# EFFECT OF INGREDIENT RATIO ON THE TEXTURE PROFILE OF COOKIES 

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#### Abstract

Although the chemistry behind how cookies are formed is well understood in industrial settings, little quantitative research has been done in the home setting. In order to understand how a cookie's ingredients affect its overall shape and taste, the ratio of sugar to butter to flour was varied and the resulting cookie's material properties were analyzed. Texture profile analysis, Weibull strength analysis, and qualitative taste tests were used to quantify taste factors and define what makes a "reasonable" cookies. No notable change in density or chewiness was found, but significant differences in hardness and brittleness were found, matching qualitative results.


## INTRODUCTION

The effect of ingredient ratio on the mechanical properties of cookies is an important relationship to understand to get the desired cookie texture. However, although cookies are extremely popular, responsible for a third of all dessert consumption in the US [1], few understand the relationship between ingredient amounts and final product. Many industrial studies analyzing how ingredient substitutions quantitatively affect the final product exist [2-4], but those results have not been carried over to the qualitative studies done in a household kitchen [5].

To bridge this gap in understanding, nine batches of cookies were baked with varying ratios of sugar, butter and flour - the core 3 ingredients of a cookie - and then characterized via density measurements, texture profile analysis results, and qualitative taste tests. Cookie density provided a measure for how light or airy the cookies were, while texture profile analysis provided a quantitative way to determine hardness, brittleness and chewiness. Qualitative taste tests provided a base line to
compare how far each batch was from a baseline cookie as well as confirm the texture profile analysis results [6].

## BACKGROUND

## INGREDIENT INTERACTIONS IN COOKIES

Cookies are fundamentally made of three ingredients: butter (or other fats), flour, and sugar. These ingredients work together to create or inhibit a gluten network, the main structural element of the cookie (See Figure 1). Other ingredients such as eggs, baking soda, and water help enhance these actions by providing more protein for the gluten network or encouraging air pockets within the network to expand [7]. This study focuses solely on sugar, butter and flour.

Flour works with the water present in the butter to form a gluten network, creating the main structure of the cookie as well as its elastic properties. [4]. The more gluten present, the more chewy and less crumbly the baked good gets. [8] If too much flour is present however, the dough will become brittle and inconsistent, as the network bonds are not sufficient to stabilize the structure.

Sugar not only contributes to the sweetness of the pastry, but also causes the dough to become softer. Sugar may compete with flour for the water that is present, causing less gluten bonds to form and making the cookie less cohesive as a result. Depending on the amount of sugar present, the sugar may either help make the cookie crispier through crystallization or will soften the cookie by taking up water [4].

Butter or fat acts as a lubricant, giving the cookie a soft texture. It also prevents a gluten network from forming due to its hydrophilic nature and may make the dough less elastic. [4] The texture and temperature of the butter matters quite a bit as the emulsion within butter will break down at higher temperatures, making it not coat the flour
as effectively. Procedures like creaming will help preserve these emulsive properties by aerating the butter and allowing the sugar to be distributed more evenly [7].

Knowing these chemical interactions, this suggests that key physical parameters to measure would be hardness and brittleness (how strong is the gluten network) as well as chewiness (how much effect do sugar and butter cause in weakening the gluten network). Although these parameters are easy to evaluate qualitatively, a quantitative approach for these parameter was needed to more directly understand how ingredient ratios affect these characteristics.


Figure 1: Diagram summarizing the chemical interactions behind cookie qualities.

## TEXTURE PROFILE ANALYSIS

Texture Profile Analysis (TPA) is a widely used measurement in food science to quantify many physical properties of food, including hardness, brittleness and chewiness. TPA is a compression test that is designed to mimic the first two bites one takes when eating food. Using a texture analyzer, a machine very similar to a universal testing machine, the force is measured over the time it takes a plunger to compress the material twice, with a waiting time in between each bite to allow the material to rise up again [9].


