MARK KOFI TETTEH
Measuring Blueberry Firmness and Modeling Quality Changes for Delays in Cooling Using the FirmTech II
(Under the Direction of Professor Stanley E. Prussia)

Blueberry firmness values (g/mm) measured by a FirmTech II depended on calyx orientation (up, down, or horizontal). A 3-D plot showed large changes in firmness resulting from different minimum and maximum settings. A recommended standard is to use only the first measurement with the calyx horizontal at 50-g minimum and 150 g maximum force. Applications of Hertz contact equations (ASAE standard S368.4) showed a need for including the 3/2th power on the deformation value in the FirmTech II output and the radius of the fruit. Firmness and mass changes for different cooling delays and at different temperatures were modeled. Predictive curves were generated and plotted against actual data. Plots of predicted versus observed values showed that the models generated predicted mass losses better than firmness losses of the blueberries. Immediate cooling was less critical at 21° C and 27 °C than at 32 °C.

INDEX WORDS: Non-destructive, texture, fruit, delay of cooling, ASAE standard, Postharvest.

MEASURING BLUEBERRY FIRMNESS AND MODELLING QUALITY CHANGES FOR DELAYS IN COOLING USING THE FIRMTECH II

by

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DEDICATION

To my mum Suzzie and wife Mavis, thanks for being there for me.

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CHAPTER 1

INTRODUCTION

An instrument for measuring the firmness of blueberries and other small fruit, the FirmTech II marketed by BioWorks Inc, provides a firmness measurement that is the slope of a force-deformation curve. Depending on what maximum and minimum forces are chosen as cut-off for the slope, the firmness values obtained for the same fruit will be different, although its firmness remains the same.

Thus studies are needed for standardizing the measurement of blueberry firmness using the FirmTech II instrument. General principles are available including a rational selection of test conditions and procedures was published by Sherman (1972). Also, the American Society of Agricultural Engineers (ASAE S368.4) standards indicates that for reporting purposes, researchers must state what forces and orientation or loading positions were used.

Relationships could be established by showing the change in magnitude in firmness measurements when the minimum and maximum forces are varied. Likewise, differences in firmness measurement for different orientations (calyx down, calyx up and calyx horizontal), as well as differences in first and consequent firmness measurements, show the need to standardize.

This thesis studies all these options, exploring the use of the Young's Modulus of Elasticity, E, for the FirmTech II instrument. This property, a standard for all engineering materials, has applications with biological and agricultural materials as shown in the ASAE S. 368.4.

Studies are also needed for developing models showing how delays of cooling affect the quality of produce as evidenced from different numbers of hours of delay reported as being ideal for best quality (Crisosto et al., 2001, Thompson et al., 2001, Boyette et al., 1993, Garner et al., 1987). Cooling is usually advocated as soon as fruit are harvested, but practically, this is not possible due to cost of cooling, transportation and other issues (Boyette et al., 1993). Different researchers have advocated different methods to cool fruit as soon as possible after harvest (Thompson et al., 2001, Boyette et al., 1993). Harvesting in the cool of the mornings or late afternoons and evenings, putting produce under shade, pre-cooling to room temperatures using fans, and using portable coolers on the harvest sites are some of the methods in use.

For this thesis firmness and mass losses were modeled by using exponential and linear equations for different temperatures and different hours of simulated cooling delays. Predicted values were plotted over actual plots of the test data. The predicted values were obtained using equations obtained from slopes of firmness or mass losses versus time plots at different temperatures.

In this project, the FirmTech II instrument was evaluated for reliability in firmness values and for errors associated with its operation. It was compared to the compression tests using an universal testing machine (Instron), an industry standard, to compute firmness on both blueberries and spherical rubber balls. In addition, it was used in a practical application to determine the effectiveness of a model formulated to predict the firmness and mass losses of blueberries at different temperatures.

CHAPTER 2

LITERATURE REVIEW

An expansion of the blueberry culture in North America has occurred over the past fifteen years and is projected to continue into the 21st century (Moore, 1994). Cultivated areas have expanded 19 % in recent years, and demand for the fruit continues to grow. According to the United States Department of Agriculture (USDA's) National Agricultural Statistics Service (NASS), total production for cultivated blueberries was 84,000 tons in 2000, with a farm value of $176.6 million in 2000. This was up 4 % from a total production of 81,000 tons with a farm value of $153.7 million in 1999. This shows that the importance of the blueberry industry cannot be over-emphasized. The quality of the blueberries produced therefore becomes of paramount importance since fresh harvested fruit have the highest prices (D Morris, personal communication, June 27, 2001).

Some Important Definitions:

- Quality - in harvested plant products, quality is a composite of those characteristics that differentiate individual units of the product and have significance in determining the units' degree of acceptability to the user. Some important quality characteristics are size, shape, color, taste, odor and texture of the fruit (Kays, 1991).
- Texture - is a basic physical property of foods or the physical properties of foodstuff related to mouth-feel or eating quality or the overall physical properties perceived by the eyes, fingers or the mouth during mastication. Some primary parameters

describing texture have been reported to be hardness (firmness), cohesiveness, viscosity, springiness and adhesiveness (Hung et al. 2001).

