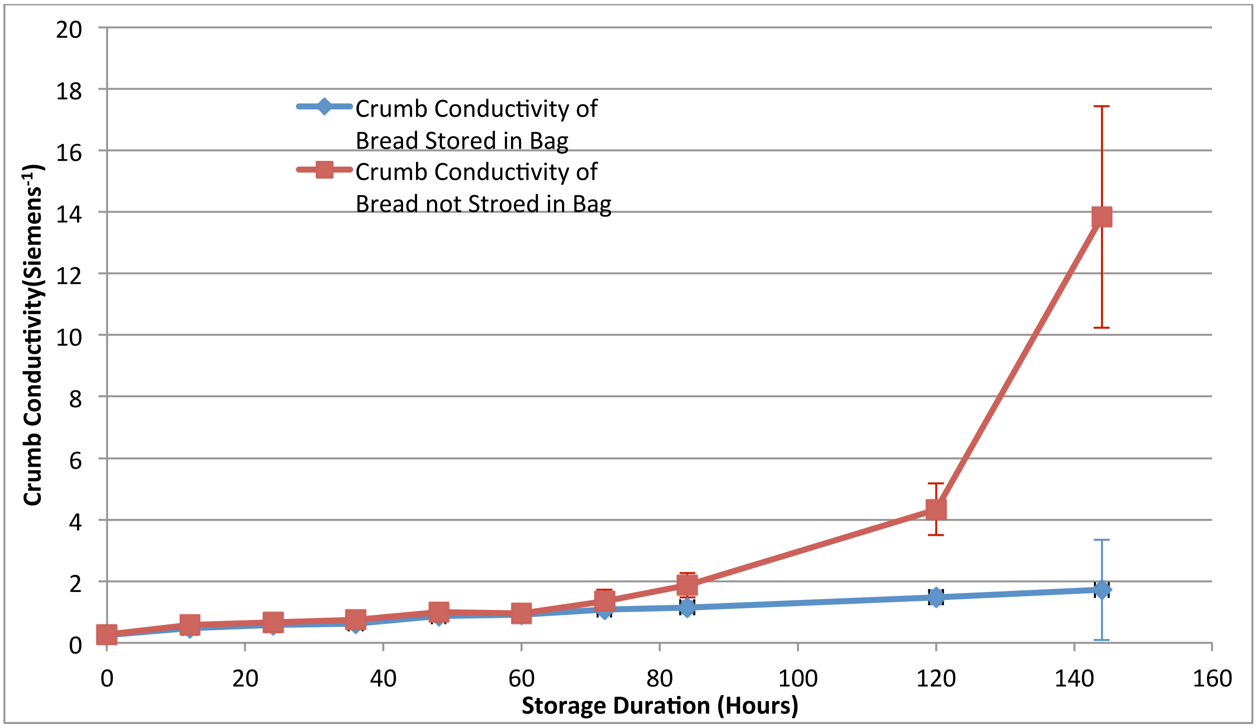

Figure 7: Relationship between crumb conductivity and hours elapsed since baking for storage methods of in a commercial plastic re-sealable freezer bag and in open air.