Figure 2: Schematic illustration of Texture Profile Analysis (TPA) and its derivative measurements. The main properties of this study - hardness, brittleness and chewiness are all derived from various aspects of the force-time curve (Modified image from [10]).
This paper will focus on brittleness / fracturability, hardness, and chewiness. Hardness is defined as the maximum force of the first compression. Fracturability is the first peak of the first compression if there are more than one peak present. Not all materials may fracture, so this measure is not always present. Chewiness is defined as the product of hardness, cohesiveness and springiness. Cohesiveness is defined as the area of work during the second compression divided by the area of work during the first compression. Springiness is the ratio between the second compression's height and the first compression's compression distance. These different parameters are summarized by Figure 1 [11].

In addition to TPA tests, density was measured for both the cookie and the TPA sample as well. The amount of air trapped within a cookie will cause cookies to taste "lighter" or "richer", a characteristic which can be captured by density measurements but not by TPA analysis. Uncertainties given in both TPA and density measurements represent the $95 \%$ confidence interval.

## WEIBULL STATISTICS

Cookies are a brittle material, which means that there is much higher variation in how much force is needed to cause a cookie to fail. To accurately characterize the cookie strength, a Weibull distribution was fitted to the data, a common technique for characterizing the failure rate and strength of brittle materials [12].

The Weibull distribution for reliability is defined as

$$
F(\sigma)=1-\exp \left(-\left(\frac{\sigma}{\sigma_{0}}\right)^{m}\right)
$$

where $F(\sigma)$ is the probability of failure, $\sigma_{0}$ is the scale parameter and $m$ is the shape parameter. Visually, on a probability plot, the scale parameter is the $y$-intercept and the shape parameter is the slope. On a probability density plot, the scale parameter is where the peak of the curve occurs while the shape parameter is the width of the curve.

Given a Weibull distribution, the characteristic strength is defined as the scale parameter as it is the point where the probability of survival is $1 / \mathrm{e}$, aka. about $63 \%$ of the material samples can survive to this point. The shape parameter, on the other hand, gives a sense of variability - how much different samples will differ from this characteristic strength. This quantity is the Weibull modulus and is used to calculate the $95 \%$ uncertainty region for the TPA results [13, 14].

As a visual check on whether data fits a Weibull distribution, a Weibull probability plot can be drawn. By plotting probability vs. data on a semilog plot, the Weibull distribution appears as a line which can then be compared visually to the dataset. This is purely a visual test for "straightness", not a rigorous test for fit. Although data points near the origin do not match the linear probability plot as well, that is expected because more variability is present at lower probability events and thus matter less in a visual test for "straightness" [15]

## METHODS

## BAKING THE COOKIES

The same basic recipe was followed for all cookies - only the initial mass ratio of ingredients was changed. The butter was first creamed with a stand mixer (KitchenAid Classic) for 2 minutes on a low setting. Then, the sugar was added and mixed with the butter for 90 seconds on one setting higher. The flour was then added and mixed on the lowest setting for 30 seconds or until the dough started forming, whichever came first. 1 inch balls were then hand scooped and formed and then pressed down onto a baking sheet lined with parchment paper.

For some ratios, dough never formed past a powdery stage, no matter how much mixing was done. For these ratios, the dough balls were also unable to be pressed
down as the powdery form they were in would break immediately upon pressure, even before baking.

Cookies were baked in an oven at 325 degrees Farhenheit (163 degrees Celsius) for 15 minutes. The cookies were then allowed to cool to room temperature ( $\sim 30$ degrees Celsius) before further measurements were taken. The oven temperature was monitored with a thermocouple to ensure that there were no abnormalities. Likewise, at each stage in the process, a IR Thermometer monitored the temperature of the butter and the dough as it moved throughout the process.


Figure 3: Overall experimental setup. Cookies were first baked in the oven with temperature of butter and the oven monitored and mass of ingredients weighed. Then, density measurements were taken with calipers and a scale for both the cookies and a 1 cm2 sample. Finally, the cookies were taken to the texture analyzer to measure the cookie's material properties.

