EXAMINING THE RELATIONSHIP BETWEEN FRYING TIME, HARDNESS, AND FLEXURAL MODULUS OF FRENCH FRIES

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ABSTRACT

French fries are a snack enjoyed worldwide, and are most commonly prepared using a deep-frying process. Many consumers of fries prefer crispy fries with a crunchy outer crust. In this investigation, fries were prepared using 5 different frying times in order to characterize the relationship between the crust hardness (crunchiness) and flexural modulus (crispiness) of the fries and the duration of frying. Two tests, a puncture test and a three-point bend test, were used to analyze the mechanical properties of the fries. Both crust hardness and flexural modulus were found to increase with frying time, and the relationships can be characterized by power functions. The relationship between frying time and crust hardness was characterized by the function $f(x) = A * x^3$, where A = 0.00371 ± 0.0004, and the relationship between frying time and flexural modulus was characterized by $f(x) = A * x^3$, where $A = 4.80 * 10^{-6} \pm 4.5 * 10^{-7}$.

1. INTRODUCTION

French fries, like other fried foods, are usually prepared by deep-frying in a pan or fryer. [1]. This method is used commonly in both household and commercial settings due to its speed, efficiency, and low cost. The simplest method of cooking French fries is to start with room-temperature or chilled fries and to fry them only once, in hot (350-400° F) oil. An alternative method involves par-frying, where the fries are first cooked for several minutes in lower-temperature (300-325° F) oil, allowed to cool, and then fried again in hot (350-400° F) oil. Par-frying has been shown to increase the hardness of the outer crust of the fries [1], which correlates strongly with perceived fry crispiness [2].

There is abundant literature on the effects of both oil temperature and frying time, among other factors, on the crunchiness of fries [3, 4, 5]. However, the majority of these studies investigated the par-frying cooking method. This process takes longer than the simpler method, and can be intimidating to novice chefs, as well as time-prohibitive.

For this reason, this study investigated the effects of frying time on fry hardness and flexural modulus for the simpler, one-step frying method. Five batches of fries, each cooked for a time ranging from 6 to 14 minutes, were prepared. Crust hardness was used to indicate the crunchiness of the fries and was measured using a puncture test, during which the peak force was recorded for each of 12 samples per batch. A three-point bend test was used to indicate the crispiness of the fries, and was used calculate the flexural modulus using equations describing the deformation behavior of rectangular beams as an approximation of the fries. This test was performed on 6 samples from each batch. The data from both tests was fit to power functions, which can be used to predict the mechanical properties of fries cooked at varying frying times.

2. BACKGROUND

2.1 PREVIOUS STUDIES ON THE PROPERTIES OF FRENCH FRIES

Deep-fat frying is a complex process that results in structural changes in the fried food due to mass and heat transfer between the food and the oil. When food is submerged in hot oil (350-400° F), the water molecules in the food are rapidly replaced with the oil while the outside is cooked by the hot oil, resulting in a crunchy exterior texture and a strengthened crust[4]. This crunchy texture is a “highly desirable trait” [3] of fried food for many consumers. The crust then blocks more oil from entering the interior of the fry, and conduction within the potato cooks and softens the interior.

Previous studies indicate that the “hardness”, or crunchiness, of French fries is positively correlated with the temperature of the oil they are fried in, i.e. the force required to puncture the fry increases as the oil temperature increases [2]. There have been many studies on the effects of factors such as frying time, oil type, and frying temperature on the oil and water content of fries [1, 2, 3]. According to these studies, the oil content of the fries increases over time but is not strongly correlated with oil temperature.

2.2 TRANSLATING FRY CHARACTERISTICS INTO MEASURABLE PARAMETERS

The intention of deep-fat frying French fries is to create a fry that has a crunchy, hard outer crust. For this experiment, two parameters were chosen: hardness of the outer crust and flexural modulus.

The hardness of the crust is a measure of the peak force required to puncture the outer crust of the fry, and is reliant on both the amount of oil allowed to seep into the fry and how quickly the outer layer of the potato cooks. As mentioned earlier, two main processes are occurring during frying – the forming of the crust and the cooking of the interior of the potato. As the hot oil cooks the outside of the fry, it creates a crust that prevents additional oil from entering the potato. Because of this, oil temperature and cooking time are crucial to the mechanical properties of French fries. If the temperature is too low, the crust forms slowly, and too much oil will seep in. If the temperature is too high, the outside will burn. If the fries are cooked too long, they will burn or become too crunchy, and if they aren't cooked long enough, the crust will not have time to form and the inside will not have time to cook fully. A cross-section of the crust and interior of fries finish-fried for 80 and 160 seconds is shown in Figure 1 [4].

