2014

RHEOLOGICAL, FOAM, AND PHYSICAL PROPERTIES OF LOW SUCROSE MERINGUE AND ANGEL FOOD CAKE FORMULATED WITH NON-NUTRITIVE SWEETENERS AND POLYDEXTROSE

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Dr. Clair Hicks, Major Professor
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RHEOLOGICAL, FOAM, AND PHYSICAL PROPERTIES OF LOW SUCROSE MERINGUE AND ANGEL FOOD CAKE FORMULATED WITH NON-NUTRITIVE SWEETENERS AND POLYDEXTROSE

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the College of Agriculture, Food and Environment at the University of Kentucky

By

Kevin J O’Niones

Lexington, KY

Director: Dr. Clair Hicks, Professor of Food Sciences

Lexington, KY

2014

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ABSTRACT OF THESIS

RHEOLOGICAL, FOAM, AND PHYSICAL PROPERTIES OF LOW SUCROSE MERINGUE AND ANGEL FOOD CAKE FORMULATED WITH NON-NUTRITIVE SWEETENERS AND POLYDEXTROSE

The object of this research was to determine if an acceptable angel food cake alternative could be produced that had reduced calories and sucrose content. This was accomplished through replacing sucrose in meringue, angel food cake batter, and baked angel food cakes with polydextrose and either sucralose, acesulfame-K, or Rebaudioside A at different replacement levels (25, 50, 75, 100%). Meringue and cake batter properties were measured using rheological techniques. Baked angel food cakes were analyzed based on height, weight loss, moisture content, color, and TPA analysis. With meringue batter, 100% sucrose replacement was unacceptable since undissolved polydextrose made analyzing and end products impractical. While 75% sucralose and acesulfame-K sucrose replacement exhibited comparable air incorporation to the sucrose control in cake batter, baked angel food cakes showed a decrease in functional properties. Polydextrose was likely the cause. 25% sucralose and acesulfame-K sucrose replacement were no different from sucrose cakes in regards to height, overall textural appearance, crumb pore size, and hardness. These cakes resulted in an overall calorie reduction of 18.7%. In every experiment, Rebaudioside A replacement treatments exhibited trends opposite of sucralose and acesulfame-K treatments. Rebaudioside A treatments performed the worst for rheological properties and TPA analysis.

KEYWORDS: Egg Foam, Angel Food Cake, Artificial Sweeteners, Polydextrose, Viscoelasticity

Kevin J. O'Niones
(Author Signature)

April 18, 2014
(Date)
RHEOLOGICAL, FOAM, AND PHYSICAL PROPERTIES OF LOW SUCROSE MERINGUE AND ANGEL FOOD CAKE FORMULATED WITH NON-NUTRITIVE SWEETENERS AND POLYDEXTROSE

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ACKNOWLEDGEMENTS

The endeavor to obtain a Masters in Food Science has been from the beginning an uphill battle. Since my educational and professional background was in culinary, hospitality, and business management, the enormity and breadth of the food science world were quite unknown. Despite this, when all other doors were closed, Dr. Hicks, my mentor and Academic Advisor, was willing to take a risk and accepted me into this program. It is with such a glad heart that I thank you for providing this opportunity. My passion for the food and the food industry have only galvanized since being a part of this program. You saw potential in me that even I did not know was present. I would also like to extend my gratitude to my other committee members, Dr. Youling Xiong and Dr. Gregg Rentfrow. Your patience, tutelage, and knowledge have been instrumental components in providing the building blocks to construct a sound cornerstone of knowledge to begin my lifetime pursuit of understanding the world of food science.

While I had been the purchasing agent for alcoholic beverages previously, I was still not completely prepared for the rather challenging process of procuring product for this research. The ease of which Sharon Leath-Malone of Celanese/Nutrinova, Marlene Smothers of Wild Flavors, Cathy Miller of Dupont, and the customer service team of Tate and Lyle familiarized me to this process is commendable. Thank you for your patience, understanding, and generosity.

In the midst of completing this monumental task, I have been blessed to meet many new colleagues that have developed into enduring friendships. Yen-Chang 'Henry' Tseng, you have been always been an excellent sounding board to help find reason and logic when none seemed to exist. Dani True, you have always been willing to help make the unknown known when locating, borrowing and using equipment. Leann Slaughter and Rebecca Delles, the technical and procedural support that you provided have helped make the fruition of this project possible. Thanks to each of you for providing the time, guidance, and support to help keep my sanity intact and focus unerringly on the end goal.

My parents have also played a monumental role in helping this all come to a finale. Not only did you sacrifice your time, energy, and resources raising me to be the man I am today, but you still continue to provide such support. It truly amazes and
gladdens my heart to be a witness of such unconditional love. I am truly blessed to have such a solid foundational support.

My wife, Amber O'Niones, has caught the brunt of the burden of this entire process. You and I truly had no idea of the sacrifices that were to be required when saying yes to this degree. Even so, you have faithfully endured by being the support system that I never even knew would be needed. Even in times of doubt you have always been strong. Through it all, you have kept the axiom of our marriage close to heart, "To us!" You have no idea how much your servant heart has opened up my eyes to a world that I never knew existed. It has only caused my love for you to grow even more.

Lastly, none of this would have been possible with my Heavenly Father, God. You opened doors and opportunities that I didn't think were possible. You loved and encouraged me through times of doubt and discouragement. You made possible to what seemed impossible. You somehow always knew what was out ahead, and guided me through both the mire and the blessing. I am ever thankful that you have helped open up my eyes to know that the whole purpose was for me to get to know you better. Thank you Lord for being sovereign over all things.
TABLE OF CONTENTS
ACKNOWLEDGEMENTS ................................................................. iii
LIST OF TABLES .............................................................................. viii
LIST OF FIGURES ........................................................................... ix
CHAPTER 1 -- INTRODUCTION AND LITERATURE REVIEW .......... 1
Introduction .................................................................................. 1
Objectives .................................................................................... 3
Abbreviation of Terms ................................................................. 3
Literature Review ......................................................................... 4
  Introduction ................................................................................ 4
  Non-Nutritive Sweeteners ......................................................... 4
    Saccharin ............................................................................... 4
    Aspartame ............................................................................. 5
    Acesulfame-K ........................................................................ 5
    Sucralose ............................................................................. 6
    Rebaudioside A ..................................................................... 6
  Bulking Agents ........................................................................ 9
    Maltodextrin ......................................................................... 9
    Polydextrose ......................................................................... 9
    Inulin .................................................................................. 11
  Egg White Foams .................................................................... 13
  Rheology .................................................................................. 15
  Effects of Baking ..................................................................... 18
  Texture Profile Analysis ........................................................... 20
CHAPTER 2–MERINGUE EXPERIMENTS ........................................... 21
Objectives .................................................................................... 21
Materials ..................................................................................... 21
Methods ..................................................................................... 22
  Meringue Preparation ............................................................. 22
  Foam Capacity ........................................................................ 23
  Foam Stability ......................................................................... 23
Cross-section and Longitudinal Pictures .......................................................... 67
Moisture Content ............................................................................................. 67
Texture Profile Analysis .................................................................................. 68
Statistics .......................................................................................................... 68
Results and Discussion .................................................................................... 69
  Weight Loss and Moisture Content ............................................................... 69
  Cake Height and Pore Structure .................................................................. 69
  Crumb, Crust, and Overall Color Variation .................................................. 72
  Texture Profile Analysis .............................................................................. 73
Conclusions ....................................................................................................... 75
Research Conclusions ..................................................................................... 89
REFERENCES ................................................................................................. 91
VITA .................................................................................................................. 95
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Select Non-Nutritive Sweeteners and Their Properties</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>Meringue Ingredients for Control and Polydextrose and Sucralose, Acesulfame-K, or Rebaudioside A Treatment</td>
<td>31</td>
</tr>
<tr>
<td>3</td>
<td>Foam Capacity and Rheological Properties of Egg White Foam and Effects of Sucralose, Acesulfame-K, and Rebaudioside A Replacement for Sucrose</td>
<td>32</td>
</tr>
<tr>
<td>4</td>
<td>Angel Food Batter for Control and Polydextrose and Sucralose, Acesulfame-K, or Rebaudioside A Sucrose Replacement Treatments</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>Rheological Measurements of Angel Food Cake Batter Based on the Effects of Polydextrose and Sucralose, Acesulfame-K, or Rebaudioside A Sucrose Replacement</td>
<td>51</td>
</tr>
<tr>
<td>6</td>
<td>Physical Properties of Angel Food Cake and Effects of Polydextrose and Sucralose, Acesulfame-K, and Rebaudioside A on Angel Food</td>
<td>76</td>
</tr>
<tr>
<td>7</td>
<td>TPA Analysis of Angel Food Cake and the Effects of Polydextrose and Sucralose, Acesulfame-K, or Rebaudioside A Replacement for Sucrose</td>
<td>77</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Chemical Structure of Select Non-Nutritive Sweeteners</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Comparison of the Solubility of Polydextrose, Sucrose, and Select Polyol</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Newtonian and Non-Newtonian Viscosity Graphs</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Apparent Viscosity for Control and Sucralose Replacement Treatments (SU) for Meringue Foam</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Apparent Viscosity for Control and Acesulfame-K Replacement Treatments (AK) for Meringue Foam</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Apparent Viscosity for Control and Rebaudioside A Replacement Treatments (RA) for Meringue Foam</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Log-Log Plot of Shear Stress and Shear Rate for Control and Sucralose (SU) Replacement for Meringue Foams</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Log-Log Plot of Shear Stress and Shear Rate for Control and Acesulfame-K (AK) Replacement for Meringue Foams</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Log-Log Plot of Shear Stress and Shear Rate for Control and Rebaudioside A (RA) Replacement for Meringue Foams</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Concentration/Viscosity Relationship</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Apparent Viscosity for Control and Sucralose Replacement Treatments (SU) for Angel Food Cake Batter</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Apparent Viscosity for Control and Acesulfame-K Replacement Treatments (AK) for Angel Food Cake Batter</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Apparent Viscosity for Control and Rebaudioside A Replacement Treatments (RA) for Angel Food Cake Batter</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Log-Log Plot of Shear Stress and Shear Rate for Control and Sucralose (SU) Replacement for Angel Food Cake Batter</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Log-Log Plot of Shear Stress and Shear Rate for Control and Acesulfame-K (AK) Replacement for Angel Food Cake Batter</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Log-Log Plot of Shear Stress and Shear Rate for Control and Rebaudioside A (RA) Replacement for Angel Food Cake Batter</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Cross-sectional View of Control and Sucralose (SU) Treatments for Angel Food Cake Batter</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Cross-sectional View of Control and Acesulfame-K (AK) Treatments for Angel Food Cake Batter</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Cross-sectional View of Control and Rebaudioside A (RA) Treatments for Angel Food Cake Batter</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Texture Profile Analysis (TPA) 2-Cycle Compression Test</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Photos of Sucrose and Sucralose Baked Angel Food Cakes</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Photos of Sucrose and Acesulfame-K Baked Angel Food Cakes</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Photos of Sucrose and Rebaudioside A Baked Angel Food Cakes</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Photos of Angel Food Cake Crumb for Sucrose and Sucralose Treatments</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Photos of Angel Food Cake Crumb for Sucrose and Acesulfame-K Treatments</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Photos of Angel Food Cake Crumb for Sucrose and Rebaudioside A Treatments</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 1 -- INTRODUCTION AND LITERATURE REVIEW

Introduction

Sucrose has proven to be a culinary workhorse in baking. Moisture retention, sweetness, browning, and bulking properties are just a few of its many positive attributes. Because of the range of benefits, it is difficult to find a single alternative ingredient that can replicate all of sugar's functional properties. Even so, the need to do so has become ever more pertinent. As discovered by Ford et al. (2011) from 1999 to 2008 body mass index increased for males from 27.8 to 28.5. Furthermore, over the past 20-30 years, obesity in children ages 2-5 has doubled and ages 6-19 has tripled (Hedley et al., 2004). These figures are staggering since obesity has been shown to increase a multitude of diseases including, but not limited to, cardiovascular disease, heart disease, and Type II diabetes (Rappange et al., 2009). The increasing waist line of Americans had an estimated cost of $147 billion in medical costs in 2008 compared to the still staggering $78.5 billion in 1998 (Finkelstein et al., 2009). If these trends are left unchecked, the detrimental side effects of obesity are going to become ever bleaker.

Because of these factors, competition has become quite fierce to find an acceptable solution. The basic concept of reducing weight is quite simple: calories expended > calories consumed. Implementation of this concept has proven to be quite complicated, though. Since it seems (which research supports) that humans have an innate desire for sweet products (Pinheiro, 2005), sucrose laden products further contribute to the obesity pandemic. Non-nutritive sweeteners provide unique benefits and properties that could help start turning the tide of the ever expanding waste line. For instance, consumption of these sweeteners may enhance weight loss (Raben et al., 2002), reduced energy intake (Wiebe et al., 2011), and reduced BMI (Wiebe et al., 2011). Furthermore, the annual growth, competition entry, and product development that this market has experienced in the latter part of the twentieth century (Prance, 2007) is also clear evidence of increasing demand for them.

The desire for these products began when the first non-nutritive sweetener, saccharin, was introduced in 1879 (Jamieson, 2008). Since then, several other non-nutritive sweeteners have also been approved by the FDA, aspartame in 1981,
acesulfame-K in 1988, sucralose in 1998, and neotame in 2002 (Jamieson, 2008). Rebiving A, which was approved as Generally Recognized as Safe (GRAS) in 2008 (FDA, 2008), was the most recent non-nutritive sweetener to enter the retail market.

Non-nutritive sweeteners have several benefits when replacing sucrose. For example, they can effectively reduce or eliminate sucrose content which also reduces calories, but still provide the same pleasant, sweet characteristic (Viscoine, 2005). For calorie reduction, this is primarily due to the human body’s inability to digest these products, and, since they are 200-600x sweeter than sucrose (w:w), much less is needed when in a formulation (Viscoine, 2005). Reduced sweetener quantities could also maintain or even reduce overall product food cost. For instance, aspartame has been on the market for several decades and, until recently, has been well received by consumers (Jamieson, 2008). Both of these factors have helped drive down ingredient cost.

Despite the pros, a major shortcoming is also found in one of the strengths of non-nutritive sweeteners. Sucrose has been found to increase the aqueous bulk phase and, therefore, increase foam stability in egg foam products (Lomakina and Míková, 2006). When used to replace sucrose, due to the smaller quantity needed, non-nutritive sweeteners do not exhibit the same bulking properties as sucrose. To overcome this limitation, non-nutritive sweeteners are often paired with substances that are able to mimic sucrose’s functional properties. Some such products include maltodextrin, polydextrose, and cellulose (Bullock et al., 1992). Inulin has also been used (Martínez-Cervera et al., 2012) for this purpose.

While the effects of bulking agents and non-nutritive sweeteners have been researched on many products, very little has been performed on angel food cakes. Unlike other baked goods, angel food cake predominately relies on foaming properties of egg whites. Leavening agents and creaming methods (whipped sugar and fat) are not used. The short list of ingredients, the singular leavening agent, and lack of fat make angel food cake a unique baked good to study for sucrose replacement and for providing a starting platform for reducing consumer calorie intake.
Objectives

- To determine which levels of replacement (25, 50, 75, and 100%) for polydextrose and either sucralose, acesulfame-K, or Rebaudioside A treatments were similar to the sucrose control. Those that were successful were used in later experiments.
- To observe trends that may occur with increasing sucrose replacement.
- To monitor any differences that may occur between the different non-nutritive sweeteners (sucralose, acesulfame-K, and Rebaudioside A).

These objectives were accomplished by producing meringue foam, angel food cake batter, and baked angel food cake. For meringues, foam capacity, foam stability, and viscoelastic properties were monitored. For angel food cake batter, viscoelastic and bubble evolution properties were measured. Lastly, for baked angel food cake, crumb and crust color, cake height, weight loss, moisture content, and Texture Profile Analysis (TPA) were analyzed.