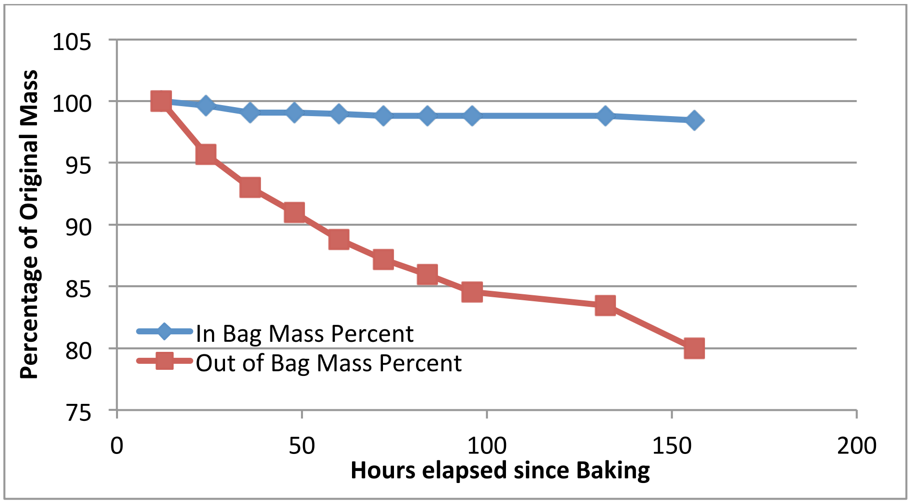

Figure 8: Relationship between percent of original mass of a loaf of bread and time for storage methods of in a commercial plastic re-sealable freezer bag and in open air.

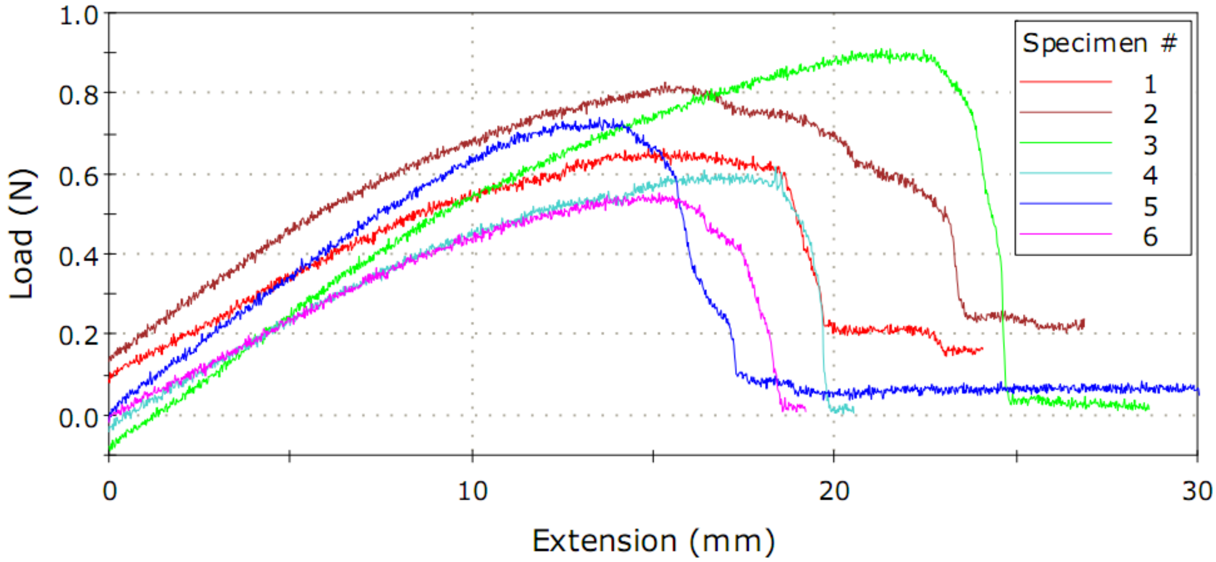

Figure 9: Graph showing load versus extension curves for six samples of chewy bread. The six samples are from two loaves, 1-3 from the first and 4-6 from the second.