To measure the fries' crispiness, the flexural modulus was found by using a three-point bend test, as shown in Figure 2 [6]. The fry is supported on either end and a downward force is applied to the middle. The flexural modulus, also known as the modulus of elasticity, is similar to the Young's modulus. However, the flexural modulus is measured by bending a sample rather than loading it axially [7]. The fries are not homogenous and therefore are not perfect beams, however, they can be approximated as such for the purposes of this and similar experiments [2].

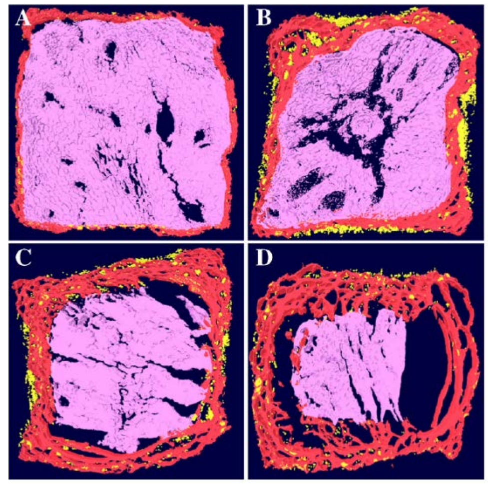

Figure 1: Par-fried and finish-fried fries fried at 375°F for varying lengths of time. The crust is highlighted in red, the core in purple, and the oil in yellow. **A** shows par-frying for 20 s, **B** par-frying for 60 s, **C** finish-frying for 80 s, and **D** finish-frying for 160 s [4]

As the fry cooks, the flexural modulus initially decreases over time as the potato softens. However, as the crust forms, the modulus begins to increase as the fry's structure hardens. After sufficient cooking time, the fries consist entirely of crust, and will fracture instead of bending.

The deflection δ of the beam during the three-point bend test is recorded and related to the force F by the moment of the beam I and the flexural modulus E. The moment of the beam I is derived from the width w and height h of the fry [6]:

$$I = \frac{1}{12} w h^3 \tag{1}$$

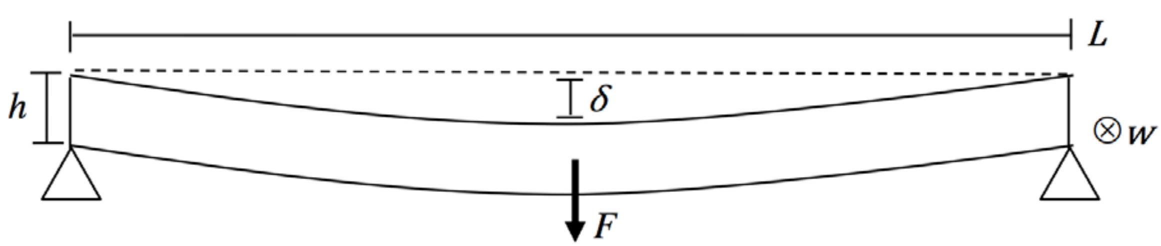

Figure 2: Diagram of a three-point bending test of a rectangular beam. The fry is supported at either end and a force is applied by the Texture Analyzer machine, which records the force and deflection of the beam.

The deflection δ, force F, length L, and moment I as derived in Equation (1) can be combined to find the flexural modulus E of the fry beam, as seen in Equation 2.

$$E = \frac{FL^3}{4wh^3\delta} \tag{2}$$

3. EXPERIMENTAL DESIGN

To obtain the flexural modulus and hardness of fries in relation to frying time and oil temperature, fries were cooked for several different time intervals and then subjected to a three-point bend test and a puncture test. The hardness was found by identifying the peak force during the puncture test, and the flexural modulus was determined from the dimensions of the fry and the three-point bend test Force versus Deformation plot.

3.1 FRY PREPARATION

Samples were prepared by frying for five different fry times. Each frying time produced 12 samples, 6 of which were used tested for flexural modulus and 6 of which were tested for crust hardness. Potatoes used in this experiment were Idaho Russet potatoes, and the fries were cut by hand and the width and height measured before frying. The width and height of each fry were approximately equal. The mean dimension of the fries was 6.86 ± 0.19 mm.