- Firmness - is defined as the slope of a force per deformation plot obtained from a compression test (Mohsenin, 1970).
- Modulus of Elasticity - is defined as the ratio of stress to the corresponding strain below the limit of proportionality (Mohsenin, 1970).

Firmness of food products has been a very useful indicator to determine the quality of produce. It is a textural attribute of food products. The texture has been shown to be one of the essential factors for determining harvest dates and market grades of produce (Mohsenin, 1970). In a study by Sczezeniak and Bourne (1969), it was reported that the sensory firmness test employed depended on the firmness of food. This means that fruit like carrots are held in two hands and bent whilst tomatoes are compressed between the index finger and thumb among many others. The term firmness has been used severally to apply to different levels of firmness from low (whipped toppings) to very high (as in carrots).

According to Szczesniak and Bourne (1969), the primary parameters describing texture are hardness, cohesiveness, viscosity, springiness, and adhesiveness. According to Hung et al. (2001), some words that have been used to describe texture favorably have been crisp, crunchy, tender, juicy, creamy, firm, spongy and smooth.

Mohsenin (1970) states firmness as an important textural attribute in fruits and vegetables concerning readiness of the crop for harvest and for quality evaluation during storage for fresh market, as well as prior to processing. Additionally, firmness may provide a correlation between the quality of the raw material and that of the processed or manufactured product. The texture of fruits and vegetables are therefore very important in postharvest operations, and it is imperative that the physical property be correctly assessed. Mohsenin (1970) and (Finney and Norris, 1968) have reported the use of the engineering modulus of elasticity for firmness as a means of standardizing the different methods and units currently used in firmness measurements.

As reported by Hung et al. (2001), the measurement of food texture is divided into two categories: instrumental and sensory methods (figure 2.1). Instrumental methods can be divided into destructive and nondestructive methods, with several different principles of evaluation. As shown below many instruments are in use for texture measurements, particularly firmness.

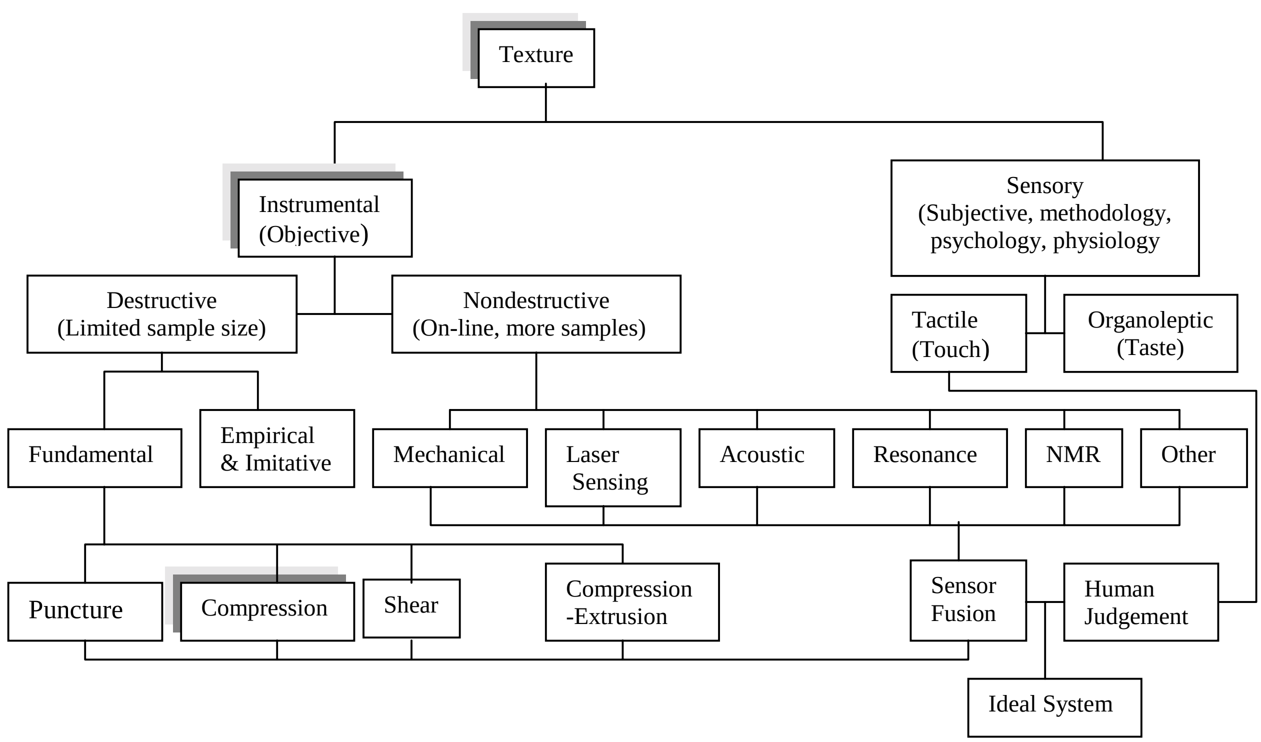

Figure 2.1: Classification of texture-assessment methods (From Hung et al. (2001))

Hung et al. (2001) further simplified these methods into two broad categories: those with mechanical contact with the food sample and the others with no mechanical contact.