Abbreviation of Terms

Because of the frequency of use, throughout this report several terms have been abbreviated. These include:

- Polydextrose: PD
- Sucralose: SU
- Acesulfame-K: AK
- Rebaudioside A: RA

Additionally, the different sucrose replacement treatments (25, 50, 75, and 100%) will be shortened. For example, meringue batter that has had 25% of the sucrose replaced with sucralose and polydextrose will be condensed to 25 SU.
Literature Review

Introduction

Many factors are involved in the current obesity epidemic that the United States is experiencing. Sucrose intake has shown indications of being a major contributor to adolescent obesity (Striegel-Moore et al., 2006). It is because of this that many researchers and producers have attempted to find sucrose alternatives that have the same browning, structural, and sweetening capabilities. Typically, though, no one ingredient can replicate all of these functions. Throughout this chapter, some of the most common ingredients used to replace sucrose will be discussed. Furthermore, some methods, theories, and research performed on replacing sucrose in meringue foam and angel food cake will be detailed.

Non-Nutritive Sweeteners

Saccharin

Saccharin was discovered in 1879 and is the oldest non-nutritive sweetener produced (Jamieson, 2008). This crystalline white powder can be made from toluene (Remsen-Fahlberg process) or phthalic anhydride (Maumee process) (Lipinski, 2000). It is approximately 300x sweeter than sucrose and is most commonly used as a table top sweetener (Jamieson, 2008).

While it is the most economical of the non-nutritive sweeteners (Jamieson, 2008), it has received unfavorable press due to health concerns. Specifically, in 1977 the United States FDA placed a ban on the sweetener (Jamieson, 2008). Consumer backlash resulted, and in 1991 the FDA acquiesced, but required labeling on any saccharin containing product indicating its potentially harmful and carcinogenic effects (Jamieson, 2008). This label was eventually removed in 2000 (Jamieson, 2008), but much damage had been done to this sweeteners’ reputation. Despite its low-cost, quick sweetness onset, and high stability at elevated temperatures and low pH (Jamieson, 2008), saccharin's
popularity has waned due to its tumultuous history and bitter, metallic aftertaste caused by its benzene ring (Pinheiro et al., 2005).

Aspartame

Aspartame was discovered in 1965 by G.D. Searle and Company and was approved by the United States FDA in 1981 (Jamieson, 2008). It is composed of two amino acids, aspartic acid and phenylalanine, and is about 200x sweeter than sucrose (Jamieson, 2008). Unlike saccharin, aspartame has no bitter, metallic aftertaste, but its production has been constantly met with consumer skepticism in regards to its safety (Jamieson, 2008).

Further, because it contains the amino acid phenylalanine, individuals that have been diagnosed with phenylketonuria, a rare metabolic disease where phenylalanine cannot be metabolized, are warned not to consume products that contain aspartame (Jamieson, 2008). Lastly, aspartame has been found to be unstable at high temperatures and low pH (Jamieson, 2008). It is because of this that it cannot be used in cooking or baking (Mortensen, 2006).

Acesulfame-K

In 1967, acesulfame-K was discovered by German scientists and was approved by the United States FDA in 1988 (Jamieson, 2008). It is created via synthesis and purified by recrystallization (Mortensen, 2006). Unlike aspartame, it is heat stable and does not produce any by-products under normal beverage storage conditions (Mortensen, 2006). It is also approximately 200x sweeter than sucrose, stable at high temperatures and low pH, slightly bitter in aftertaste (Jamieson, 2008), and used in numerous products including beverages, yogurt, ice cream, jellies, and baked goods (Mortensen, 2006).
**Sucralose**

Sucralose is a white, crystalline solid that is 600x sweeter than sucrose (Jamieson, 2008). Also known as 4, 1’,6’ – trichlorosucrose, sucralose was approved by the FDA in 1998 (Jamieson, 2008). It is similar in structure to sucrose except that three chlorine atoms are selectively substituted for three hydroxyl groups at positions 4, 1’, and 6’ of a sucrose molecule (Pinheiro et al., 2005). Because of the substitution of hydroxyl groups, sucralose has a lower reactivity than sucrose (Pinheiro et al., 2005). Sucralose is also highly soluble in water, stable in acidic conditions, thermally stable at high temperatures, chemically inert, noncarcinogenic, and has no bitter or metallic after taste (Pinheiro et al., 2005). It is because of these properties that sucralose can be used in many applications such as yogurt, candy, ice cream, jelly, and baked goods.

**Rebaudioside A**

The most recently approved non-nutritive sweetener is Rebaudioside A. This non-nutritive sweetener is about 200-300x sweeter than sucrose, has been used for centuries in South America, and is one of the many compounds that can be extracted from the leaves of the Stevia plant (Jamieson, 2008). This extraction process distinguishes Rebaudioside A from the other non-nutritive sweeteners mentioned thus far. Unlike synthetically created non-nutritive sweeteners, Rebaudioside A is considered a natural sweetener since it is derived from the leaves of a plant (Jamieson, 2008). The FDA has only recently begun to receive and approve GRAS notifications for this sweetener with the first being in 2008 (FDA, 2008). Because of this, Rebaudioside A has not been used in a variety of food products, but its slightly bitter and black licorice flavor may lend well to products such as chocolate (Jamieson, 2008).

Figure 1 shows the chemical structures for saccharin, aspartame, acesulfame-K, and sucralose (Pinheiro et al., 2005) and Rebaudioside A (Prakash, 2009). Also, Table 1 provides a synopsis of the relative sweetness and taste characteristics of the most commonly used non-nutritive sweeteners (Jamieson, 2008).
### Table 1: Select Non-Nutritive Sweeteners and Their Properties

<table>
<thead>
<tr>
<th></th>
<th>Aspartame</th>
<th>Acesulfame-K</th>
<th>Rebaudioside-A</th>
<th>Saccharin</th>
<th>Sucrose</th>
<th>Neotame</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sweetness Potency</strong></td>
<td>180 – 200</td>
<td>130 – 250</td>
<td>200 – 300</td>
<td>300 – 500</td>
<td>500 – 700</td>
<td>8,000 – 15,000</td>
</tr>
<tr>
<td><strong>Taste/Profile</strong></td>
<td>Slow onset, lingering sweetness</td>
<td>Quick onset with no significant lingering sweetness</td>
<td>Moderate to quick onset with little to no lingering sweetness</td>
<td>Quick onset with no significant lingering sweetness</td>
<td>Clean sweetness with slow onset and lingering sweetness</td>
<td>Slow onset, lingering sweetness</td>
</tr>
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<td></td>
<td>Clean sweetness with little to no aftertaste</td>
<td>Can have a bitter aftertaste</td>
<td>Potential for bitter or black licorice aftertaste</td>
<td>Potential for metallic, bitter aftertaste</td>
<td>Clean sweetness with little to no aftertaste</td>
<td>Clean sweetness with little to no aftertaste</td>
</tr>
<tr>
<td><strong>Stability</strong></td>
<td>Limited stability when exposed to elevated temperature and low pH</td>
<td>Good stability at elevated temperatures and low pH</td>
<td>Good stability at elevated temperatures and low pH</td>
<td>Good stability at elevated temperatures and low pH</td>
<td>Good stability at elevated temperatures and low pH</td>
<td>Limited stability when exposed to elevated temperature and low pH</td>
</tr>
<tr>
<td><strong>Blending Options</strong></td>
<td>Good synergy with aspartame and saccharin</td>
<td>Good synergy with aspartame and saccharin</td>
<td>N/A</td>
<td>Good synergy with aspartame and saccharin</td>
<td>Good synergy with acesulfame-K and saccharin</td>
<td>Good synergy with acesulfame-K and saccharin</td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
<td>Widely used, sweetness profile and cost-effectiveness</td>
<td>Stability and synergies with other HFCS</td>
<td>“Natural” status and stability</td>
<td>Cost-effectiveness and stability</td>
<td>Sweetness profile, branding and stability</td>
<td>Sweetness profile and cost-effectiveness</td>
</tr>
</tbody>
</table>

The following provides a description of the most commonly used non-nutritive sweeteners. Sweetener potency varies based on the amount of electronegative centers and overall electronegativity of the molecule (Jamieson, 2008).
Figure 1: Chemical Structure of Select Non-Nutritive Sweeteners
This adapted figure shows the chemical structures for saccharin, aspartame, acesulfame-K, and sucralose (Pinheiro, 2005) and Rebaudioside A (Prakash, 2009), one of the many compounds that can be derived from the leaves of the Stevia plant.
Bulking Agents

The intensity of non-nutritive sweeteners necessitates that only a small amounts be used on w:w basis when substituting sucrose. Because of the resulting bulk reduction, a loss of functionality in baked goods is commonly experienced (Pinheiro et al., 2005; Nelson et al., 2000). Maltodextrin, polydextrose, and inulin are common bulking agents that have been used in tandem with non-nutritive sweeteners to overcome the loss in functionality (Martínez-Cervera et al., 2012; Lakshminarayan et al., 2006; Savitha et al., 2008).

Maltodextrin

Maltodextrin is a partial hydrolysate of starch that is prepared with acids or enzymes (Lakshminarayan et al., 2006). It exhibits many similar properties as sucrose such as contributing to batter viscosity, Maillard browning, and water solubility (Jamieson, 2008). Since it is classified as a carbohydrate, its calorie content is 4 kcal/g; the same as sucrose (Jamieson, 2008). While this limits the use of maltodextrin in reduced calorie products, it also imparts other textural characteristics that are not achievable with sucrose. The positive effects on mouth feel and batter viscosity have encouraged research oriented on partial and complete fat replacement in baked goods. Varying levels of success have been found (Lakshminarayan et al., 2006; Khouryieh et al., 2005; Conforti et al., 2001). In general, the most successful recipes have been formulated with lower levels of maltodextrin for fat.

Polydextrose

Polydextrose is composed of numerous glucose molecules that have been randomly cross-linked with sorbitol which cause it to vary in molecular weight and size (Jamieson, 2008). Because it is such a large molecule, it can only be partially digested by the human body which results in a caloric content of 1 kcal/g (Jamieson, 2008). When used in low- or no-calorie products, this property allows for an overall calorie reduction.
Its molecular size also contributes to the viscosity of most formulations (Jamieson, 2008). Specifically, at 20°C and 70% solution concentration, polydextrose is 1000 cp more viscous than sucrose (Murray, 1988).

Unlike the crystalline structure of sucrose, polydextrose is an amorphous powder; (Kocer, 2007). It is because of the structural differences that high polydextrose concentrations in cake batter resulted in reduced air-holding capacity, an increase in bubble size variation and average bubble size, and slower bubble expansion rates (Pateras et al., 1994). Here, the crystalline structure of sucrose captured and retained air bubbles during baking so that cakes set properly, but the amorphous characteristics of polydextrose prevented products containing higher levels from performing as well.

Further, polydextrose is quite soluble in water. Solutions up to 80% concentration can be obtained, but dissolvability can be difficult to obtain at such high levels (Murray, 1988). The shear rate, shear stress, and manner that polydextrose is added to water can influence dissolvability of it in water (Murray, 1988). Figure 2 illustrates the solubility of polydextrose in comparison to sucrose and several polyols (Roller and Jones, 1996).

Lastly, polydextrose can be considered a prebiotic, or dietary fiber, since it is only partially digested by the human body (Jamieson, 2008). Over consumption then can be a concern. While it is generally well tolerated by most consumers, 21 CFR 172.841 states that any product containing more than 15 g of polydextrose per serving must contain a warning that states “excessive consumption may cause laxation.” Bacteria found in the human colon digest polydextrose resulting in fermentation and, with overconsumption, laxation.
Inulin

Inulin is found naturally in bananas, onions, asparagus, and Jerusalem fruit, and is composed of fructose molecules that have been linked together at the end with a glucose molecule (Jamieson, 2008). The length of the molecule ranges from 2 to 70 units long depending on the manufacturer producing it (Jamieson, 2008). Shorter chain inulin, also known as fructooligosaccharides, is sweeter than longer chain inulin (Jamieson, 2008). If used to replace sucrose, the chain length then must be considered since it could contribute to a product's total sweetness. At 1.2 kcal/g, inulin is less calorie dense than sucrose, but, like the other bulking agents, the amount consumed must be monitored since it readily ferments in the lower digestive tract (Jamieson, 2008). The result is that inulin is commonly used in smaller quantities and combined with other sugar replacements such as erythritol and isomalt in chocolate (Jamieson, 2008). Even so, Radványi et al. (2012) used fructooligosaccharides for partial sucrose replacement in egg white foams, and produced an acceptable sucrose alternative that decreased the final product's caloric content.
Figure 2: Comparison of the Solubility of Polydextrose, Sucrose, and Select Polyol

This figure compares the percent solubility of given sweetener component in 100 mL of water (Roller and Jones, 1996).
Egg White Foams

Foams may be defined as an aqueous continuous phase and a gaseous dispersed phase in which the gaseous dispersed phase is stabilized by a thin layer of proteins that bind at the air-water interface (Damodaran al. 2008). Two main standards used to determine foaming ability are foam capacity and foam stability. Foam capacity is described as the amount of interfacial area that can be created by a protein, and foam stability is the ability of a protein to withstand gravitational and mechanical stressors (Damodaran al. 2008).

Many intrinsic and extrinsic factors affect a protein’s ability to have good foam capacity and stability. At the molecular, intrinsic level, a protein must rapidly absorb to the air-water interface, unfold and rearrange quickly, and form a viscous cohesive film through intermolecular interactions to produce effective foams (Damodaran al. 2008). The proteins found in egg whites successfully meet all three criteria (Damodaran al. 2008). As such, it is commonly used in commercial application for stable foam production. Other proteins have been used, though. For instance, Wang (2011) found that the addition of sonicated and modified soy protein isolate (SMSPI) improved foaming in a 5% egg protein system with 0.4% yolk addition. Abu-Ghoush et al. (2010) also performed a comprehensive study that replaced egg white protein with either Cryogel gelatin, Solugel collagen hydrolysates, gelatin, whey protein concentrate, fish protein, whey protein isolate (95% WPI and 90% WPI), hydrolyzed whey protein isolate, pea protein, rice protein concentrate, soy protein, corn zein, and casein. Here only WPI alternatives produced successful meringues; all other foams collapsed upon baking.

Extrinsic factors that affect foaming properties include pH, temperature, lipids, and sucrose content of the food system. For pH, Nakamura and Sato (1964) found that neutral and acidic (except for very acidic) pH produced improved foam capacity. As documented by Damodaran et al. (2008), due to slight protein denaturation, elevated temperatures showed an increase in foaming properties. Because they have poor cohesive and viscoelastic properties and more readily absorb at the air-water interface, lipids impair foaming properties by disrupting air particles and protein layer formation (Damodaran et al. 2008). Due to the increase in viscosity of the aqueous bulk phase,
sucrose content has been found to decrease foam capacity but increase foam stability (Lomakina and Míková, 2006). Bovsková and Míková (2011) found that aluminum sulphate had a positive effect on both foam capacity and stability in acidified non-pasteurized egg whites. This too held true for pasteurized eggs, but only for foam stability. Radványi et al. (2012) found that egg foams produced with egg powder and sucrose (control) were best; however, fructooligosaccharide syrup showed to be a good alternative in pasteurized liquid egg white. Lastly, Abu-Ghoush et al. (2010) reported that angel food cakes produced with 95% WPI produced significantly higher shear force and significantly lower consumer acceptance than sucrose.

At this current time, very little research has been conducted using non-nutritive sweeteners in observing the foaming properties of egg whites. These products hold great potential as low-calorie and dietetic products since the human body is unable to digest them and they have a low glycemic index (Viscoine, 2005). Because they are much sweeter than sucrose, less is necessary to obtain the same level of sweetness (w:w). If used to completely replace sucrose, a reduction in bulk phase viscosity and subsequent foam properties would likely be experienced. Bulking agents such as maltodextrin, polydextrose, and inulin have been used in many experiments to overcome this shortcoming with most recipes resulting in reduced calorie formulations (Martínez-Cervera et al, 2012; Attia et al., 1993; Savitha et al., 2008; Pong et al., 1991; Khouryieh et al., 2005).

Meringue foam provides a unique platform since the ingredient list is quite short. At bare minimum, meringue recipes consist of egg whites, sucrose, and an acid. This basic setup allowed for a clear picture of how the replacement of sucrose with a non-nutritive sweetener and bulking agent had on foam properties.
Rheology

As defined by Bourne (2002), viscosity is the internal friction of a liquid or its tendency to resist flow. An important distinction must be made here. When first discovered, Isaac Newton assumed that, at a given temperature, viscosity was independent of shear rate (Brookfield Engineering Laboratories, 2005). Over time, it became evident that this was not true and, in fact, there are two main types of fluids, Newtonian and non-Newtonian fluids. With Newtonian fluids, when temperature is held constant, viscosity remains constant at all shear rates. With non-Newtonian fluids, viscosity varies based on shear rate. The latter category is where most food “fluids” are categorized.