The T-fal FF492D Mini Fryer was used to cook the fries. The oil in the fryer was heated to 375° and maintained at that temperature for at least 10 minutes before frying to ensure the oil was heated thoroughly and consistently for each batch prepared. Canola oil was used due to its prevalence in deep frying and high smoke point. The cut fries were arranged in a single layer in the fry basket to avoid fries sticking together. A timer was set immediately after the basket was lowered into the oil. The lid was closed and was not re-opened during frying. After the fries had cooked for either 6, 8, 10, 12 or 14 minutes, they were removed from the oil and laid on a single napkin to absorb excess oil. For every batch, the samples were allowed to rest for 9 minutes before testing began to allow the fries to cool to room temperature, to ensure the fry temperature changed minimally over the course of testing.

3.2 METHOD

Samples were tested on the Stable Micro System TA.XT Plus Texture Analyzer, and force was measured in grams, with a resolution of 0.1 g and 0.001 mm. Two tests were conducted: a three-point bending test to determine the flexural modulus, and a puncture test to determine the hardness of each fry.

For all tests, the TA.XT Plus was used with a 50 kg load cell. The testing began 9 minutes after the fries were removed from the fryer. In every case, the puncture test was performed before the three-point-bend test.

3.2.1 PUNCTURE TEST METHOD

For each frying time, six fries were tested using the puncture test. Each fry was tested twice, once at each end, resulting in 12 data points for each batch. For each test, a fry was placed on the Texture Analyzer base plate as shown in Figure 3 and lowering a TA-52 2mm diameter puncture probe to just above the top of the fry. The probe traveled at 1mm/s for 4 seconds for a total puncture distance of 4 mm. The force in grams over time was plotted.

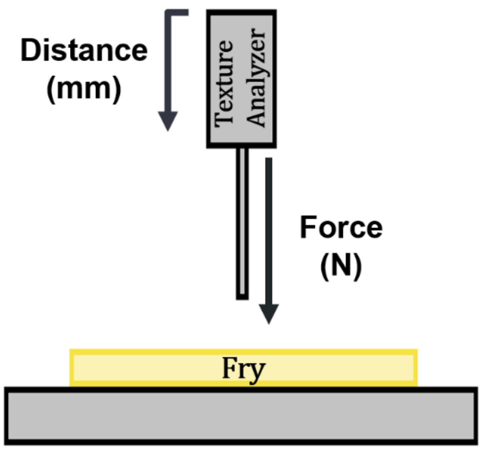

Figure 3: Diagram of the experimental setup for a puncture test. The fry is set horizontally directly below the probe. During the test, the probe applies a force onto the fry until it punctures through the outer crust.

3.2.2 THREE-POINT BEND TEST METHOD

For the three-point bend test, the fry was laid across a pair of 10mm tall metal beams, 20 mm apart. The TA-45 Incisor Blade was used to bend the fries. The probe traveled at 1mm/s for 8 seconds for a total distance of 8 mm. The force in grams over time was plotted.

4. RESULTS AND DISCUSSION

4.1 PUNCTURE TEST RESULTS

The hardness of the outer crust was found to increase over time. This behavior can be attributed to the decrease in moisture content in the crust with increased frying time, which has been shown to contribute to an increased crust strength of fried foods [2, 5].

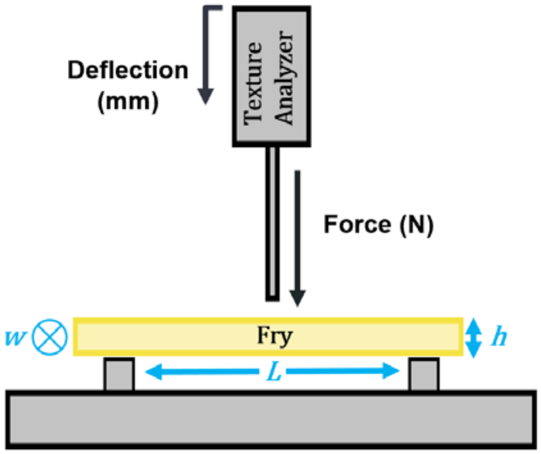

Figure 4: Diagram of the experimental setup of a three-point bending test of a rectangular beam. The fry is supported at either end and a downward force is applied by the Texture Analyzer machine, which records the force and deflection of the beam.