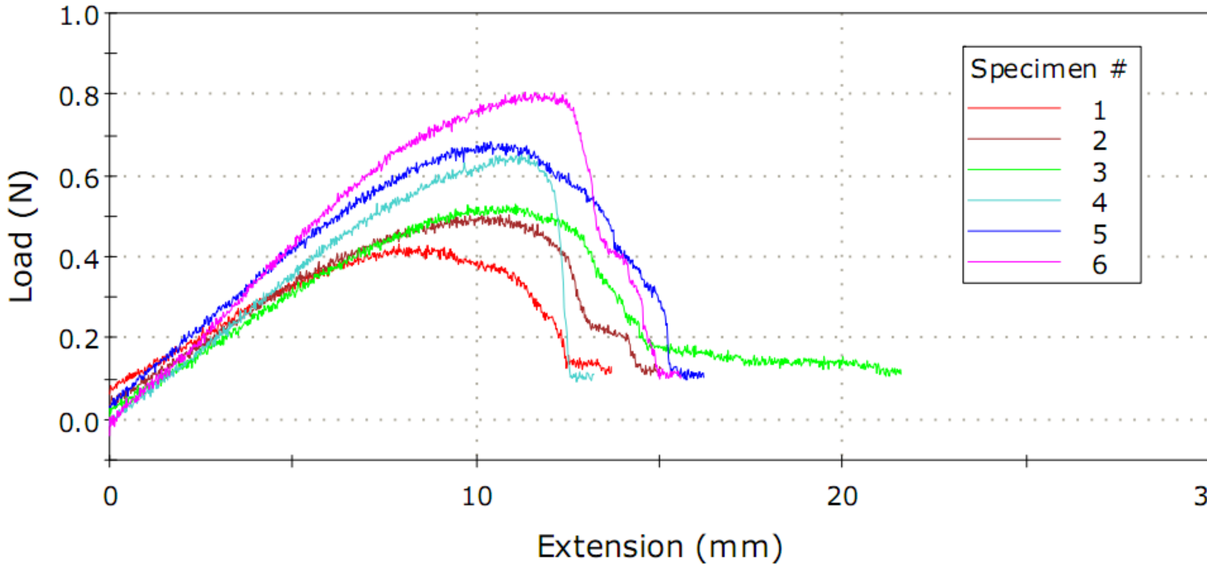

Figure 10: Graph showing load versus extension curves for six samples of not chewy bread. The six samples are from two loaves, 1-3 from the first and 4-6 from the second.

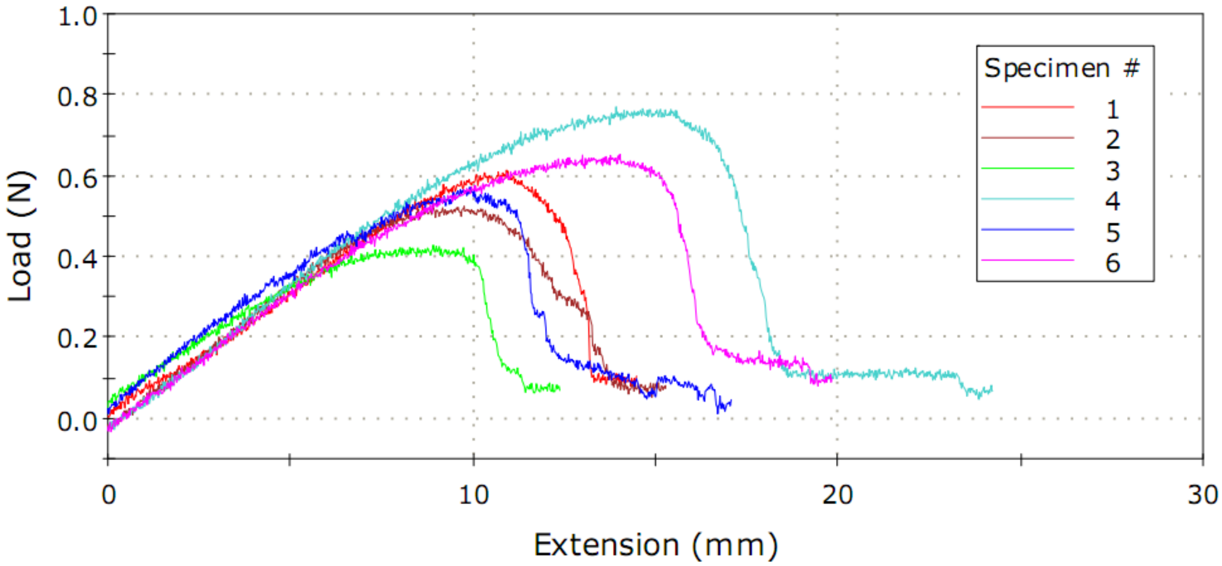

Figure 11: Graph showing load versus extension curves for six samples of thick crust bread. The six samples are from two loaves, 1-3 from the first and 4-6 from the second.