## MEASURING MATERIAL PROPERTIES

A TPA test was run on a TA.XTPlus Texture Analyzer with a 1" diameter cylindrical probe and a load cell rated up to 5 kilograms-force ( 49 N ). A $1 \mathrm{~cm}^{2}$ sample was cut out of each cookie using a razor blade and placed underneath the cylinder. The test speed of the probe was 3 $\mathrm{mm} / \mathrm{s}$. The cookies were compressed to $75 \%$ strain and the time between compression runs was 5 seconds. These parameters are consistent with both the recommendations for good texture profile analysis and other TPA studies done on cookies [18] [3, 19]

If the sensor was overloaded or the cookie sample stuck to the probe, that run's data was discarded as TPA would no longer provided accurate results for the entire sample
[11]. Afterwards, brittleness, hardness, and chewiness were calculated through the Exponent software that came with the Texture Analyzer, using the definitions of hardness, brittleness and chewiness as defined in Section 2.2. Data was then fitted to a Weibull distribution. The scale parameter was taken as the representative value for each characteristic, as per standard practice for finding the Weibull modulus. (See Section 2.3 for further details).

For density calculations, a pair of calipers were used to measure the dimensions of the cookie and cookie sample in order to calculate the volume. For volume calculations, cookies were estimated to be a cylinder while the cookie samples were estimated to be a $1 \mathrm{~cm}^{2}$ rectangular prism. The mass was measured with an Ohaus Scout Pro scale. Density was then calculated as mass divided by volume.

## QUALITATIVE TASTE

To see if it was possible to connect the qualitative layman's intuition with the quantified material properties, an informal survey was given out. After all experiments were completed, cookies were given out to an untrained assortment of taste testers. Taste testers were asked "How would you describe this cookie?" and "What kind of cookie would you classify this as?" Comments were written down and later summarized.

## RESULTS

## QUALITATIVE TASTE

| Table 1: Summary of Cookies Baked <br> (Sugar:Butter:Flour) |  |  |  |
| :---: | :---: | :---: | :---: |
| Mass Ratio | Qualitative <br> Description <br> (See Sec. 4.4) | Density <br> Measured? | TPA Tests Done? |

Nine batches of cookies were made in total, although complete quantitative data was taken for only 5 batches. Qualitative taste test data was taken for all cookies. Table 1 summarizes what data was taken for what cookie types. The odd fractional ratios (1:1.65:1.4 and 1:2.3:4.8) come from initial recipes that were based on volume rather than
mass. Notably, although both of those batches had a 1:2:3 volume ratio, their mass ratios varied quite wildly.


Figure 4: Qualitative images of the representative cookies for each type (shortbread, halfway-between-shortbread-and-sugar, butter cookies, sugar cookies and "flour cookies")
The temperature of the oven remained mostly constant. Although there were notable oscillations within the data (See figure 3), the oscillations were fairly constant between batches, implying that this is just normal oven behavior. Characterizing the effect of oven temperature on cookie material properties is outside the scope of this project.


Figure 5: Example graph showing oven temperature over time. Note the steep drop in temperature at $\sim 1600 \mathrm{~s}$ and 2500 s that occur when the oven door was opened. Also note the oscillations that occur throughout the graph due to the oven's poor control system. The average temperature is a bit less with the set temperature of $325^{\circ} \mathrm{F}\left(163{ }^{\circ} \mathrm{C}\right)$, but still on par with the other trials.

Butter temperatures were also about as expected based on previous creaming data, as seen in Table 7 [7]. Although the average measured temperature did not fit exactly in the regions specified by the creaming data, the overall trend is matched, especially given the higher room temperature.