Non-Newtonian fluids are broken down into three types. Plastic (or Bingham) fluids require a minimum shear stress or yield stress before flow occurs (Bourne, 2002). Examples here include ketchup and mayonnaise. Next, dilatant fluids exhibit an increase in viscosity as shear rate increases (Bourne, 2002). These substances, also known as shear thickening fluids, include corn starch in water and candy compounds. Lastly, pseudo plastic or shear-thinning fluids are the final type of non-Newtonian fluid. Viscosity here decreases as shear rate increases (Bourne, 2002). Salad dressings are the most common example. As presented later, meringue and angel food cake batter also followed pseudo plastic flow behavior. Figure 3 (Brookfield Engineering Laboratories, 2005) illustrates graphical examples of each of the four types of flow behavior.

Since viscosity for non-Newtonian fluids varies based on shear rate, establishing a single numerical value to represent viscosity of a food item is not possible. This creates a challenge when attempting to compare one food fluid to another. Many variations of the general viscosity formula have been created as a result. The general viscosity equation (Bourne, 2002) is as follows: \( \sigma = b\gamma^s + C \) where \( \sigma \) is shear stress (Pa*s), \( b \) is a proportionality factor, \( \gamma \) is shear rate (1/s), \( s \) is pseudo plasticity constant, and \( C \) is yield stress. The model of the general viscosity equation used in a given situation depends on the substances type of flow and correlation with the equation. Most commonly, only equations that have a high r-value based on the plot of log shear stress versus log shear rate are used.
As found by Psimouli and Oreopoulou (2011), Sanz et al. (2009), Martínez-Cervera et al. (2012), and Radványi et al. (2012), cake batter, muffin batter, and egg foams, respectively, showed that a pseudo plastic or shear-thinning behavior occurred. All but Radványi et al. (2012) used the Ostwald de Waale Power Law, a variation of the general viscosity equation, to calculate empirical viscoelastic values used to compare treatments. The Ostwald de Waale Power Law is expressed by the following equation (Bourne, 2002): \( \sigma = k\gamma^n \) where \( \sigma \) is shear stress (Pa*s), \( k \) is the consistency index, \( \gamma \) is the shear rate (1/s), and \( n \) is the flow index. \( K \) and \( n \) values are the quantitative measures used to compare treatments to one another. Consistency index (\( K \)) is defined as the viscosity or stress at a shear rate of 1/s, and flow index (\( n \)) is the measure of a substances non-Newtonian-ness (Cunningham, 2005). For the flow index, values that are close to \( n=1 \) exhibit characteristics that are more Newtonian in nature; whereas, values further from \( n=1 \) exhibit characteristics that are more non-Newtonian.
Figure 3: Newtonian and Non-Newtonian Viscosity Graphs

This is a representation of the different types of Newtonian and non-Newtonian flow. In these graphs, η represents viscosity and S represents shear rate. Graph A shows Newtonian flow, Graph B shows plastic or Bingham flow, Graph C shows dilatant flow, and Graph D shows pseudo plastic flow. (Brookfield Engineering Laboratories, 2005).
Effects of Baking

Cake baking is a very fragile process. Poor ingredient selection, improper ingredient amounts, and incorrect baking procedures can all influence the final outcome. Because the actual mechanisms that occur during the baking process are quite complex, it is often difficult to understand how the introduction of new ingredients could affect the end result. Because of increasing consumer demand for no- and low-sugar and reduced calorie products (Prance, 2007), the increase in healthcare costs (Finkelstein et al., 2009), and the increasing concern over the expanding waste line of United States citizens (Ford, 2011), non-nutritive sweeteners and reduced calorie bulking agents have been examined using various product-oriented models to determine which combination holds the most promise in producing an acceptable product with reduced caloric content.

Some of the most common non-nutritive sweeteners include saccharin, sucralose, aspartame, acesulfame-K, neotame, and, the most recent addition, Rebaudioside A. Table 1 (Jamieson, 2008) illustrates the relative sweetness and taste characteristics of each. The actual sweetness level depends on how the manufacturer processes the ingredient. Each has had varying levels of success in regards to sucrose replacement in baked goods. For example, Martínez-Cervera et al. (2012) showed that muffins produced with 25% sucralose and polydextrose replacement had similar batter viscoelastic properties and final baked product results as sucrose. Furthermore, with sensory evaluation, up to 50% sucralose and polydextrose replacement was found to be acceptable. Zahn et al. (2013) established that up to 30% sucrose replacement with Stevia and inulin or polydextrose in muffins were comparable to the sucrose control. These researchers also found that Stevia and inulin replacement could be designated as a “good source of fiber” since these products contained 4.6 g of fiber per 100 g of product, and Stevia and polydextrose replacement could be designated as “high in fiber” since these muffins contained 7.1 g of fiber per 100 g of product. Lastly, Swihart and Caporaso (1995) utilized a mixture of aspartame, saccharin, and acesulfame-K in an angel food cake mix. In this experiment, a 58% sugar reduction was used; however, sensory panels rated the treatment higher in sweetness intensity and lower in texture, flavor, and overall acceptability compared to the sucrose counterpart.
As supported by these experiments, very seldom are non-nutritive sweeteners used alone. When used to replace sucrose, much less by weight of each is required due to their higher sweetness potency. Functionality is lost as a result, but bulking agents such as polydextrose, maltodextrin, and inulin have been used to replicate these particular properties of sucrose. For instance, polydextrose was comparable to the control (sucrose) (Kocer, 2007) in high-ratio cake systems with 25%-fat and 22% sugar-replacement. Also, Pateras (1994) found that high-ratio cakes produced with 50% and 100% polydextrose had bubble movement that ceased at higher temperatures than the sucrose control, 87-95°C and 90-97°C, respectively. These results suggest that cakes produced with increasing levels of polydextrose are able to have a longer time to expand the final cake structure. Pateras (1990) also found that in high-ratio cakes 25% polydextrose replacement produced cakes with similar textural properties in comparison to conventional, sucrose cakes. Higher substitution produced cakes with a denser crumb that were more prone to structural breakdown. Lastly, Lakshminarayan et al. (2006) used maltodextrin as a fat replacer in cake and found that a progressive increase from 10-80% maltodextrin had an adverse effect on batter viscosity and baked cake functionality. In fact, these researchers concluded that maltodextrin was not an acceptable substitute.

As illustrated by all of these examples, very few experiments have been conducted to examine the effects of sucrose replacement on angel food cakes. Unlike other cakes, cake expansion is dependent on only thermal expansion of the protein foam (Song et al., 2009). Creamed fat and sugar and chemical leavening agents are not present. Also, because it would interfere with foam properties (Damodaran et al., 2008), angel food cakes are naturally low in fat. These properties make angel food cake a unique product to further investigate since they align well with producing a low-calorie and low-sugar products for consumers.
Texture Profile Analysis

To create an objective method that replicated the actions of the human mouth, General Foods Corporation Technical Center developed Texture Profile Analysis (DeMan, 1976). In the original test developed, a bite-sized 1-2 cm³ cube was subjected to compression between two plates. To imitate the action of chewing, the product was compressed to 75% of its original height twice (Rao and Steffe, 1992). This resulted in a force-time graph with two curves. These curves could be used to calculate several textural measurements. These measurements were found to correlate well with sensory evaluation of the same product (DeMan, 1976).

The specific textural measurements derived include hardness, cohesiveness, fracturability, adhesiveness, springiness, gumminess, and chewiness. As described by DeMan (1976) these attributes are described as follows. Hardness is the peak force found under the first curve. Cohesiveness is defined as the ratio between the area under the second curve and the area under first curve ($A_2/A_1$). The force at which the first significant break takes place in the first curve is defined as fracturability. The negative force created from withdrawing the first stroke from the food product is defined as adhesiveness. Springiness is classified as the ratio of the distance that the food recovered after the first compression to the food product’s original height. Hardness multiplied by cohesiveness is defined as gumminess. Lastly, chewiness is described as the product of gumminess and springiness.

Several of the previously mentioned publications used TPA analysis. For instance, Psimouli (2011) did not find any statistical difference between polydextrose and the sucrose high ratio cakes. For Martínez-Cervera et. Al (2012), after exceeding 25% sucralose and polydextrose replacement, muffins began showing a lower hardness and springiness values. Lastly, Ronda et al. (2005) found a firmness decrease in sugar-free sponge cakes that used polydextrose.
CHAPTER 2–MERINGUE EXPERIMENTS

Objectives

The primary objectives for the meringue experiments were to better understand how sucralose (SU), acesulfame-K (AK), and Rebaudioside A (RA) replacement affected foam properties, and which treatments should not be used for later tests. The primary hypothesis was that, as sucrose replacement increased, meringue functionality would decrease. Because less non-nutritive sweetener is needed to provide the same amount of sweetness as sucrose, the second hypothesis was that no difference in viscoelastic properties would be found at the same substitution level for sucrose replacement treatments.

Materials

For control meringues, Grade AA raw liquid egg white, sucrose, and citric acid were used. Liquid egg whites (Crystal Farms, All White – 100% Egg White, Minnetonka, MN) and sucrose (Kroger Granulated Sugar, Cincinnati, OH) were obtained from The Kroger Co. Citric Acid was obtained from Acros Organics (New Jersey).

For treatment meringues, in addition to the ingredients used for the control, polydextrose and SU, AK, or RA were used for sucrose replacement. Polydextrose (PD) (Litesse Powder, New Century, KS, Batch #: 1921906457) was obtained from Danisco USA, SU (Splenda micronized, London, United Kingdom, Lot #: XM2L630701) was obtained from Tate and Lyle PLC, AK (Sunnett particle size A, Frankfort am Main, Germany, Lot #: 0000608585) was obtained from Nutrinova Nutrition and Food Ingredients Specialists, and RA (Nat Sunwin Stevia Reb-A-80, Erlanger, KY, Lot #: H12102512C) was obtained from Wild Flavor Inc.
Methods
Meringue Preparation

Low-sugar and sugar-free egg foams were created by replacing 0%, 25%, 50%, 75%, and 100% of the original amount of sucrose in the recipe with a non-nutritive sweetener (SU, AK, and RA) and PD mixture. Each non-nutritive sweetener was added in an amount based on its’ sweetness index to sucrose. For example, SU is 600x sweeter than sucrose (Jamieson, 2008) so the amount of SU added in the replacement experiments was reduced by 600x the sucrose that it was replacing (w:w). For AK and RA, the amount added to each recipe was reduced 200x (Jamieson, 2008). Table 2 provides a complete breakdown of ingredient quantities used for the control, SU, AK, and RA treatments. The weight of sucrose in the control, 93 g, was used to determine all replacement values. For 25 SU replacement, 23.25 g (25% of 93 g) of sucrose were replaced with PD and SU blend. SU was 0.039 g (23.25 g divided by 600) and PD was 23.211 g (23.25 g less the amount of sucralose used). The total amount of sucrose, PD, and non-nutritive sweetener always added to 93 g for each treatment.

For the meringue preparation, a modified version of Radványi et al. (2012) foam recipe was used. Liquid egg whites were brought to room temperature (approximately 20° C). Using a hand mixer (120 V Betty Crocker 4-Speed Hand Mixer Model Number BC-1202K) liquid egg whites (g) and citric acid (g) were whipped at speed 4 for 30 s. At speed 2, the appropriate non-nutritive sweetener (g) and PD (g) were added in ¼ batches every 30 s for a total of 2 min. The mixer speed was then increased to speed 4 and allowed to mix for 10 min.
Foam Capacity

Final foam volume was calculated by using the volume formula of a cylinder, \( V = 2\pi rh \) where ‘r’ was the radius (cm) of the beaker and ‘h’ was the leveled height (cm) of the meringue. As described by Vega and Sanghi (2012) foam capacity was then found by the following equation:

\[
\text{Overrun (foam capacity \%) = } \left[ \frac{\text{Final Volume} - \text{Initial Volume}}{\text{Initial Volume}} \right] \times 100
\]

Five replications of this experiment were performed.

Foam Stability

A modified version of Philips et al. (1990) foam stability method was used. Foams were covered with plastic wrap in the 600 mL beaker used to make them. These were then stored at room temperature and liquid drainage was recorded at 30 min, 1 h, and 2 h. The overall loss of liquid was documented at each of these time intervals. This experiment was performed in triplicate.

Rheological Test

Apparent viscosity (Pa*s) was found using the method as described by Psimouli and Oreopoulou (2011). Using a Brookfield viscometer (RVT 115V), three meringues each from the control and experiment groups were analyzed. Immediately after whipping a number six spindle was placed into the center of the meringue batters. Each sample was allowed to sit for 1 min to equilibrate the spring/readout. The spindle guard was not used. Apparent viscosity was then measured by performing a continuous ramp down of the spindle speed (RPM) from 100-0.05 s\(^{-1}\) over a 5 min period. Readings were taken at room temperature (20-24 °C) and measured at each spindle speed after 30 s had passed. A standard Brookfield R.V.T. conversion factor (Brookfield Dial Viscometer Manual Number: M/85-150-P700) which is spindle and speed dependent was used to convert the
readout (in torque) to apparent viscosity. Also, as outlined by Mitschka (1982), the speed (RPM) was converted to shear rate (1/s) and apparent viscosity (Pa*s) was converted to shear stress (Pa*s). These results were plotted on a graph with apparent viscosity (Pa*s) on the y-axis and shear rate (1/s) on the x-axis. Also, for each treatment, a log-log plot of shear stress and shear rate was created.

As described by Mitschka (1982) both flow index (n) and the consistency index (K) were determined by plotting log shear stress versus log shear rate and using the Ostwald de Waale Power equation, $\sigma = K\gamma^n$ where $\sigma$ is shear stress (Pa*s), K is the consistency index, $\gamma$ is the shear rate (1/s), and n is the flow index. The slope of log shear stress and log shear rate is equivalent to flow index (n); the x-intercept is the consistency index (K).

Statistics

The results from all experiments were recorded and an analysis of variance (ANOVA) was performed on each characteristic using the General Linear Model of SAS (2012) Institute, Inc. If significance was found ($P<0.5$) when comparing means, Least Significant Differences were determined using the Tukey test. Results that were statistically different were denoted by different letters (e.g. a, b, c…). Foam capacity, flow index (n), and consistency index (K) were assigned as dependent variables; the treatments (e.g. 25 RA, 50 RA, 75 RA, 100 RA) were assigned as the independent variable.
Results and Discussion

Foam Capacity

Meringues are one of the most basic formulations of foam. Since it consists of only egg whites, sucrose, and an acid, starting with a meringue recipe as an initial experiment allowed for a focused view on the most fundamental ingredients involved in foam formation. It also allowed for an easy introduction of sucrose replacement components and for studying the potential effects that they might have. Currently, very little research is available about the effects of non-nutritive sweeteners on the functionality of meringues and angel food cake.

Out of the non-nutritive sweeteners, acesulfame-K and sucralose are the most heat stable (Mortensen, 2006; Pinheiro, 2005). Because of its recent approval as GRAS (U.S. FDA, 2008), Rebaudioside A has the least amount of research performed. It is because of these factors that sucralose, acesulfame-K, and Rebaudioside A were selected for use in all experiments. The results from meringue experiments specifically were an excellent platform to garner an understanding of how to proceed with more in-depth research where angel food batter and cake were prepared.

As sucrose replacement increased, variation from the control became more evident. In general, as SU and RA concentration increased, foam capacity increased. The opposite was true for AK replacement; it instead produced a decrease in foam capacity as concentration increased. None of these results, though, were significantly different from the control (P>0.5). Specific amounts for foam capacity are located in Table 3. These results were expected since, as Damodaran et al. (2008) expressed, foaming power (or capacity) is mostly affected by protein concentration. In this experiment, the variable was sucrose content not protein concentration. As such, these findings suggest that sucrose replacement treatments had little effect on foam capacity.
Foam Stability

Foam stability is not always directly correlated with foam capacity as each measures a different aspect of foam. For instance, increasing egg white temperature has been shown to improve both foam capacity and stability (Damodaran et al., 2008). On the other hand, sucrose has been shown to decrease foam capacity, but increase foam stability (Lomakina and Míková, 2006). These findings suggest that foam capacity and stability do not always trend the same, and are not always directly correlated with one another. While no significant differences were found for foam capacity, differences were found among foam stability.