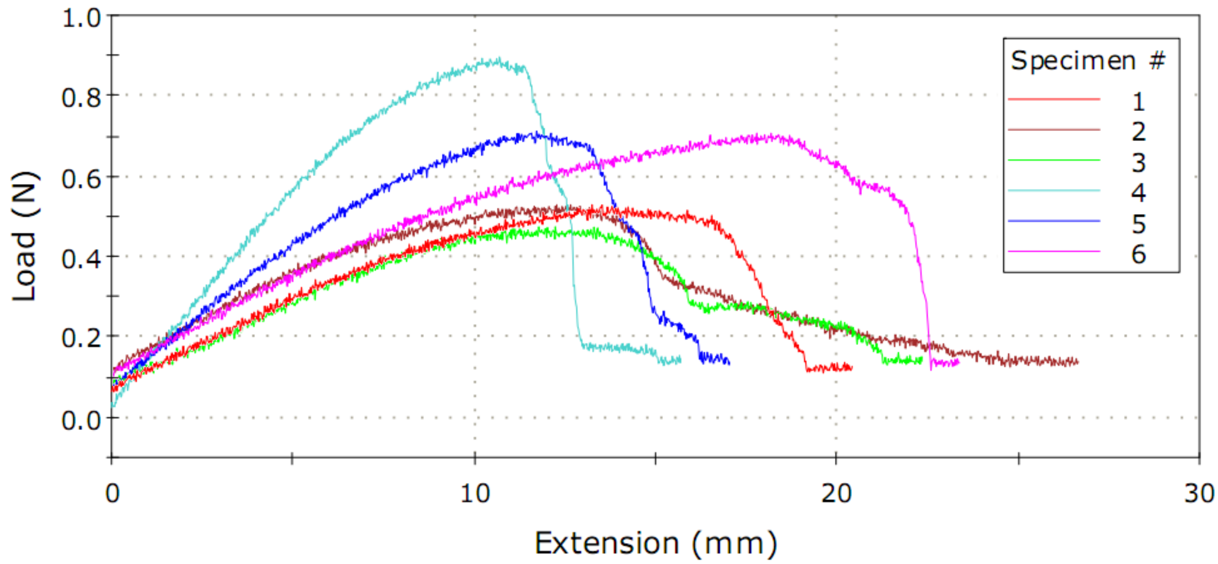

Figure 12: Graph showing load versus extension curves for six samples of thin crust bread. The six samples are from two loaves, 1-3 from the first and 4-6 from the second.