Table 2: Mixture Temperature Summary

| Stage | Expected <br> Temperature <br> $\left({ }^{\circ} \mathrm{C}\right)($ Converted <br> from [7]) | Average <br> Measured <br> Temperature <br> $\left({ }^{\circ} \mathrm{C}\right)$ |
| :---: | :---: | :---: |
| Room <br> Temperature | 23 | $26.2 \pm 0.2$ |
| Butter just out of <br> fridge | $5.5-6.7$ | $9.4 \pm 0.5$ |
| Butter after <br> cutting | $5.5-6.7$ | $9.5 \pm 1.1$ |
| Butter after <br> creaming | 15.6 | $14.6 \pm 1.5$ |
| Butter + Sugar | $17.2-18.3$ | $18.3 \pm 1.7$ |
| Butter + Sugar + <br> Flour | $20-22.2$ | $21.7 \pm 1.0$ |
| Cookies on the <br> sheet | $20-22.2$ | $26.2 \pm 0.7$ |

## DENSITY

Density data for flour cookies was not taken because those cookies were way too brittle to be cut into a $1 \mathrm{~cm}^{2}$ sample, exploding into lots of powder when cut.

There was no significant difference in density across cookies, as seen in Figure 4. This is probably because no baking powder or baking soda was used. These ingredients increase the size of any air bubbles that are present in the dough and would probably have caused a greater difference in density. Changing the ingredient ratios thus does not have a noticeable effect on the air bubble size.


Figure 6: Bar graph showing density of various cookie batches. There is no significant difference in density between ingredient ratios.

## TEXTURE PROFILE ANALYSIS

The sugar cookies were too stiff for the 5 kg load cell on the texture profile analyzer which makes sense given that other papers studying cookies use 25 kg load cells [2]. This implies that the sugar's crystallization effect outweighed the softening effect caused by outcompeting flour for the water. The flour cookies were still too brittle to cut a sample out of them.

Despite not being able to take TPA measurements for most of the cookie batches, the results still agreed with the chemical background. There was not much difference in the hardness between the shortbread-esque cookies, but there was a significant change in hardness for the much softer butter cookies. This is consistent with the known chemistry behind baking cookies. Shortbread and halfway-cookies had more flour content and thus had stronger (and more brittle) gluten networks, while the butter cookie's large amount of butter prevented the gluten network from forming and was thus much softer.

The lack of significance in chewiness results may suggest that "chewiness" is not a good description for cookies. What everyday speech calls "chewy" cookies may actually be better characterized by stiffness. Although there is no clear explanation in the literature for what "chewiness" for TPA measurements means, it's likely that they actually intended that metric to be more for gum or tough pieces of meat.


Figure 7: Weibull probability plots for the hardness (a), brittleness (b), and chewiness (c) of cookies with mass ratios of 1:2:3, 1:1:1 and 1:3:2 of sugar to butter to flour. Note that the empirical data measurements visually appear to match to the Weibull lines, making the assumption that a Weibull distribution was a good fit in Section 2.3 an accurate one. The poor fit for data near the origin is expected.




Figure 8: Plots of the probability density function for the hardness (a), brittleness (b), and chewiness (c) of cookies with mass ratios of 1:2:3, 1:1:1 and 1:3:2 of sugar to butter to flour. Note that one can get a general sense of the characteristic strength just by looking at the peak location.




Figure 9: Bar graphs for the hardness (a), brittleness (b), and chewiness (c) of cookies with mass ratios of 1:2:3, 1:1:1 and 1:3:2 of sugar to butter to flour. The softness of the butter cookies (1:3:2) was accurately captured, while there was no significant difference in chewiness between cookie types.

Table 3: Qualitative Taste Test Summary

| Mass Ratio (Sugar:Butter:Flour) | What would you name the cookie? | How would you describe the cookie? (Top responses) | Reasonable cookie? <br> (summarized responses) |
| :---: | :---: | :---: | :---: |
| 1:2:3 | Shortbread - 7 votes | Tender, slightly dry, smooth, bland, soft | Strong Yes -4 votes Yes- 3 votes |
| 1:2:4 |  |  |  |
| 1:1:1 | Shortbread - 4 votes Sweet shortbread - 5 votes Sugar cookies -4 votes | Buttery, sugary, generic, slightly moist | Strong Yes -4 votes <br> Yes -5 votes <br> No -4 votes |
| 1:1.65: 1.4 |  |  |  |
| 1:3:2 | Butter "cookies" - 5 votes <br> Shortbread / sugar cookies with extra butter -4 votes | Too much butter, too much sugar, moist | Yes-1 vote <br> No- 7 votes <br> Extreme No-1 vote |
| 2:1:1 | Sugar Cookies -3 vote Rock Candy - 1 vote | Very hard, very sweet, not enough butter | Yes -2 votes <br> No - 2 votes |
| 1:1:2 | Flour Cookies / Balls of Flour - 6 votes Balls of short bread -4 votes Pecan Snowballs - 1 vote | Very dry, extremely powdery/ crumbly | Yes -2 votesYes but wrong texture -4votesNo -5 votes |
| 2:1:3 |  |  |  |
| 1:2.3:4.8 |  |  |  |