When whipped meringues were allowed to sit for 30 min, 1 h, and 2 h with liquid drainage collected at each interval, no liquid was collected for the control, SU, or AK treatments (data not shown). Only RA replacement exhibited drainage. Liquid drainage was quite noticeable beginning at 1 h for both 75 RA and 100 RA replacements. Since the meringues readily flowed for all RA treatments (viscosity seemed to decrease as replacement increased), liquid drainage could not reliably be measured. It is because of the visible viscosity differences amongst treatments and the inability to collect physical evidence that viscoelastic properties were also measured.

Rheological Tests

Since foam drainage did not produce any viable results, viscoelasticity was also used to measure foam stability. Batter viscosity is important since, when viscosity increases, foam stability also increases (Stadelman and Cotterill, 1995). Furthermore, initial foam or batter viscosity determines air incorporation and retention, bubble stability, and generation of convection currents in batter during baking (Martínez-Cervera et al., 2012).

At one time, the Brookfield R.V.T. viscometer used for this experiment had a severe limitation; it could not be used to calculate shear rate and shear stress. As expressed by Walter (1980), “the Brookfield device is very easy to use, but the interpretation of the experimental results in terms of (η, q) data (viscosity functions) is far
from straightforward”. In short, the limitation lies in the fact that the Brookfield viscometer does not provide output for shear stress or shear rate. Instead, the readout is expressed in torque not shear stress, and the ‘speed’ knob (0.5 – 100 1/s) is measured in revolutions per minute (RPM) and not shear rate. Fortunately, the limitation has been identified and overcome. In his article, Mitschka (1982) established a procedure for accurately determining shear rate and shear stress and, therefore, flow index and consistency index from the Brookfield R.V.T. output. When shear stress and shear rate are plotted on a log-log graph, the slope of this line is equivalent to the flow index (n) and the x-intercept is equivalent to the consistency index (K) (Mitschka, 1982). Since this experiment used the Brookfield R.V.T. viscometer, the method established by Mitschka (1982) was used to determine the flow and consistency index.

Also, as indicated by the Brookfield R.V.T. manual, readout values of 10% torque and less are not recommended. This is because of the increasing amount of error exhibited as % torque reaches 0. So that the same spindle could be used for all samples, some values, especially at 0.5 RPM, fell below 10% torque. This error was evident when fitting the values to the Ostwald de Waale Power law. At the lowest, the r-value reduced to 0.80 when 0.5 RPM torque/apparent viscosity values were used; however, the r-value increased to above 0.98 for all treatments when these values were removed. While the Brookfield R.V.T. manual stated that values below 10% torque could be used, it is because of the lower r-value and increase in error, that 0.5 shear rate values were removed from this experiment when determining flow and consistency index.

Figure 4, Figure 5, and Figure 6 illustrate noticeable trends in apparent viscosity for each sucrose replacement. Specifically, as replacement increased for SU and AK treatments, apparent viscosity also increased. Only 100 SU was an exception to the overall trend for SU treatments. These figures also show that apparent viscosity for SU and AK treatments trended higher than sucrose. The log-log graphs of Figure 7 and Figure 8 further galvanize these trends. Here, the plots of log shear rate versus log shear stress for SU and AK treatments all trended higher than the control. This data suggests that, as sucrose replacement increased for SU and AK treatments, foam stability and bubble retention also increased.
SU and AK treatments showed promising results for apparent viscosity, but 100 SU did not follow the general increasing trend for apparent viscosity and log shear stress. This is likely due to PD’s solubility in water. According to the product specifications for Danisco’s Litesse® Powder, 80 g of the powder can be dissolved per 100 mL of water at 20°C. The data in Figure 2 (Roller and Jones, 1996) supports this finding, but such concentration levels have been found to be difficult to obtain (Murray, 1988). The shear rate, shear stress, and method that polydextrose was added to water determined the amount solubilized (Murray 1988). This was likely due to polydextrose's penchant for resisting hydrolysis. Specifically, the cross-linked glucose bonds of polydextrose that are predominantly at the β(1,6) position resist hydrolysis two to four times more than bonds found at α(1,2), α(1,3), and α(1,4) bonds (O'Donnell and Kearsley 2012). While sucrose solubilizes at lower concentration levels than polydextrose, as indicated in Figure 2, the glycosidic bond of sucrose, α(1,2) position, allowed it to more readily dissolve and required fewer mechanical stressors than polydextrose. An increase in water temperature and slow addition of polydextrose to a product have proven to be solutions to this barrier (Murray, 1988).

For this research, in every 100 SU, 100 AK, and 100 RA replacement batches, unincorporated PD clumped together to form hard yellow balls, much like sugar syrup cooked to a hard-ball state, and a few times hit the side wall of the beaker shattering the container. These findings further support that, while PD can overall solubilize at higher concentrations in water than sucrose (Roller and Jones, 1996), extra measures such as increased temperature, increased shear rate, or decreased particle size are required to overcome the stronger β(1,6) bond that is predominantly found in polydextrose. The results for complete replacement then depended on the amount of polydextrose that could be coaxed into meringue batter. This is both not practical for large scale production or for consistent research results.

Further, an interesting dichotomy took place between SU and AK versus RA treatments. As revealed in Figure 6, unlike the SU and AK treatments, RA treatments exhibited a downward trend in apparent viscosity. In fact, all RA treatments had lower apparent viscosity values than the control. The decrease in log shear rate as sucrose replacement increased as shown in Figure 9 further emphasized this difference. Given
that the amount of PD used at each replacement level (25, 50, 75, and 100%) was the same across SU, AK, and RA treatments and that PD has been shown to increase viscosity as concentration increases (Figure 10, Murray, 1988), the divergent trend was unexpected. These results suggest that despite the small amount of non-nutritive sweetener and the bulking properties attributed to PD, RA seemed to be having a detrimental effect on meringue batter’s apparent viscosity. No current research is available to support why this may have occurred; however, later experiments in this research provide consistent findings and more evidence on what could be occurring. Because of this, theories are presented in subsequent chapters.

While useful, apparent viscosity does not provide a single empirical value to compare one treatment to another. As such, because of a high correlation (r>.98) and pseudoplastic (decrease in apparent viscosity as rate of shear increased) behavior, the Ostwald de Waale Power law was used to calculate both flow index (n) and consistency index (K). The results from these calculations may be found in Table 3. For consistency index (K), 50 RA, 75 RA, and 100 RA were significantly lower (P<0.5) than the control. For flow index (n), 50 RA, 75 RA, 100 RA, 75 SU, and 75 AK had significantly higher values (P<0.5) than the control; whereas, all other treatments were not different (P>0.5) from the control. Also, 75 RA and 100 RA had the highest values (P<0.5) for n.

As mentioned previously, batter viscosity has been shown to be directly related to the volume development of batter (Paton et al., 1981). Higher batter viscosity indicates greater bubble incorporation into the product. The decreased K and apparent viscosity values for 50 RA, 75 RA, and 100 RA treatments suggest that less air incorporation took place in these meringue batters. Since flow index values (n) closer to n=1 exhibit a less complex and more Newtonian behavior (Bourne, 2002), the higher n values found for RA further suggest reduced foam stability. Psimouli and Oreopoulou (2011) found a similar correlation when PD was used to completely replace sucrose in cake batter. Both K and n values for 25 SU, 50 SU, 25 AK, and 50 AK were not different (P>0.5) from the control. This suggests that these meringues have similar bubble retention and foam stability properties as the control. While not quite the same as meringue batter, Martínez-Cervera et. al (2012) showed similar K and n indexes in muffin batter that had 25, 50 and 75% of the sucrose replaced with sucralose and polydextrose.
Conclusions

This subset of experiments showed that the lower replacement for SU and AK treatments performed just as well as the sucrose control. Furthermore, as indicated by apparent viscosity and log-log plots, SU and AK treatments at 75% replacement exhibited better air incorporation than the sucrose control. Interestingly, the exact opposite trends occurred with RA treatments. Instead, a decrease in apparent viscosity and K values were experienced. Lastly, unincorporated PD particles were present in all 100% replacement treatments. This is most likely due to the predominant β(1,6) glycosidic bond of PD resisting hydrolysis. Because of this, complete replacement treatments were removed from future experiments. Despite exhibiting decreased bubble incorporation and foam stability, RA treatments were retained for use in later experiments because of the unexpected dichotomy found between it and the other non-nutritive sweeteners.
Table 2: Meringue Ingredients for Control and Polydextrose and Sucralose, Acesulfame-K, or Rebaudioside A Treatment

<table>
<thead>
<tr>
<th>Ingredient (g)</th>
<th>0 (Control)</th>
<th>25**</th>
<th>50**</th>
<th>75**</th>
<th>100**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Egg White</td>
<td>83.500</td>
<td>83.500</td>
<td>83.500</td>
<td>83.500</td>
<td>83.500</td>
</tr>
<tr>
<td>Citric Acid</td>
<td>0.700</td>
<td>0.700</td>
<td>0.700</td>
<td>0.700</td>
<td>0.700</td>
</tr>
<tr>
<td>Sucrose</td>
<td>93.000</td>
<td>69.750</td>
<td>46.500</td>
<td>23.0250</td>
<td>0.000</td>
</tr>
<tr>
<td>SU*</td>
<td>0.000</td>
<td>0.0390</td>
<td>0.0780</td>
<td>0.116</td>
<td>0.155</td>
</tr>
<tr>
<td>PD*</td>
<td>0.000</td>
<td>23.211</td>
<td>46.422</td>
<td>69.634</td>
<td>92.845</td>
</tr>
</tbody>
</table>

This table provides the ingredients and ingredient amounts used for preparing meringue recipes for the control and polydextrose and sucralose, acesulfame-K, or Rebaudioside A treatments. The amount of sweetener used always summed to 93 g, the amount of sucrose found in the control.

*SU, AK, RA, and PD stand for sucralose acesulfame-K, Rebaudioside A and polydextrose, respectively.

*0, 25, 50, 75, and 100 represent the percentage of sucrose replacement.
Table 3: Foam Capacity and Rheological Properties of Egg White Foam and Effects of Sucralose, Acesulfame-K, and Rebaudioside A Replacement for Sucrose

<table>
<thead>
<tr>
<th>Sample</th>
<th>Foam Capacity (%)</th>
<th>Flow Index (n)</th>
<th>Consistency Index (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>515.70&lt;sup&gt;ab&lt;/sup&gt; (48.134)</td>
<td>0.390&lt;sup&gt;c&lt;/sup&gt; (0.019)</td>
<td>3.738&lt;sup&gt;ab&lt;/sup&gt; (0.289)</td>
</tr>
<tr>
<td>25 SU*</td>
<td>467.6&lt;sup&gt;ab&lt;/sup&gt; (61.012)</td>
<td>0.399&lt;sup&gt;de&lt;/sup&gt; (0.006)</td>
<td>3.906&lt;sup&gt;a&lt;/sup&gt; (0.116)</td>
</tr>
<tr>
<td>50 SU*</td>
<td>493.26&lt;sup&gt;ab&lt;/sup&gt; (32.156)</td>
<td>0.414&lt;sup&gt;cde&lt;/sup&gt; (0.016)</td>
<td>3.848&lt;sup&gt;ab&lt;/sup&gt; (0.183)</td>
</tr>
<tr>
<td>75 SU*</td>
<td>509.35&lt;sup&gt;ab&lt;/sup&gt; (31.853)</td>
<td>0.459&lt;sup&gt;abc&lt;/sup&gt; (0.023)</td>
<td>3.423&lt;sup&gt;ab&lt;/sup&gt; (0.243)</td>
</tr>
<tr>
<td>100 SU*</td>
<td>472.44&lt;sup&gt;ab&lt;/sup&gt; (19.506)</td>
<td>0.439&lt;sup&gt;bcdde&lt;/sup&gt; (0.006)</td>
<td>3.708&lt;sup&gt;ab&lt;/sup&gt; (0.147)</td>
</tr>
<tr>
<td>25 AK*</td>
<td>528.25&lt;sup&gt;a&lt;/sup&gt; (37.317)</td>
<td>0.393&lt;sup&gt;e&lt;/sup&gt; (0.013)</td>
<td>3.878&lt;sup&gt;a&lt;/sup&gt; (0.267)</td>
</tr>
<tr>
<td>50 AK*</td>
<td>493.16&lt;sup&gt;ab&lt;/sup&gt; (62.334)</td>
<td>0.429&lt;sup&gt;bcdde&lt;/sup&gt; (0.008)</td>
<td>3.521&lt;sup&gt;ab&lt;/sup&gt; (0.061)</td>
</tr>
<tr>
<td>75 AK*</td>
<td>480.52&lt;sup&gt;ab&lt;/sup&gt; (32.153)</td>
<td>0.456&lt;sup&gt;abcd&lt;/sup&gt; (0.013)</td>
<td>3.308&lt;sup&gt;abc&lt;/sup&gt; (0.206)</td>
</tr>
<tr>
<td>100 AK*</td>
<td>444.89&lt;sup&gt;ab&lt;/sup&gt; (31.909)</td>
<td>0.443&lt;sup&gt;bcdde&lt;/sup&gt; (0.026)</td>
<td>3.542&lt;sup&gt;ab&lt;/sup&gt; (0.383)</td>
</tr>
<tr>
<td>25 RA*</td>
<td>437.39&lt;sup&gt;b&lt;/sup&gt; (42.204)</td>
<td>0.413&lt;sup&gt;cde&lt;/sup&gt; (0.029)</td>
<td>3.199&lt;sup&gt;bc&lt;/sup&gt; (0.357)</td>
</tr>
<tr>
<td>50 RA*</td>
<td>429.60&lt;sup&gt;ab&lt;/sup&gt; (25.123)</td>
<td>0.476&lt;sup&gt;ab&lt;/sup&gt; (0.029)</td>
<td>2.731&lt;sup&gt;bc&lt;/sup&gt; (0.108)</td>
</tr>
<tr>
<td>75 RA*</td>
<td>470.36&lt;sup&gt;ab&lt;/sup&gt; (27.741)</td>
<td>0.511&lt;sup&gt;a&lt;/sup&gt; (0.009)</td>
<td>2.390&lt;sup&gt;d&lt;/sup&gt; (0.053)</td>
</tr>
<tr>
<td>100 RA*</td>
<td>460.13&lt;sup&gt;ab&lt;/sup&gt; (37.524)</td>
<td>0.515&lt;sup&gt;a&lt;/sup&gt; (0.036)</td>
<td>2.391&lt;sup&gt;d&lt;/sup&gt; (0.238)</td>
</tr>
</tbody>
</table>
Table 3 (cont'd): The values in table represent foam capacity, flow index, and consistency index for the control and polydextrose and sucralose, acesulfame-K, or Rebaudioside A sucrose replacements for meringue foam. Flow index and consistency index are determined from the Ostwald de Waale Power Law equation, $\sigma = K\gamma^n$ where $\sigma$ is shear stress (Pa*s), $K$ is the consistency index, $\gamma$ is shear rate (1/s), and $n$ is the flow index. Samples with different letters (a,b,c,d,e) designate a significant difference (P<0.5). Values in parenthesis () represent the standard error of the sample above it.