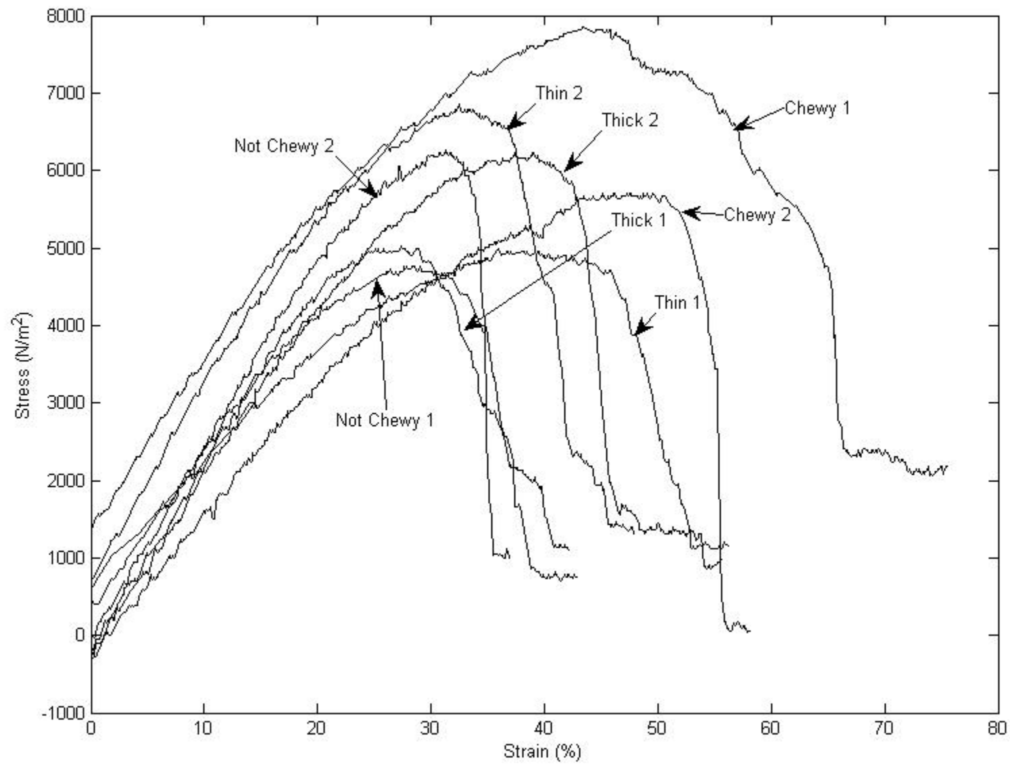

Figure 13: Stress vs. strain graphs for each of the four characteristic breads: thick crust, thin crust, chewy, and not chewy. Each bread is represented by two curves, labeled individually, each of which is a representative sample from multiple trials on a single loaf.

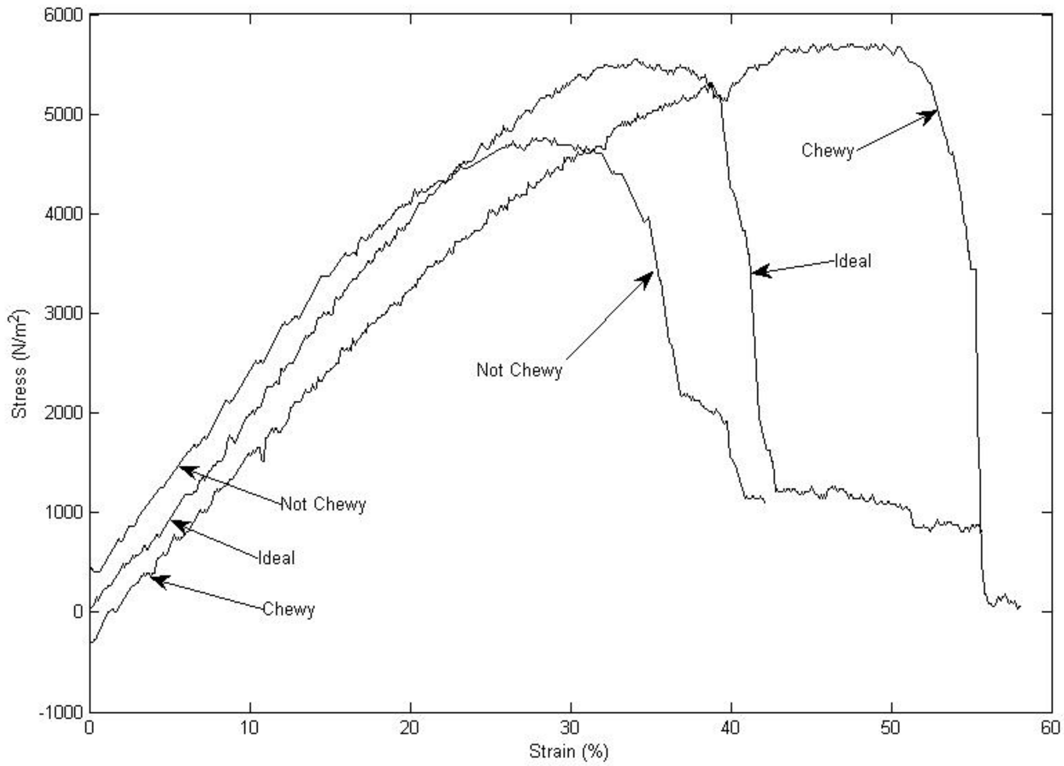

Figure 14: Plot of stress vs. strain curves for a sample of chewy and not chewy breads for comparison with the 'ideal' bread. Each of the curves displayed is a sample deemed representative of the loaf from which it came and from the type of bread overall.