The qualitative taste tests (summarized below in Table 3) combined with the visual appearance of different batches, motivated the groupings used in the rest of the study for classifying what type of cookie was each batch.

Overall, the qualitative taste tests provided more of a complement to the TPA results rather than directly affirming them. The testers tended to describe things less in terms of typical TPA parameters (hardness, brittleness and chewiness) but more in terms of moisture and "crumbliness", making it difficult to directly compare the results. While the testers were able to tell the same brittleness / hardness problems with the flour and sugar cookies, the shortbread was described as "soft" when in fact the shortbread was one of the harder types of cookies

From these taste tests, a graph of all possible ratios (See figure 10). Ideally, the values of the TPA measurements would be matched on to this graph, but not enough batches were baked in order to do this interpolation. However, plotting this space still allows us to get a qualitative sense of which ratios give reasonable cookies, based on taste test data.


Figure 10: 3D plot of all possible recipe ratios (represented by gray) and the region of "reasonable cookie space" (represented by green). All cookie batches tested were plotted as points with their qualitative taste test descriptive name.
The gray region represents all possible ratios, the plane $\mathrm{x}+\mathrm{y}+\mathrm{z}=1$ bounded from 0 to 1 on all axes. The region of "reasonable cookies" is the region on $\mathrm{x}+\mathrm{y}+\mathrm{z}=1$ bounded by the points ( $0.13,0.27$, $0.60)$, ( $0.375,0.325,0.3$ ), and ( $0.2,0.5,0.3$ ). Note the very small change in ratio needed to go from a reasonable shortbread cookie to a strange tasting "flour cookie" at the top corner of the reasonable cookie graph, as seen by how close ( $0.13,0.27$, 0.60 ) is to $1: 2: 4$ and 1:2.3:4.8.

## CONCLUSIONS

This study was able to confirm the known chemistry behind cookies, informal qualitative studies as well as quantitative industrial studies using TPA measurements and taste tests. Varying the recipes’ flour content did indeed result in stronger cookies due to the increased gluten network while decreasing the recipes' butter content made softer and less brittle cookies.

We also gathered some surprising insights, such as the small space of recipe ratios that resulted in "reasonable" cookies and the fact that "chewiness" was not actually an accurate description for softer / less stiff cookies. In particular, the difference between having a recognizable shortbread cookie to a nearly inedible flour cookie was surprisingly small. This work will help bakers in the future adjust cooking ratios for desired tastes - ex. softer cookies or more brittle cookies.

For future study, improving data acquisition would help characterize a larger number of cookies.. Getting a larger load cell would also help us take data for the sugar cookies and flour cookies that were too stiff. A larger load cell would also enable a larger probe to be used, removing the need to cut a small sample for each cookie (as TPA requires that the entire sample be crushed).

In addition, more work could be done to fully link qualitative taste tests with quantitative ones. A moisture sensor would also be useful to evaluate taste testers' claims of dryness / moistness. To measure how crumbly a cookie is - another popular description from qualitative taste tests, we could perhaps measure the amount of cookie remaining after a single compression to a certain force.

This study differed in many ways from typical TPA studies through its use of Weibullian statistics and differed from other 2.671 cookie studies by not using a 3 point bending test as the basis for stiffness. Contrasting the accuracy and ease of use between these two methods would help future researchers decide on the most appropriate tool for their work.

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