*SU, AK, and RA stand for sucralose, acesulfame-K, and Rebaudioside A, respectively. 25, 50, 75, and 100 represent the percentage of sucrose replacement.
Figure 4: Apparent Viscosity for Control and Sucralose Replacement Treatments (SU) for Meringue Foam

This graph describes the apparent viscosity (Pa*s) that was measured from 100-0.05 s\(^{-1}\) RPM on a Brookfield R.V.T. viscometer. 25, 50, 75, and 100 represent the percentage of sucrose replacement. Values for torque were converted to shear rate (1/s). Also, the graph’s horizontal axis was “zoomed-in” to a shear rate of 30 1/s for better clarity. Here, in general viscoelasticity increases as sucrose replacement increases.
Figure 5: Apparent Viscosity for Control and Acesulfame-K Replacement Treatments (AK) for Meringue Foam

This graph describes the apparent viscosity (Pa*s) that was measured from 100-0.05 s\(^{-1}\) RPM on a Brookfield R.V.T. viscometer. 25, 50, 75, and 100 represent the percentage of sucrose replacement. Values for torque were converted to shear rate (1/s). Also, the graph’s horizontal axis was “zoomed-in” to a shear rate of 30 1/s for better clarity. Here, viscoelasticity increases as sucrose replacement increases.
Figure 6: Apparent Viscosity for Control and Rebaudioside A Replacement Treatments (RA) for Meringue Foam

This graph describes the apparent viscosity (Pa*s) that was measured from 100-0.05 s\(^{-1}\) RPM on a Brookfield R.V.T. viscometer. 25, 50, 75, and 100 represent the percentage of sucrose replacement. Values for torque were converted to shear rate (1/s). Also, the graph’s horizontal axis was “zoomed-in” to a shear rate of 30 1/s for better clarity. Unlike SU and AK replacement treatments, viscoelasticity decreases as sucrose replacement increases.
Figure 7: Log-Log Plot of Shear Stress and Shear Rate for Control and Sucralose (SU) Replacement for Meringue Foams

Here the log of shear rate and the log of shear stress were plotted creating a straight line for each treatment. 25, 50, 75, and 100 represent the percentage of sucrose replacement. Like apparent viscosity, as sucrose replacement increased for sucralose treatments, log shear stress also increased indicating an increase in foam stability.
Figure 8: Log-Log Plot of Shear Stress and Shear Rate for Control and Acesulfame-K (AK) Replacement for Meringue Foams

Here the log of shear rate and the log of shear stress were plotted creating a straight line for each treatment. 25, 50, 75, and 100 represent the percentage of sucrose replacement. Like apparent viscosity, as sucrose replacement increased for Acesulfame-K treatments, log shear stress also increased indicating an increase in foam stability.
Figure 9: Log-Log Plot of Shear Stress and Shear Rate for Control and Rebaudioside A (RA) Replacement for Meringue Foams

Here the log of shear rate and the log of shear stress were plotted creating a straight line for each treatment. 25, 50, 75, and 100 represent the percentage of sucrose replacement. Unlike sucralose and acesulfame-K replacement, a decrease in log shear stress occurred as sucrose replacement increased for Rebaudioside A treatments indicating a decrease in foam stability.
Figure 10: Concentration/Viscosity Relationship
This graph illustrates that at 25°C polydextrose increases solution viscosity as concentration increases. Further, at all temperature, the viscosity of polydextrose solution is greater than that of the sucrose solution (Murray, 1988).
CHAPTER 3 – ANGEL FOOD CAKE BATTER

Objectives

The second phase of this research involved observing the effects of sucralose (SU), acesulfame-K (AK), and Rebaudioside A (RA) on angel food cake batter. The primary objective was to determine which cake batter treatments were most similar to the control. Because of findings from similar experiments (Martínez-Cervera, et al., 2012 and Lakshminarayan et al., 2006) and findings from Chapter 2, the hypothesis here was that lower sucrose replacement treatments would be similar to the control. This was analyzed through measuring viscoelastic and specific gravity properties among the sucrose replacement treatments (SU, AK, and RA). The results from Chapter 2 indicated that RA treatments should underperform in comparison to SU and AK treatments. Also, because of the findings from Chapter 2, 100% sucrose replacement was not advanced to this subset of experiments.

Materials

Control angel food cake batter was prepared with Grade AA liquid egg whites, sucrose, cream of tartar, salt, and all-purpose flour. Liquid egg whites (Great Value Brand, Bentonville, AZ) were obtained from Wal-Mart Stores Inc. Sucrose (Kroger Granulated Sugar, Cincinnati, OH), cream of tartar (Kroger Private Selection Brand, Cincinnati, OH), salt (Kroger Free Flowing Salt, Cincinnati, OH), and all-purpose flour (Kroger Enriched, Bleached All Purpose Flour, Cincinnati, OH) were obtained from The Kroger Co.

Angel food cake batter with sucrose replacement used the same sucrose, cream of tartar, salt, and all-purpose flour as the control batter, but polydextrose (PD) and SU, AK, and RA were also used. PD (Litesse Powder, New Century, KS, Batch #: 1921906457) was obtained from Danisco USA, SU (Splenda micronized, London, United Kingdom, Lot #: XM2L630701) was obtained from Tate and Lyle PLC, AK (Sunnett particle size
A. Frankfort am Main, Germany, Lot #: 0000608585) was obtained from Nutrinova Nutrition and Food Ingredient Specialists, and RA (Nat Sunwin Stevia Reb-A-80, Erlanger, KY, Lot #: H12102512C) was obtained from Wild Flavor Inc.

**Methods**

**Batter Preparation**

Sucrose control and sucrose replacement treatments with 25, 50, and 75% of the sucrose replaced with a blend of PD and either SU, AK, or RA were prepared. Table 4 provides an example of the ingredient quantities for all treatments. The amount of sucrose used in the control, 53 g, was used to calculate the components for the sucrose replacement. For example, for 25 RA replacement, 13.25 g (.25 X 53 g) of sucrose were replaced with a PD and RA blend. Of these, RA was 0.07 g (13.25 g divided by 200, Rebaudioside A’s comparative sweetness to sucrose, w:w) and PD was 13.18 g (13.25 g less 0.07 g). The amount of sucrose, PD, and non-nutritive sweetener always totaled 53 g for each treatment.

To make the batter, liquid egg whites (g), salt (g), and cream of tartar (g) were mixed at speed 4 for 30 s using a hand mixer (120 V Betty Crocker 4-Speed Hand Mixer Model Number BC-1202K). Sucrose (g) and/or the non-nutritive sweetener (g) and PD (g) were then mixed at speed 2 in four equal installments every 15 s for a total of 1 min. The mixer speed was increased to speed 4 and the batter was whipped for 5 min. Lastly, all-purpose flour (g) was added and whipped at speed 2 in two equal installments every 15 s for a total of 30 s.
Rheological Tests

With only a few modifications, the same test as used in Chapter 2 for meringues was also used for this experiment (Psimouli and Oreopoulou, 2011). Specifically, approximately 65 g of angel food cake batter were placed in a 150 mL beaker and spindle five and no guard attachment were used. Apparent viscosity was then determined by performing a continuous ramp down for RPMs of 100-0.05 s\(^{-1}\) for 5 min. Readings were taken at 30 s intervals for each RPM. These results were plotted with apparent viscosity (Pa*s) on the y-axis and shear rate (1/s) on the x-axis. The flow index and consistency index were found using the Ostwald de Waale Power Law formula, \(\sigma = K\gamma^n\), as described by Mitschka (1982). Also, for each treatment, a log-log plot of shear stress and shear rate was created. Due to potential increased error in data, the values for 0.5 RPM were removed from these results. These experiments were performed in triplicate.

Specific Gravity

As performed by Martínez-Cervera et al. (2012), the specific gravity of each batter was determined. The weight (g) ratio of a standard container filled with batter (flattened at the top of beaker with a spatula) to the same container filled with water was calculated. The standard container for this experiment was a 30 mL beaker. Measurements were taken immediately after creating the angel food cake batter. This experiment was performed in triplicate.

Cross-section Pictures

Pictures of each treatment were taken from the flattened surface of the angel food cake batter. These pictures were taken using a Casio Exilim 5.0 Mega Pixel Digital Camera (model #: EX-Z57) with macro focus, no flash settings, and 0.01 s shutter speed. These pictures were taken just before the specific gravity tests were performed and after the batter had been placed in the 30 mL beaker. All images were cropped to the outside edges of the beaker.
Statistics

The results from all experiments were recorded and an analysis of variance (ANOVA) was performed on each characteristic using the General Linear Model of SAS (2012) Institute, Inc. If significance was found (P<0.5) when comparing means, Least Significant Differences were determined using the Tukey test. Results that were statistically different were denoted by different letters (e.g. a, b, c…). Specific gravity, flow index (n), and consistency index (K) were assigned as dependent variables; the treatments (e.g. 25 RA, 50 RA, 75 RA) were assigned as the independent variable.

Results and Discussion

Rheological Tests

The success or failure of a final baked product has been shown to be directly correlated with batter viscosity. Specifically, air incorporation and retention, bubble stability, and the generation of convection currents in batter during baking are dependent on batter and bulk viscosity evolution during heating (Martínez-Cervera et al., 2012). Higher viscosity values indicate better bubble incorporation; whereas, the opposite is true for lower viscosity values. Because of these facts, rheological properties using a viscometer were calculated for angel food cake batter.

To determine apparent viscosity a Brookfield R.V.T. viscometer with a ramp down between 100-0.05 RPM was used. Figure 11, Figure 12, and Figure 13 show the affects SU, AK, and RA replacement, respectively. For better visual clarity, only shear rates from 0 to 25 1/s were shown. For SU and AK replacements, apparent viscosity increased as sucrose replacement increased. 75 SU and 75 AK exhibited higher viscosity values than the control. These results suggest that 75 SU and 75 AK batters had greater bubble incorporation than the sucrose control. This would further elucidate that the final baked product would provide more volume. This conclusion, as will be discussed in Chapter 4, is incorrect.
Unlike SU and AK treatments, apparent viscosity for RA treatments decreased as sucrose replacement increased. In fact, apparent viscosity values for all RA treatments were lower than the sucrose control. This data suggests that increasing RA replacement resulted in lower bubble holding capacity which would produce an angel food cake with decreased volume. This conclusion was further supported in the final set of experiments for this research. This will be discussed in further detail in Chapter 4.

The conclusions derived from Figure 11, Figure 12, and Figure 13 have an inherent limitation. For pseudoplastic products, apparent viscosity is general and not easily compared since a single empirical point doesn't exist. Fortunately, such values may be derived from other viscoelastic functions. Because of the high correlation (r>.98), the Ostwald de Waale Power Law, was used to determine flow index (n) and consistency index (K) for angel food cake batter. Log-log graphs of log shear stress and log shear rate were also determined.

Figure 14, Figure 15, and Figure 16 show the results for log-log graphs for all treatments. Here, much like with apparent viscosity, a general upward trend was found with SU and AK treatments as sucrose replacement increased. 75% sucrose replacement treatments were significantly (P<0.5) higher than the control. RA treatments trended the exact opposite with a decreasing trend as sucrose replacement increased. Specifically, all replacement treatments were trended lower (P<0.5) than the sucrose control.

As shown in Table 5, all flow values exhibited an n<1 or pseudoplastic behavior. This type of flow is consistent with muffin batter replaced with sucralose and polydextrose (Martínez-Cervera et al., 2012) and the meringue batter experiments in Chapter 2. For flow index (n), 75 SU and 75 AK were not significantly different from the control (P>0.5). Martínez-Cervera et al. (2012) also found no statistical difference with 75% sucrose replacement treatments when sucralose and polydextrose were used in muffin batter. These researchers did experience an upward trend with flow index; whereas, the results of this experiment exhibited a downward trend. This could be due to the different ingredients used in angel food cake versus muffins. RA sucrose replacement treatments, exhibited the exact opposite behavior. These treatments had an increasing n value which indicates a simpler, more Newtonian (n=1) structure. In fact, 50 RA and 75 RA had values that were higher (P<0.5) than the control and all other treatments. Since
RA is still relatively new to the market, no current research is available to show a point of comparison.

As for consistency index (K), these values followed the same trends as apparent viscosity. The consistency index (K) increased with SU and AK treatments as sucrose replacement increased. Like the flow index, the consistency index (K) for 75 SU and 75 AK were not significantly different (P>0.5) from the control. Martínez-Cervera et al. (2012) found similar results in 75% replacement of sucralose and polydextrose in muffins. Since higher apparent viscosity and consistency index values indicate better foam stability (Stadelman and Cotterill, 1995), this would suggest that 75 SU and 75 AK have similar stability properties to the control. As will be shown in the discussion of Chapter 4, this conclusion is not complete. Alternately, RA replacements performed worse than both the control and other treatments. In fact, RA replacements had the lowest K values (P<0.5) with 75 RA performing the worst (P<0.5). This data indicated that increasing RA replacement decreased foam stability.

**Specific Gravity**

Much like apparent viscosity and consistency index (K), specific gravity is also an indicator of air incorporation with lower values indicating greater bubble intake (Frye and Setser, 1991). As shown in Table 5, only 75 AK had a higher specific gravity than the control for SU and AK treatments. This difference, while significant, in practical terms is still quite small. All other SU and AK replacements were no different (P>0.5) from the sucrose control. In alternative research, a decrease in specific gravity was found in muffin batter with sucralose and polydextrose replacement (Martínez-Cervera et al., 2012). While a different trend was found, muffin batter relies on other factors besides foam formation for lift and may not be practical to compare these products to angel food cake batter. Also, even though significance was found for 75 AK, in practical terms this difference was quite small. Lastly, for RA treatments, unlike SU and AK treatments, these produced the highest values for specific gravity (P<0.5). This again suggests that RA replacement produced the worst bubble incorporation and foam stability.
Cross-section Pictures

Figure 17, Figure 18, and Figure 19 illustrate cross-sectional pictures of each batter at 0 min. Very little difference in bubble evolution was noticeable with SU and AK treatments and the sucrose control. For RA replacement, an evident increase in bubble evolution took place as sucrose replacement increased. This further supports the results found with specific gravity, flow index, and consistency index.

Results from other research helped provide perspective. In similar research, smaller, more evenly distributed bubbles produced baked goods that had substantial lift during the initial stages of baking, but this lift didn't compromise overall cake integrity (Martínez-Cervera et al., 2012; Kocer et al., 2007; Pateras et al., 1994). Alternately, Pateras et al. (1994) reported that increasing sucrose replacement with PD produced cake batters with increasing mean air-bubble size and widening air-bubble distribution. The larger bubbles coalesced and then escaped from the batter during baking. The increase in air-bubble size and distribution prevented the usual mechanism of protein coagulation and starch gelatinization to entrap bubbles successfully (Pateras et al, 1994). As a result, an increase in PD replacement resulted in a decrease in cake functional properties (Pateras et al., 1994).

As Figure 19 clearly shows, increasing amounts of RA created angel cake batters with larger bubbles. As with Pateras’ experiments, these bubbles are likely to coalesce, escape from the batter before thermosetting, and produce angel food cakes of inferior quality. Interestingly, even though all sucrose replacement cakes contained the same amount of polydextrose at each replacement level (25, 50, and 75%), SU and AK treatments differed from RA treatments in relation to the amount of visible bubbles created.

A final explanation for the differences found between treatments could be the affects that the non-nutritive sweeteners could have on the surface tension of the bubble surface. For SU, previous research has shown that a 1% (w:w) sucralose and water solution had a surface tension (mN m⁻¹) value of 66.3, and that a 10% sucrose (w:w) and water solution had a surface tension (mN m⁻¹) value of 74.0 (Mathlouthi and Hutteau, 1999). This reduction in surface tension could encourage egg white protein denaturation.
and formation at the bubble surface for SU samples. For AK, several metal cations such as Cu$^{+2}$ and Zn$^{+2}$ have been shown to increase the stability of ovotransferrin (Bovsková and Miková, 2011), a egg white globulin that interacts at the air-water interface of foams. Here, the positive cation found in acesulfame-K, potassium, could be reacting similarly with ovotransferrin resulting in the more stable AK batter treatments. For RA, no unique molecules exist; however, it is a much larger molecule with a molecular weight of 967.1 g/mol versus SU at 397.63 g/mol, AK at 201.24 g/mol, and sucrose at 342.30 g/mol (Sigma-Aldrich, 2014). The larger size RA could be producing an inhibitory effect on protein denaturation and successful foam formation. Further investigation focused primarily on surface activity would need to be performed to substantiate these theories.
Conclusions

The findings from the meringue experiments paved the way for angel food cake batter experiments. Specifically, the results from Chapter 2 showed that lower SU and AK replacement performed similar to the control, all RA sucrose replacements performed worse than the control, and complete sucrose replacement with non-nutritive sweeteners was not practical. The results for angel food cake batter further galvanized these previous findings.