The force was converted from Grams to Newtons before analysis. The Applied Force versus Distance Traveled was plotted after each test. Figure 5 shows a typical Force versus Distance graph for a single fry. The sample in this test was fried for 6 minutes.

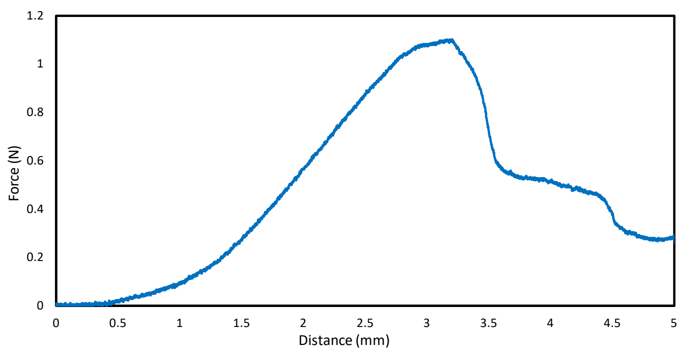

Figure 5: A typical Force (g) vs Time (s) plot for a puncture test. The force increases linearly before reaching a maximum, at which the crust is fully punctured. As the probe continues to push into the soft interior of the fry, the force drops to 0.

The Hardness (N) of each fry was determined to be the maximum force the fry experienced before the probe broke through the crust layer. The hardness of each fry was found from the plot, and the mean and standard deviation were calculated for each trial. Figure 6 displays Hardness plotted against Frying Time for samples cooked for 6, 8, 10, 12, and 14 minutes. The spread of the Hardness values increases with frying time due to the random nature of frying.

The mean Hardness value for each frying time was calculated. Figure 7 displays the mean Hardness value from each frying time, and the data has been fitted with a power curve.

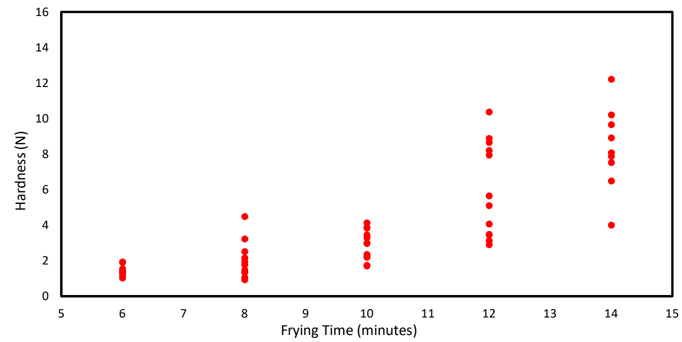

Figure 6: Hardness (g) plotted against frying time for varying frying times. The data has a wide vertical spread that increases as the frying time increases.

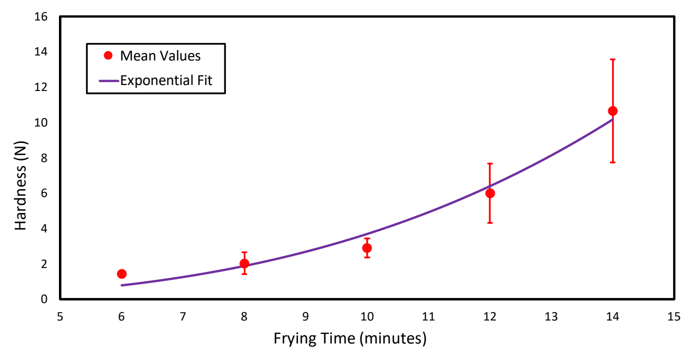

Figure 7: Mean value of Hardness (g) plotted against frying time. The vertical error bars represent the uncertainty in the mean. The data has been fitted with a power curve with equation $f(x) = A * x^3$, where A = 0.00371 ± 0.0004.

4.2 THREE-POINT BEND TEST RESULTS

The Flexural Modulus was found to correlate positively with frying time, and the relationship can be modeled well with a power function. As with the hardness, this increase can be explained by the basic process of frying in which oil replaces water in the fry's crust.

The measured force was converted from Grams to Newtons before analysis. The Applied Force versus Time was plotted for each test. Figure 8 displays an example plot from this test. The plot has a linear initial portion, and force decreases after the fry fractures.