Most notable is that 75 SU and 75 AK did not significantly differ from the control for flow index (n) and consistency index (K) indicating good bubble incorporation. Apparent viscosity and cross-sectional pictures for SU and AK treatments further supported these results. Even so, as will be discussed in Chapter 4, increased bubble incorporation does not alone ensure improved final baked products. Because of this, while lower SU and AK sucrose replacement treatments seemed to have decreased functional properties when compared to the control, the results of Chapter 4 helped illustrate that apparent viscosity, flow index, and consistency index do not always provide a complete picture.

Lastly, again RA treatments performed worst. To be precise, specific gravity was higher, consistency index was lower, flow index was higher, and apparent viscosity was lower. RA treatments showed decreased functionality and bubble incorporation even though the amount of polydextrose in each treatment was the same as SU and AK sucrose replacement treatments at each given replacement level (25, 50, and 75%). The only difference between these treatments was the type of non-nutritive sweetener. These findings indicated that RA had a detrimental effect on air incorporation of angel food cake batter.
Table 4: Angel Food Batter for Control and Polydextrose and Sucralose, Acesulfame-K, or Rebaudioside A Sucrose Replacement Treatments

<table>
<thead>
<tr>
<th>Ingredient (g)</th>
<th>Control</th>
<th>25**</th>
<th>50**</th>
<th>75**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Egg White</td>
<td>50.00</td>
<td>50.00</td>
<td>50.00</td>
<td>50.00</td>
</tr>
<tr>
<td>Sucrose</td>
<td>53.00</td>
<td>39.75</td>
<td>26.50</td>
<td>13.25</td>
</tr>
<tr>
<td>SU*</td>
<td>0.000</td>
<td>0.007</td>
<td>0.015</td>
<td>0.022</td>
</tr>
<tr>
<td>PD*</td>
<td>0.000</td>
<td>13.248</td>
<td>26.456</td>
<td>39.684</td>
</tr>
<tr>
<td>AP Flour</td>
<td>18.00</td>
<td>18.00</td>
<td>18.00</td>
<td>18.00</td>
</tr>
<tr>
<td>Salt (sodium chloride)</td>
<td>0.200</td>
<td>0.200</td>
<td>0.200</td>
<td>0.200</td>
</tr>
<tr>
<td>Cream of Tartar</td>
<td>0.050</td>
<td>0.050</td>
<td>0.005</td>
<td>0.050</td>
</tr>
</tbody>
</table>

The data presented in this table represents the ingredients and amount of each used for both the control and polydextrose and either sucralose, acesulfame-K, or Rebaudioside A sucrose replacement treatments for angel food cake batter. The amount of sweetener used always summed to 53 g, the amount of sucrose found in the control.

*SU, AK, RA and PD stand for sucralose, acesulfame-K, Rebaudioside A and polydextrose, respectively.

**25, 50, and 75% represent the percentage of replacement.
Table 5: Rheological Measurements of Angel Food Cake Batter Based on the Effects of Polydextrose and Sucralose, Acesulfame-K, or Rebaudioside A Sucrose Replacement

<table>
<thead>
<tr>
<th>Sample</th>
<th>Specific Gravity</th>
<th>Flow Index (n)</th>
<th>Consistency Index (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.560&lt;sup&gt;f&lt;/sup&gt; (0.002)</td>
<td>0.587&lt;sup&gt;e&lt;/sup&gt; (0.003)</td>
<td>1.883&lt;sup&gt;a&lt;/sup&gt; (0.016)</td>
</tr>
<tr>
<td>25 SU*</td>
<td>0.577&lt;sup&gt;ef&lt;/sup&gt; (0.009)</td>
<td>0.647&lt;sup&gt;c&lt;/sup&gt; (0.017)</td>
<td>1.584&lt;sup&gt;b&lt;/sup&gt; (0.061)</td>
</tr>
<tr>
<td>50 SU*</td>
<td>0.586&lt;sup&gt;def&lt;/sup&gt; (0.010)</td>
<td>0.634&lt;sup&gt;c&lt;/sup&gt; (0.017)</td>
<td>1.692&lt;sup&gt;b&lt;/sup&gt; (0.071)</td>
</tr>
<tr>
<td>75 SU*</td>
<td>0.601&lt;sup&gt;de&lt;/sup&gt; (0.015)</td>
<td>0.592&lt;sup&gt;c&lt;/sup&gt; (0.016)</td>
<td>1.931&lt;sup&gt;a&lt;/sup&gt; (0.087)</td>
</tr>
<tr>
<td>25 AK*</td>
<td>0.575&lt;sup&gt;ef&lt;/sup&gt; (0.013)</td>
<td>0.635&lt;sup&gt;c&lt;/sup&gt; (0.004)</td>
<td>1.613&lt;sup&gt;b&lt;/sup&gt; (0.039)</td>
</tr>
<tr>
<td>50 AK*</td>
<td>0.602&lt;sup&gt;de&lt;/sup&gt; (0.009)</td>
<td>0.628&lt;sup&gt;cd&lt;/sup&gt; (0.010)</td>
<td>1.660&lt;sup&gt;b&lt;/sup&gt; (0.089)</td>
</tr>
<tr>
<td>75 AK*</td>
<td>0.609&lt;sup&gt;d&lt;/sup&gt; (0.013)</td>
<td>0.595&lt;sup&gt;de&lt;/sup&gt; (0.011)</td>
<td>1.928&lt;sup&gt;a&lt;/sup&gt; (0.065)</td>
</tr>
<tr>
<td>25 RA*</td>
<td>0.642&lt;sup&gt;c&lt;/sup&gt; (0.010)</td>
<td>0.663&lt;sup&gt;c&lt;/sup&gt; (0.013)</td>
<td>1.406&lt;sup&gt;c&lt;/sup&gt; (0.034)</td>
</tr>
<tr>
<td>50 RA*</td>
<td>0.690&lt;sup&gt;b&lt;/sup&gt; (0.012)</td>
<td>0.703&lt;sup&gt;b&lt;/sup&gt; (0.012)</td>
<td>1.172&lt;sup&gt;d&lt;/sup&gt; (0.064)</td>
</tr>
<tr>
<td>75 RA*</td>
<td>0.721&lt;sup&gt;a&lt;/sup&gt; (0.004)</td>
<td>0.770&lt;sup&gt;a&lt;/sup&gt; (0.010)</td>
<td>0.919&lt;sup&gt;e&lt;/sup&gt; (0.037)</td>
</tr>
</tbody>
</table>
Table 5 (cont'd): The values in this graph represent specific gravity, flow index, and consistency index for the control and polydextrose and either sucralose, acesulfame-K, or Rebaudioside A sucrose replacement treatments for angel food cake batter. Specific gravity provides an indicator for the total air holding capacity of a product. This was determined by the weight (g) ratio of a standard container filled with batter (flattened at the top of beaker with a spatula) to the same container filled with water. Low values suggest increased bubble holding capacity and foam stability. Flow (n) and consistency (K) index are empirical values that exhibit the level and Newtonian-ness and foam stability, respectively. These values were derived from plotting log shear stress (Pa*s) and log shear rate (1/s) and using the Ostwald de Waale Power Law, $\sigma = K\gamma^n$ where $\sigma$ is shear stress (Pa*s), $k$ is the consistency index, $\gamma$ is the shear rate (1/s), and $n$ is the flow index. Values in parenthesis () represent the standard error of the sample above it. Samples with different letters (a,b,c,d,e,f) designate a significant difference ($P<0.5$).

*SU, AK, and RA stand for sucralose, acesulfame-K, and Rebaudioside A, respectively. 25, 50, and 75 represent the percentage of sucrose replacement.
Figure 11: Apparent Viscosity for Control and Sucralose Replacement Treatments (SU) for Angel Food Cake Batter

This graph describes the apparent viscosity (Pa*s) that was measured from 100-0.05 s⁻¹ RPM on a Brookfield R.V.T. viscometer. Values for torque were converted to shear rate (1/s). Also, the graph’s horizontal axis was “zoomed-in” to a shear rate of 25 1/s so that it would be easier to see the differences between the treatments. As the graph shows, as sucrose replacement increases, apparent viscosity also increases. Only 75 SU exhibited a higher value than the control.
Figure 12: Apparent Viscosity for Control and Acesulfame-K Replacement Treatments (AK) for Angel Food Cake Batter

This graph describes the apparent viscosity (Pa*s) that was measured from 100-0.05 s\(^{-1}\) RPM on a Brookfield R.V.T. viscometer. Values for torque were converted to shear rate (1/s). Also, the graph’s horizontal axis was “zoomed-in” to a shear rate of 25 1/s so that it would be easier to see the differences between the treatments. As the graph shows, as sucrose replacement increases, apparent viscosity also increases. Only 75 AK exhibited a higher value than the control.
Figure 13: Apparent Viscosity for Control and Rebaudioside A Replacement Treatments (RA) for Angel Food Cake Batter

This graph describes the apparent viscosity (Pa*s) that was measured from 100-0.05 s\(^{-1}\) RPM on a Brookfield R.V.T. viscometer. Values for torque were converted to shear rate (1/s). Also, the graph’s horizontal axis was “zoomed-in” to a shear rate of 25 1/s so that it would be easier to see the differences between the treatments. As this graph illustrates, all RA treatments exhibited a lower apparent viscosity than the control. In fact, a decreasing trend for apparent viscosity occurred as the amount of RA increased. This is the exact opposite trend when compared to SU and AK treatments.
Figure 14: Log-Log Plot of Shear Stress and Shear Rate for Control and Sucralose (SU) Replacement for Angel Food Cake Batter

Here the log of shear rate and the log of shear stress were plotted creating a straight line for each treatment. 25, 50, and 75 represent the percentage of sucrose replacement. Log shear rate 0.5 RPM were removed due to increased error of data. Like apparent viscosity, as sucrose replacement increased for sucralose treatments, log shear stress also increased indicating an increase in foam stability. Only 75 SU trended higher than the control.
Figure 15: Log-Log Plot of Shear Stress and Shear Rate for Control and Acesulfame-K (AK) Replacement for Angel Food Cake Batter

Here the log of shear rate and the log of shear stress were plotted creating a straight line for each treatment. 25, 50, and 75 represent the percentage of sucrose replacement. Log shear rate of 0.5 RPM were removed due to increased error of data. Like apparent viscosity, as sucrose replacement increased for acesulfame-K treatments, log shear stress also increased indicating an increase in foam stability. Only 75 AK trended higher than the control.
Figure 16: Log-Log Plot of Shear Stress and Shear Rate for Control and Rebaudioside A (RA) Replacement for Angel Food Cake Batter

Here the log of shear rate and the log of shear stress were plotted creating a straight line for each treatment. 25, 50, and 75 represent the percentage of sucrose replacement. Log shear rate of 0.5 RPM were removed due to increased error of data. Unlike sucralose and acesulfame-K replacement, a decrease in log shear stress occurred as sucrose replacement increased for Rebaudioside A treatments indicating a decrease in foam stability. Further, all RA treatments trended lower than the sucrose control.
<table>
<thead>
<tr>
<th>Treatment</th>
<th>0 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td><img src="image1" alt="Control Image" /></td>
</tr>
<tr>
<td>25 SU</td>
<td><img src="image2" alt="25 SU Image" /></td>
</tr>
<tr>
<td>50 SU</td>
<td><img src="image3" alt="50 SU Image" /></td>
</tr>
<tr>
<td>75 SU</td>
<td><img src="image4" alt="75 SU Image" /></td>
</tr>
</tbody>
</table>
Figure 17: Cross-sectional View of Control and Sucralose (SU) Treatments for Angel Food Cake Batter

The pictures in this table show that there was little to no visible difference in bubble evolution between the control and SU treatments. Pictures were taken at 0 min after the batter had been prepared.
<table>
<thead>
<tr>
<th>Treatment</th>
<th>0 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td><img src="image" alt="Control" /></td>
</tr>
<tr>
<td>25 AK</td>
<td><img src="image" alt="25 AK" /></td>
</tr>
<tr>
<td>50 AK</td>
<td><img src="image" alt="50 AK" /></td>
</tr>
<tr>
<td>75 AK</td>
<td><img src="image" alt="75 AK" /></td>
</tr>
</tbody>
</table>
Figure 18: Cross-sectional View of Control and Acesulfame-K (AK) Treatments for Angel Food Cake Batter
The pictures in this table show that there was little to no visible difference in bubble evolution between the control and AK treatments. Pictures were taken at 0 min after the batter had been prepared.
<table>
<thead>
<tr>
<th>Treatment</th>
<th>0 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>25 RA</td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>50 RA</td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>75 RA</td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Figure 19: Cross-sectional View of Control and Rebaudioside A (RA) Treatments for Angel Food Cake Batter

Unlike SU and AK treatments, there was quite a visible increase in the amount of bubbles formed at the surface of angel food cake batter as the amount of RA increased. This suggests that RA treatments produced less stable foam than the control, SU and AK treatments. Pictures were taken at 0 min after the batter had been prepared.
CHAPTER 4 – ANGEL FOOD CAKE PHYSICAL MEASUREMENTS AND CONCLUSIONS

Objectives

While rheological measures provide evidence of what would likely occur to a product when baked, it is the final product that gives proof of what actual variables are affecting the baking process. For instance, in their experiments Psimouli and Oreopoulou (2011) found that fructose cakes had a low specific gravity and high consistency index, but the final baked product had the lowest specific volume of all treatments. It is because of this, that the last set of experiments in this research focused on measuring physical characteristics of baked angel food cake. Specifically, crust and crumb color, cake height, weight loss, moisture content, and texture analysis were performed. Because of previous results in this research, the primary objective was to test the hypothesis that higher sucralose (SU) and acesulfame-K (AK) replacement would perform no different from the control. The second hypothesis was that a difference between sucralose (SU) and acesulfame-K (AK) sucrose replacement treatments and Rebaudioside A (RA) sucrose replacement treatments would exist in baked angel food cakes.

Materials and Methods

Materials

The same materials as used for angel food cake batter were also used for baked angel food cake. Chapter 3 indicates where each ingredient was obtained and the lot numbers associated with that ingredient.
Angel Food Cake Preparation

The same method as described in angel food cake batter preparation of Chapter 3 was used. Each recipe was doubled and prepared twice so that there were a total of four cakes per treatment. Approximately 90 g of batter for each cake were placed into a 2X8 cm angel food cake pan. Cakes were baked at 218°C for 12 min. All cakes were allowed to cool for 1 h. Afterwards, cakes were stored in air tight Ziploc™ bags for 24 h before physical characteristics were measured.

Top-Focused and Vertical Pictures

Using a Casio Exilim 5.0 Mega Pixel Digital Camera (model #: EX-Z57) with macro focus, no flash settings, and 0.01 s shutter speed, pictures were taken of both the top and vertical side of each cake approximately 30.48 cm from the cakes. All images were cropped to the outside edges of the cake.

Weight Loss

Before baking, the initial weight ($W_i$) in grams for each formulation was recorded. After baking and the 24 h resting period, the final weight ($W_f$) in g was measured. Total weight loss (%) was calculated by using the following formula:

\[
\% \text{ Weight Loss} = \frac{(W_i - W_f)}{W_i} \times 100
\]

Angel Food Cake Height

The final height for each formulation was also determined. Cakes were measured from the base to its highest point in cm as performed by Martínez-Cervera (2012).
Angel Food Cake Crust and Crumb Color

Here, a HunterLabScanXE colorimeter with illuminant A, 10° standard observer, and 2.54 diameter aperture were used. For each cake, ten readings for both crust color and crumb color were taken, and L* (lightness), a* (redness), and b* (yellowness) were recorded. These readings were then averaged for a total of four replicate values for crust and crumb color for each treatment. Lastly, as performed by Martínez-Cervera (2012), the total color difference between the control and each treatment was calculated. This was calculated using the formula:

\[ \Delta E^* = \left( (\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2 \right)^{1/2} \]

where \( \Delta E^* \) is the overall change in color from the control.

Cross-section and Longitudinal Pictures

Using a HP flatbed scanner (HP 5100 series), scans of the internal pore structure of each baked angel food cake were performed. Scans were specifically taken of both cross-sectional and longitudinal internal structures for each cake formulation.

Moisture Content

The AOAC (2000) method 925.10, 11 for drying ground flour samples was followed for determining moisture content (%). Specifically, four approximately 3 g samples from each treatment were dried for 1 h at 130°C using an Isotemp Oven (Fisher Scientific). Samples were then allowed to cool in a desiccator for 10 min prior to reweighing. Lastly, moisture content was determined by the following formula:

\[ \% \text{ Moisture Content} = \frac{(W_i - W_f)}{W_i} \times 100 \]

Where \( W_i \) was the initial weight (in g) of the angel food cake and in \( W_f \) was the final weight (in g) of the dried samples.
Texture Profile Analysis

Specifically, as described by Xiong (1999) and Martínez-Cervera et al. (2012), 2 cm³ cake samples were compressed between two parallel plates to 40% of the original height. To do this an Instron compression machine (Instron Corp., Canton, MA) with a 10 N load cell capacity, a cross-head speed 50 mm/min, and two cycles were used. Three cakes from each formulation were used. The maximum force (N) of the first peak (Hardness A) and maximum force (N) of the second peak (Hardness B) were both calculated. Deformability (%), the percent reduction in resilient force between the first and second peak, was also determined. This was calculated by ((Hardness A-Hardness B)/Hardness A) x 100. Lastly, cohesiveness was calculated using Bourne’s (1978) method which is dividing the squared peak height of the second peak by the squared peak height of the first peak. Figure 20 (Bourne, 2002) illustrates an example of the graphical output for a TPA (texture profile analysis) double compression test.

Statistics

The results from all experiments were recorded and an analysis of variance (ANOVA) was performed on each characteristic using the General Linear Model of SAS (2012) Institute, Inc. If significance was found (P<0.5) when comparing means, Least Significant Differences were determined using the Tukey test. Results that were statistically different were denoted by different letters (e.g. a, b, c…). Weight loss, cake height, crust color (L*, a*, and b*), crumb color (L*, a*, and b*), and moisture content were assigned as dependent variables; the treatments (e.g. 25 SU, 50 SU, and 75 SU) were assigned as the independent variable.
Results and Discussion

Weight Loss and Moisture Content

Both weight loss (%) and moisture content (%) were calculated for all samples. Sucrose replacement did not appear to have any effect on angel food cake weight loss. All samples were not different (P>0.5) from the control. The addition of polydextrose and SU, AK, or RA did not appear to have any effect on product loss.

As sucrose replacement increased, moisture retention decreased. Compared to the control, all replacement treatments had lower or equivalent moisture content. 25 SU, 25 AK, 50 RA, and 75 RA exhibited no difference (P>0.5) from the control; whereas, 25 RA, 50 SU, 75 SU, 50 AK, and 75 AK had significantly lower (P<0.5) moisture content values than the control. Values for both weight loss (%) and moisture content (%) may be found in Table 6.

Cake Height and Pore Structure

Cake height and pore structure showed the true tale of why rheological properties, while useful, are not the only indicator for final baked quality. As sucrose replacement increased for SU and AK treatments, a general downward trend in cake height occurred. In fact, as shown in Table 6, 75 SU and 75 AK angel food cakes were significantly shorter (P<0.5) than the control. The pictures in Figure 21 and Figure 22 also show a decreased cake height as sucrose replacement increased.

These results would seem to conflict with the findings found for angel food cake batter. The internal pore structure of baked angel food cakes provides explanation. As indicated by Figure 24, Figure 25, and Figure 26, increased sucrose replacement for SU and AK treatments resulted in increased prevalence of large air cells. Even though each cake was completely baked (toothpicks were clean after insertion into baked cake), 75 SU and 75 AK were gummy and appeared to produce cakes that were more dense at the bottom and less dense at the top. Furthermore, when these same samples first came out
of the oven, they were about twice as tall as sucrose cakes, but, as they cooled the structure quickly collapsed (Figure 24 and Figure 25).

Since the evidence from Chapter 3 showed an increase in apparent viscosity, an increase in consistency index (K), and a decrease in flow index (n) for 75 SU and 75 AK batters, why weren’t these cakes equally superior in baked form? The work from Pateras et al. (1994) provides a possible explanation. As this study indicated, increasing polydextrose content in cakes produced cake batter with greater mean air-bubble size and greater air-bubble size distribution (Pateras et al., 1994). Larger air bubbles have a tendency to coalesce with one another and to escape from the cake batter before protein coagulation and starch gelatinization occur during the baking process. As a result, cakes with higher polydextrose content collapsed after baking and cooling (Pateras et al., 1994). Conversely, Pateras et al. (1994) found that cake batters with smaller bubbles and a more even size distribution produced a finer texture in the final baked cake. These cakes, sucrose or lower polydextrose replacement, had structures which allowed bubbles to expand in more uniform manner which resulted in cakes that maintained their structure (Pateras et al. 1994).

As supported by apparent viscosity values in Figure 11 and Figure 12, more bubbles were entrapped in higher SU and AK sucrose replacement cakes. Following the logic presented by Pateras et al. (1994) and the evidence of a slight increase in larger air cells in SU and AK sucrose replacement in Figure 24 and Figure 25, the bubbles in these treatments could have also increased in size and distribution as sucrose replacement increased. If so, at the higher sucrose replacement levels the large air cells were able to support the cake structure while the gasses were hot; however, as cooling began, the gasses continued to diffuse out of the cakes. These gasses then began to contract as temperature decreased, but the structure was so fragile that it collapsed on itself. This would help explain why, in some cases, higher SU and AK sucrose replacement cakes fell to 1/3 of their original height. Increasing levels of sucrose replacement also caused reduced quality of baked goods with sucralose and polydextrose replacement in muffins (Martínez-Cervera et al., 2012), polydextrose replacement in high ratio cake (Kocer et al., 2007), and maltodextrin and emulsifiers replacement in cakes (Lakshminarayan et al., 2006).
While having the worst batter apparent viscosity and rheological properties, RA treatments did not exhibit the same baked cake trends as SU and AK treatments. The cake height for all RA replacements was no different than the control (P>0.5). Furthermore, as shown in Figure 23 and Figure 26, final baked cakes were not as detrimentally affected by increasing sucrose replacement. In fact, the final baked angel food cake structure of 50 RA and 75 RA did not collapse.

Two potential theories help support why this could have occurred. The first is that polydextrose has been found to increase the thermosetting temperature of carbohydrates (Pateras et al., 1992). As such, as polydextrose increases, cake functionality decreases due to reduced carbohydrate support. The results from SU and AK replacement were then most likely due to the addition of polydextrose and not the non-nutritive sweeteners. This theory still fails to explain the cake height for RA treatments.

The second theory is that SU and AK had a greater impact than RA treatments on surface tension and air bubble formation; however, the larger bubbles were not sufficiently stable to go through the baking process. This caused the baked product for SU and AK treatments to collapse upon cooling. Alternately, despite the fact that apparent viscosity was reduced and larger bubbles were produced (Figure 13), RA may somehow enhance the protein layer found around the few bubbles that were retained in the batter. While the larger air cells likely escaped during baking, the few remaining bubbles became entrapped and allowed these cakes to maintain their structure after baking and cooling. The protein film formed at the air-water interface of a foam is the result of many chemical interactions some of which include hydrogen bonding and hydrophobic interactions. As Figure 1 shows, RA is a much larger molecule with more hydroxyl groups. These hydroxyl groups could be forming bonds with the egg white proteins or one another at the air-water interface leading to an enhanced protein film. Because RA is such a relatively new product there is no current research available to support these theories. Further investigations would need to be made to determine the exact mechanism at work. While RA cakes did not collapse, it important to note that the resulting products may still not be acceptable to consumers. The final two discussions will describe the reasons for this in greater detail.
Crumb, Crust, and Overall Color Variation

Overall, the interior of an angel food cake is known for its pristine whiteness. Polydextrose, which is the bulk of what replaced sucrose in replacement treatments, has slight yellow and darker hue. As such, variation did occur for both crust and crumb color. The values for these results may be found in Table 6.

For angel food cake crust, all treatments were darker (P<0.5) than the control. With the exception of 75 RA which had the lowest L*-value for crust color (P<0.5), no significant difference was noticeable (P>0.5) among the sucrose replacement treatments. For crust b*-value, or degree of yellowness, in almost all treatments no significant hue difference (P>0.5) was detected when compared to the sucrose control. Lastly, for crust ∆E, or overall color difference from the control, all sucrose replacement treatments were 3 units or higher. As such, the human eye should be able to detect a difference between the replacement versus control cakes.

While an overall difference was detected for crust ∆E, it is worth noting that this difference may not actually be undesirable. Most of the overall color variation is found in the L*-value. Consumers may actually find the darker and browner crust to be more desirable. Performing sensory analysis would help provide clarity to this theory. Overall, the lower L*-values in the sucrose replacement experiments were expected since polydextrose has more carbonyls that can react with egg white protein amines which would enhance the Maillard Reaction. Similar results were found by other researchers (Martínez-Cervera et al., 2012; Kocer, 2007).

For crumb color, again, all sucrose replacement treatments had significantly lower L*-values (P<0.5) than the control with 50 RA and 75 RA being the lowest (P<0.5). A definitive yellow hue existed with all sucrose replacement treatments. 50 RA and 75 RA had the highest b*-value, but this difference was not always significantly higher than other sucrose replacement treatments. As for overall color difference, crumb ∆E, all sucrose replacements were 3 units or higher. Because of this, the human eye should be able to discern a difference from these and the control. The reason for lower L*-values and higher b*-values in SU, AK, and RA treatments is the same as those with the angel
food cake crust. These findings are consistent with muffins replaced with SU and polydextrose (Martínez-Cervera et al., 2012). Again, sensory evaluation would assist in understanding how these differences would actually be perceived by consumers.

**Texture Profile Analysis**

For this experiment, 75 SU and 75 AK angel food cake samples could not be used. These products were so gummy that they were rendered unreliable to use during Texture Profile Analysis. As such, these values were omitted. All TPA findings may be found in Table 7.

Generally speaking, most sucrose replacement samples were comparable to the control. An upward trend in hardness values (N) was experienced as sucrose replacement increased, but only 50 RA and 75 RA produced values that were significantly greater (P<0.5) than the control in both the first and second ‘chew.’ As for cohesiveness and deformability, a slight decrease was experienced with the former and slight increase was experienced with the latter for sucrose replacement samples, but none of these values were significantly different (P>0.5) from the control. The inverse relationship between cohesiveness and deformability are logical since cohesiveness is a measure of force reduction from the first to the second curve and deformability is the measure of the % of change between the two curves. Hardness results have differed for other similar experiments. Psimouli and Oreopoulou (2011) did not find any statistical difference between polydextrose replacement and sucrose high ratio cakes; Martínez-Cervera et al. (2012) found that, after exceeding 25% replacement, lower hardness values were found with polydextrose and sucralose replacement muffins; and, lastly, Ronda et al. (2005) found that firmness decreased for sponge cakes that used polydextrose. The varying results found amongst researchers could be due to different products or even the different recipes that were used.

Once again, TPA results for SU and AK treatments differed from RA treatments. In previous discussion, it was hypothesized that RA may have a positive effect on protein sorption at the air-water interface; however, an alternative explanation could exist. When baking, to set a successful product, the outward pressure from bubble expansion cannot
exceed the rate of the protein coagulation and starch gelatinization (Pateras et al., 1994). If the bubble pressure is too great, then bubbles coalesce and escape the product before a strong matrix forms. The resultant baked product either deflates or has reduced volume. Pateras et al. (1992) discovered that increasing polydextrose replacement also increased starch gelatinization setting temperatures. Because protein coagulation and starch gelatinization usually occur around the same time, the delayed onset of starch gelatinization caused decreased volume in polydextrose samples due to an unstable structure in which bubbles could not be entrapped (Pateras et al., 1992). This concept is consistent with what occurred for 75 SU and 75 AK.

In this research, the amount of polydextrose was equivalent at each replacement level. Based on Pateras' (1992) findings, all sucrose replacement cakes in this research should have had similar trends for hardness and cake height. As has been consistently shown through batter rheology, batter apparent viscosity, cake height, and cake hardness, SU and AK treatments exhibited different trends than RA treatments. Alternative research (Pateras, 1992) suggests that this should not have occurred. As discussed previously, RA could be affecting the protein layer formed around the few bubbles that were integrated during whipping. While this protein structure would promote less bubble coalescence and diffusion during baking, RA treatments simply had fewer bubbles than SU and AK treatments that were introduced into the batter. The lower apparent viscosity values of RA treatment from Chapter 3 support this logic. While height and overall structure were maintained, too few bubbles existed to create enough lift for a soft end product. Instead, increasing RA concentration decreased the amount of bubbles incorporated into the batter and subsequently produced a denser product. Since no research has yet been performed with angel food cakes and very few have been performed with other aerated confections and RA (Zahn et al., 2013), more research is required to determine where the actual truth lies.
Conclusions

From a final baked good stand-point, higher replacement values were not acceptable. The enhanced viscoelastic properties that were found in the angel food cake batter experiments were off-set by the deleterious effects of polydextrose on starch gelatinization onset temperatures. The expanded structure of these cakes simply was not able to set and resulted in collapsed products. Furthermore, both crust and crumb color deviated from the control with a lower lightness and higher yellowness value being the most notable in treatment crumb. Even so, lower sucrose replacement for SU and AK exhibited characteristics that were closer to the control. Cake height, overall textural appearance, crumb pore size, and hardness, were no different (P<0.5) from the control for 25% replacement. These products resulted in a calorie reduction of 18.7%, and could potentially be used for successful partial sucrose replacement. On the other hand, RA treatments under performed. While the structure for 75 RA was successfully maintained as indicated by the cake height, overall RA treatments produced crumb color and texture that deviated the most from the control. While the reasons for this have been speculated, since RA has only recently been approved as GRAS, very little research is evident to provide substantive evidence. As such, a closer investigation in RA’s effects on bubble size and bubble distribution in batter and protein coagulation and starch gelatinization temperatures in baked angel food cake would help illustrate a more complete picture.
Table 6: Physical Properties of Angel Food Cake and Effects of Polydextrose and Sucralose, Acesulfame K, or Rebaudioside A Replacement