The average slope of the initial linear portion of each Force vs Distance plot was found and used with the fry's dimensions to calculate the Flexural Modulus of each fry

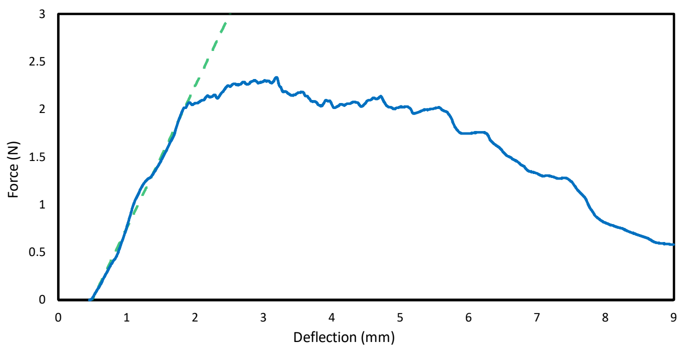

Figure 8: An example of a three-point bend test plot of a fry. The force applied to the fry is plotted against the deflection, and the slope of the initial portion can be used to calculate the flexural modulus.

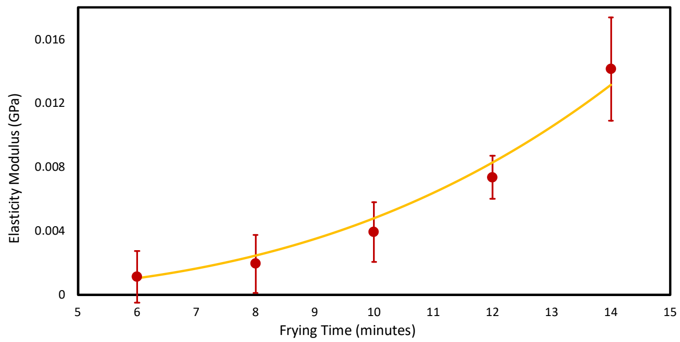

Figure 9: The mean Flexural Modulus value for each frying time. The data have been fitted with a power function with equation $f(x) = A * x^3$, where $A = (4.80 \pm 0.45) * 10^{-6}$.

using Equation 2. The moduli from each frying time were averaged and the means were plotted and fit with a power curve.

4.3 DISCUSSION

As may be expected, the crispiness of French fries increases with increased frying time. Both the hardness of the outer crust and the flexural modulus of the fries increased exponentially with frying time. The power functions found to characterize the properties in this study can be used to predict the mechanical properties of fries fried for any given time within the range of 6 to 14 minutes. Although the properties of fries can now be predicted, the properties have not been mapped to perceived taste of the fries. Although consumers generally prefer crispy fries, it is intuitive that infinitely increasingly crispiness is not desirable – there is a point where the fries become too crispy and unpalatable. Future studies should be conducted to determine the optimal frying time and mechanical properties based on perceived taste and quality.

4.4 LIMITATIONS AND POSSIBLE SOURCES OF ERROR

Although the tests were conducted as quickly as possible to ensure testing consistency, the testing did inherently take time to complete. As a result, the fries tested last from each batch sat in the room temperature air longer than those tested first. Fries sitting out leads to the oil in the crust seeping into the interior of the fry and being replaced with moisture from the air and the interior, leading to a potentially soggy fry.

Fries were cut as uniform as possible, but were cut by hand, resulting in non-perfect uniformity that could have potentially affected results. The moisture content of the potatoes used for each batch was also not measured, which could affect the final fry texture.

Oil was reused between trials, and reusing oil has been shown to have a minor effect on fry texture. To combat this and some of the other inherent possible sources of error, the batches were prepared in the order 6 min, 12 min, 8 min, 10 min, and finally 14 min to randomize the trials. However, this may not have removed all sources of error.

CONCLUSIONS

The relationships between frying time and both hardness and flexural modulus can each be modeled with a power function with equation $f(x) = A * x^3$. The relationship between the coefficients A from each relationship is not statistically significant, as is to be expected due to drastically differing scales of the flexural modulus and hardness. However, the shared factor x^3 shows that the two mechanical properties increase at the same rate. This relationship implies the surface hardness governs the flexural modulus of the fries. This makes sense, as both measures are dependent on the increased strength and thickness of the outer crust of the fry with increased frying time.

Now that the relationship between frying time and the mechanical properties of the fries has been found, there is motivation to correlate these values with the perceived taste of the fries. Future work on this project would involve taste-tests of fry samples prepared at different fry times to determine the mechanical properties of an "ideal" fry.

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