<table>
<thead>
<tr>
<th>Samples</th>
<th>Crust Color</th>
<th>a*</th>
<th>b*</th>
<th>∆E</th>
<th>Crumb Color</th>
<th>a*</th>
<th>b*</th>
<th>∆E</th>
<th>Weight Loss (%)</th>
<th>Height (cm)</th>
<th>Moisture Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>L*</td>
<td>75.754&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.659&lt;sup&gt;d&lt;/sup&gt;</td>
<td>31.073&lt;sup&gt;bcd&lt;/sup&gt;</td>
<td>L*</td>
<td>83.737&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-2.532&lt;sup&gt;d&lt;/sup&gt;</td>
<td>17.572&lt;sup&gt;d&lt;/sup&gt;</td>
<td>0.000&lt;sup&gt;f&lt;/sup&gt;</td>
<td>12.164&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.900&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>25 SU*</td>
<td>(0.974)</td>
<td>(0.964)</td>
<td>(1.566)</td>
<td>(0.000)</td>
<td>(1.372)</td>
<td>(0.060)</td>
<td>(0.404)</td>
<td>(0.000)</td>
<td>(0.413)</td>
<td>(0.000)</td>
<td>(1.183)</td>
</tr>
<tr>
<td>50 SU*</td>
<td>63.578&lt;sup&gt;b&lt;/sup&gt;</td>
<td>9.828&lt;sup&gt;c&lt;/sup&gt;</td>
<td>34.355&lt;sup&gt;a&lt;/sup&gt;</td>
<td>14.083&lt;sup&gt;c&lt;/sup&gt;</td>
<td>74.685&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.489&lt;sup&gt;c&lt;/sup&gt;</td>
<td>28.083&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>14.212&lt;sup&gt;cde&lt;/sup&gt;</td>
<td>14.570&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.175&lt;sup&gt;cd&lt;/sup&gt;</td>
<td>33.519&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>75 SU*</td>
<td>61.304&lt;sup&gt;b&lt;/sup&gt;</td>
<td>10.790&lt;sup&gt;c&lt;/sup&gt;</td>
<td>33.384&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>16.438&lt;sup&gt;c&lt;/sup&gt;</td>
<td>75.883&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.882&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>26.634&lt;sup&gt;c&lt;/sup&gt;</td>
<td>12.826&lt;sup&gt;de&lt;/sup&gt;</td>
<td>11.779&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.275&lt;sup&gt;bcd&lt;/sup&gt;</td>
<td>27.802&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>25 AK*</td>
<td>57.047&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>13.153&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>32.378&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>21.024&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>75.287&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>-0.077&lt;sup&gt;c&lt;/sup&gt;</td>
<td>27.439&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>13.233&lt;sup&gt;cde&lt;/sup&gt;</td>
<td>11.197&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.850&lt;sup&gt;a&lt;/sup&gt;</td>
<td>34.216&lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
<tr>
<td>50 AK*</td>
<td>53.025&lt;sup&gt;ac&lt;/sup&gt;</td>
<td>14.391&lt;sup&gt;a&lt;/sup&gt;</td>
<td>30.496&lt;sup&gt;cd&lt;/sup&gt;</td>
<td>25.166&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>71.272&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>1.368&lt;sup&gt;b&lt;/sup&gt;</td>
<td>29.776&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>17.913&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>13.839&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.525&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>32.644&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>75 AK*</td>
<td>59.150&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>11.204&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>33.278&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>18.407&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>72.055&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>1.462&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>30.015&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>17.550&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>14.466&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.100&lt;sup&gt;d&lt;/sup&gt;</td>
<td>32.798&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>25 RA*</td>
<td>58.252&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>13.040&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>33.947&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>20.071&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>75.910&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-0.211&lt;sup&gt;c&lt;/sup&gt;</td>
<td>28.613&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>13.742&lt;sup&gt;cde&lt;/sup&gt;</td>
<td>11.999&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.800&lt;sup&gt;a&lt;/sup&gt;</td>
<td>33.194&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>50 RA*</td>
<td>56.238&lt;sup&gt;bcd&lt;/sup&gt;</td>
<td>12.479&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>32.600&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>21.643&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>70.186&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1.864&lt;sup&gt;b&lt;/sup&gt;</td>
<td>31.519&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20.048&lt;sup&gt;a&lt;/sup&gt;</td>
<td>11.320&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.600&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>33.612&lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
<tr>
<td>75 RA*</td>
<td>49.868&lt;sup&gt;d&lt;/sup&gt;</td>
<td>13.953&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>28.442&lt;sup&gt;d&lt;/sup&gt;</td>
<td>28.100&lt;sup&gt;d&lt;/sup&gt;</td>
<td>64.092&lt;sup&gt;d&lt;/sup&gt;</td>
<td>8.914&lt;sup&gt;a&lt;/sup&gt;</td>
<td>32.298&lt;sup&gt;a&lt;/sup&gt;</td>
<td>25.583&lt;sup&gt;a&lt;/sup&gt;</td>
<td>14.595&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.675&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>34.003&lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
Table 6 (cont'd): The values in this table show crust and crumb color, weight loss, moisture content, and height results for the sucrose control and polydextrose (PD) and SU, AK, and RA replacement treatments. Samples with different letters (a,b,c,d,e,f) designate a significant difference (P<0.5). Values in parenthesis () represent the standard error of the sample above it. Weight loss (%) and moisture content (%) were calculated by Weight Loss (%) or Moisture Content (%) = \((W_i - W_f)/W_i \times 100\) where \(W_i\) was the initial product weight and \(W_f\) was the final baked weight (for weight loss) or final dried weight (for moisture content). Cake height was determined by measuring the highest point on baked and cooled cakes. Crust and crumb color were found using HunterLabScanXE colorimeter with illuminant A, 10° standard observer, and 2.54 diameter aperture. The overall change in color from the sucrose control was found by \(\Delta E^* = ((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)^{1/2}\) where \(\Delta E^*\) is the overall change in color from the control.

*SU, AK, and RA stand for sucralose, acesulfame-K, and Rebaudioside A. 25, 50, and 75 represent the percentage of sucrose replacement.
Table 7: TPA Analysis of Angel Food Cake and the Effects of Polydextrose and Sucralose, Acesulfame-K, or Rebaudioside A Replacement for Sucrose

<table>
<thead>
<tr>
<th>Sample</th>
<th>Hardness A (N)</th>
<th>Hardness B (N)</th>
<th>Cohesiveness</th>
<th>Deformability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1.128&lt;sup&gt;a&lt;/sup&gt; (0.310)</td>
<td>1.072&lt;sup&gt;a&lt;/sup&gt; (0.300)</td>
<td>0.902&lt;sup&gt;a&lt;/sup&gt; (0.009)</td>
<td>5.011&lt;sup&gt;a&lt;/sup&gt; (0.484)</td>
</tr>
<tr>
<td>25 SU*</td>
<td>1.156&lt;sup&gt;a&lt;/sup&gt; (0.220)</td>
<td>1.090&lt;sup&gt;a&lt;/sup&gt; (0.204)</td>
<td>0.889&lt;sup&gt;a&lt;/sup&gt; (0.007)</td>
<td>5.728&lt;sup&gt;a&lt;/sup&gt; (0.389)</td>
</tr>
<tr>
<td>50 SU*</td>
<td>1.406&lt;sup&gt;a&lt;/sup&gt; (0.175)</td>
<td>1.300&lt;sup&gt;a&lt;/sup&gt; (0.176)</td>
<td>0.854&lt;sup&gt;a&lt;/sup&gt; (0.033)</td>
<td>7.593&lt;sup&gt;a&lt;/sup&gt; (1.764)</td>
</tr>
<tr>
<td>75 SU*</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>25 AK*</td>
<td>1.094&lt;sup&gt;a&lt;/sup&gt; (0.098)</td>
<td>1.033&lt;sup&gt;a&lt;/sup&gt; (0.101)</td>
<td>0.891&lt;sup&gt;a&lt;/sup&gt; (0.022)</td>
<td>5.635&lt;sup&gt;a&lt;/sup&gt; (1.186)</td>
</tr>
<tr>
<td>50 AK*</td>
<td>1.239&lt;sup&gt;a&lt;/sup&gt; (0.239)</td>
<td>1.161&lt;sup&gt;a&lt;/sup&gt; (0.241)</td>
<td>0.875&lt;sup&gt;a&lt;/sup&gt; (0.047)</td>
<td>6.477&lt;sup&gt;a&lt;/sup&gt; (2.487)</td>
</tr>
<tr>
<td>75 AK*</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>25 RA*</td>
<td>1.306&lt;sup&gt;a&lt;/sup&gt; (0.010)</td>
<td>1.228&lt;sup&gt;a&lt;/sup&gt; (0.010)</td>
<td>0.884&lt;sup&gt;a&lt;/sup&gt; (0.014)</td>
<td>5.956&lt;sup&gt;a&lt;/sup&gt; (0.718)</td>
</tr>
<tr>
<td>50 RA*</td>
<td>2.283&lt;sup&gt;b&lt;/sup&gt; (0.260)</td>
<td>2.156&lt;sup&gt;b&lt;/sup&gt; (0.271)</td>
<td>0.890&lt;sup&gt;a&lt;/sup&gt; (0.035)</td>
<td>5.672&lt;sup&gt;a&lt;/sup&gt; (1.856)</td>
</tr>
<tr>
<td>75 RA*</td>
<td>1.972&lt;sup&gt;b&lt;/sup&gt; (0.077)</td>
<td>1.850&lt;sup&gt;b&lt;/sup&gt; (0.060)</td>
<td>0.880&lt;sup&gt;a&lt;/sup&gt; (0.021)</td>
<td>6.178&lt;sup&gt;a&lt;/sup&gt; (1.117)</td>
</tr>
</tbody>
</table>

Texture Profile Analysis (TPA) was observed for sucrose and SU*, AK*, and RA* replacement treatments for angel food cake. Samples with different letters (a,b,c,d,e,f) designate a significant difference (P<0.5). Standard error is represented by the values in parenthesis (). Hardness A and Hardness B were the maximum force (N) in the first and second compression, respectively. Deformability (%) was calculated by ({Hardness A-Hardness B}/Hardness A) x 100. The squared peak height of the second peak by the squared peak height of the first peak was used to calculate cohesiveness (Bourne, 1978).

*SU, AK, and RA stand for sucralose, acesulfame-K, and Rebaudioside A, respectively. 25, 50, and 75 represent the percentage of sucrose replacement.
Figure 20: Texture Profile Analysis (TPA) 2-Cycle Compression Test

This figure illustrates a schematic of the TPA 2-cycle compression test that was performed using an Instron machine for angel food cake samples. The peak of the first compression is meant to correlate to the maximum force experienced during the first bite of a food material. The peak of the second curve represents the same, but for the second bite. (Bourne, 2002)
<table>
<thead>
<tr>
<th></th>
<th>Top</th>
<th>Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Control</strong></td>
<td><img src="image1" alt="Control Top" /></td>
<td><img src="image2" alt="Control Horizontal" /></td>
</tr>
<tr>
<td><strong>25 SU</strong></td>
<td><img src="image3" alt="25 SU Top" /></td>
<td><img src="image4" alt="25 SU Horizontal" /></td>
</tr>
<tr>
<td><strong>50 SU</strong></td>
<td><img src="image5" alt="50 SU Top" /></td>
<td><img src="image6" alt="50 SU Horizontal" /></td>
</tr>
<tr>
<td><strong>75 SU</strong></td>
<td><img src="image7" alt="75 SU Top" /></td>
<td><img src="image8" alt="75 SU Horizontal" /></td>
</tr>
</tbody>
</table>
Figure 21: Photos of Sucrose and Sucralose Baked Angel Food Cakes
This figure shows both top and horizontal pictures of sucrose and sucralose (SU) replacement in angel food cake. 25, 50, and 75 represent the % replacement.
<table>
<thead>
<tr>
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<th>Top</th>
<th>Horizontal</th>
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</thead>
<tbody>
<tr>
<td>Control</td>
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<td><img src="image" alt="Control Horizontal" /></td>
</tr>
<tr>
<td>25 AK</td>
<td><img src="image" alt="25 AK Top" /></td>
<td><img src="image" alt="25 AK Horizontal" /></td>
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<tr>
<td>50 AK</td>
<td><img src="image" alt="50 AK Top" /></td>
<td><img src="image" alt="50 AK Horizontal" /></td>
</tr>
<tr>
<td>75 AK</td>
<td><img src="image" alt="75 AK Top" /></td>
<td><img src="image" alt="75 AK Horizontal" /></td>
</tr>
</tbody>
</table>
Figure 22: Photos of Sucrose and Acesulfame-K Baked Angel Food Cakes
This figure shows both top and horizontal pictures of sucrose and acesulfame-K (AK) replacement in angel food cake. 25, 50, and 75 represent the % replacement.
<table>
<thead>
<tr>
<th></th>
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<th>Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
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<td><strong>50 RA</strong></td>
<td><img src="image5" alt="50 RA Top" /></td>
<td><img src="image6" alt="50 RA Horizontal" /></td>
</tr>
<tr>
<td><strong>75 RA</strong></td>
<td><img src="image7" alt="75 RA Top" /></td>
<td><img src="image8" alt="75 RA Horizontal" /></td>
</tr>
</tbody>
</table>
Figure 23: Photos of Sucrose and Rebaudioside A Baked Angel Food Cakes
This figure shows both top and horizontal pictures of sucrose and Rebaudioside A (RA) replacement in angel food cake. 25, 50, and 75 represent the % replacement.
Figure 24: Photos of Angel Food Cake Crumb for Sucrose and Sucralose Treatments

The pictures in this figure exhibit horizontal and vertical internal crumb pictures for sucrose and sucralose (SU) replacement treatments. 25, 50, and 75 represent the % replacement of sucrose. As replacement increased, physical properties of the angel food cake degraded.
<table>
<thead>
<tr>
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<tr>
<td>75 AK</td>
<td><img src="image" alt="75 AK" /></td>
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</tr>
</tbody>
</table>

**Figure 25: Photos of Angel Food Cake Crumb for Sucrose and Acesulfame-K Treatments**

The pictures in this figure exhibit horizontal and vertical internal crumb pictures for sucrose and acesulfame-K (AK) replacement treatments. 25, 50, and 75 represent the % replacement of sucrose. As replacement increased, physical properties of the angel food cake degraded.
<table>
<thead>
<tr>
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<th>Horizontal</th>
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<tbody>
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<tr>
<td>75 RA</td>
<td><img src="image" alt="75 RA" /></td>
<td><img src="image" alt="75 RA" /></td>
</tr>
</tbody>
</table>

Figure 26: Photos of Angel Food Cake Crumb for Sucrose and Rebaudioside A Treatments

The pictures in this figure exhibit horizontal and vertical internal crumb pictures for sucrose and Rebaudioside A (RA) replacement treatments. 25, 50, and 75 represent the % replacement of sucrose. As replacement increased, internal pore bubble volume seemed to increase in angel food cakes for replacement cakes.
Research Conclusions

The detrimental consequences of diabetes and obesity have been a growing hot
topic for many decades. In the United States, obesity alone had an estimated health care
cost of $78.5 billion in 1998 which only further increased to $147 billion in 2008
(Finkelstein et al., 2009). Often poor diet and inactivity (Finkelstein et al., 2009) have
been the two main cited causes for this epidemic. How are food processors, health care
providers, and other business supposed to combat this when consumers seem to have an
innate desire for calorie-dense sweet products (Pinheiro, 2005)? Finding an answer to
this conundrum provides an excellent growth opportunity for many businesses. During
the course of this research, the overall goal was to determine if an acceptable formulation
for sucrose replacement could be determined so that calorie and sucrose content could be
reduced in angel food cake. Non-nutritive sweeteners such as sucralose (SU),
acesulfame-K (AK), and Rebaudioside A (RA) with the assistance of bulking agents such
as polydextrose (PD) have shown promise in this area.

After performing several analysis, lower sucrose replacement values for SU and
AK, specifically 25%, were found to be an acceptable substitute to the sucrose control.
Meringue batter showed some deviation at lower replacement levels; however, in angel
food cake batter the addition of the structural components, namely flour, seemed to help
resolve these differences. In fact, the baked product height, weight loss, moisture
content, hardness, cohesiveness, and deformability characteristics were all comparable to
the sucrose control resulting in a calorie reduction of 18.7% from control cakes. Other
researchers have also found that lower sucrose replacement values were comparable to its
sucrose counterpart. Such studies include muffins replaced with 25% polydextrose and
sucralose (Martínez-Cervera et al., 2012), biscuits replaced with 30% maltodextrin and
0.05% sucralose (Savitha et al., 2008), cupcakes formulated with aspartame, fructose, and
polydextrose (Pong et al., 1991), and cakes with polydextrose, fructose, and acesulfame-
K or aspartame. In this research, only crust and crumb color deviated substantively from
the sucrose control. This difference was statistically noticeable with all sucrose
replacement treatments. Conducting a sensory panel would assist in determining if these
differences were actually detectable by consumers and, if so, whether this characteristic
was either pleasant or unpleasant.
Higher replacement values for SU and AK did not perform as well in baked angel food cake. Despite rising to about twice the height of sucrose control when initially removed from the oven, the final, cooled structures of 75 SU and 75 AK completely collapsed. Further, they were gummy, had a layer of what appeared to be settled polydextrose, and could not be used for TPA analysis. This was not expected since results from the angel food cake batter experiments exhibited improved apparent viscosity and other rheological properties which suggested enhanced bubble incorporation. According to Pateras (1992 and 1994), this decreased functionality was likely due to polydextrose. Pateras (1992 and 1994) found that increasing amounts of polydextrose raised the starch gelatinization onset temperature and increased average bubble size and bubble size variation. During baking, these larger bubbles were found to coalesce and escape the batter before a successful angel food cake structure could form. While the results were not promising in general, it is interesting to note that RA samples did exhibit the same trends as SU and AK treatments despite the same amount of polydextrose being present at each replacement level.

At the beginning of this research, noticeable differences between SU, AK, and RA replacement treatments were not expected. Because it has recently been approved as GRAS, very little research has been performed with RA and its effects on baked goods. As found in this research, as sucrose replacement increased for RA treatments, reduced apparent viscosity, increased flow index (n), and reduced consistency index was found in both meringue and angel food cake batters. At 50 RA and 75 RA sucrose replacement, meringue batter, angel food cake batter, and baked angel food cake consistently performed worse than the control and SU and AK treatments. Furthermore, crumb color and texture, or hardness, noticeably deviated in all baked angel food cakes. Whether these differences were caused by variations in protein coagulation and starch gelatinization onset temperatures, bubble size and distribution, or some other factor is currently unknown, as this was outside the scope of this research.
REFERENCES


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