Mohsenin (1970) mentions several mechanical devices including the tenderometer, puncture tester, texturometer, maturometer, fibrometer and succolumeter among many others. A few instruments mentioned by Hung et al. (2001) based on the different firmness evaluation methods are the Magnes and Taylor penetrometer, the FirmTech, the mechanical thumb, and the laser-puff among others.

One of these instruments, the FirmTech II, was specifically designed for firmness measurements of blueberries, cherries, grapes, and other small fruit (Timm et al., 1996). Firmness is assessed by placing 25 fruit into shallow pockets on an aluminum turntable that automatically rotates and aligns each fruit in segments under a load cell attached to a linear stepper motor (Figure 2.2).

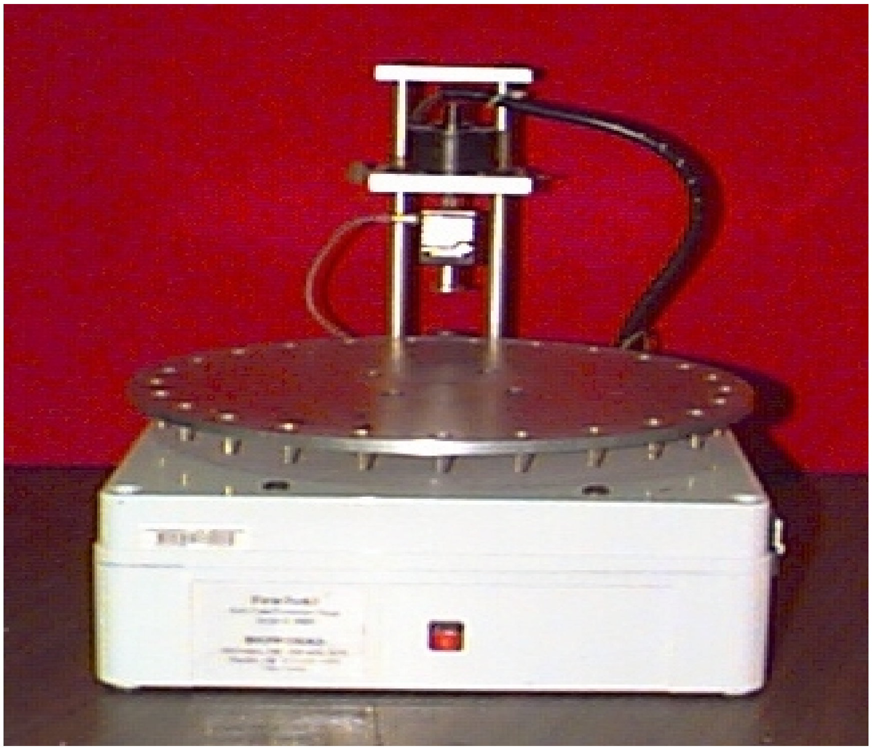

Figure 2.2: The FirmTech II instrument

This motor moves the load cell downward to compress the fruit and upward after compression. The hardware components (the load cell and the turntable motors) are linked to a computer through data acquisition cards and are controlled by a computer program. The software for the FirmTech II includes a configuration file with settings for maximum and minimum forces, load-cell travel speed, turntable speed, sample size, compression mode, and other functions. The equipment comes with a 250g mass, which is used to calibrate the load-cell before the instrument is used. Timm et al. (1996) described the FirmTech II as being suitable for distinguishing between bruise treatments, harvest treatments, and fruit maturity levels.

Mitcham et al. (1998) placed the FirmTech only second to the well-known Instron in a study comparing the repeatability and relative variability of non-destructive devices. The instrument is in use in research laboratories in the United States, Europe and Australia (P. Armstrong, personal communication, August 23, 2000). Available literature shows the FirmTech II has been used in research by different authors in various studies. Nesmith et al. (2002) used the FirmTech II to estimate the percentage firmness losses of blueberries due to different harvesting and grading methods with mechanical harvesting being the worst case (20 – 30 % loss). Allan-Wojtas et al. (2001) reported that the slight compression used to measure blueberry firmness caused separation between the sub-epidermal and flesh layers, thus questioning the non-destructive designation of the FirmTech II.

Although the FirmTech II is used by scientists the world over, there has been no study to examine the instrument settings and their effect on the output. An informed choice is what this study offers for users of the instrument. The first paper in this thesis examines the instrument and makes recommendations as to its proper use for the best possible results in its applications.

The quality of fresh-market blueberry fruit is of paramount importance to the blueberry industry, growers, packers and consumers alike. Field conditions at harvesting, as well as type of harvesting method used, transportation and handling all influence the final product quality. One of the major field conditions in this regard is temperature.

Delay of cooling during postharvest handling has been known to negatively impact the shelf life of fresh fruit and vegetables ranging from bananas, pears, blueberries and many others (Thompson et al., 2001). In a review of the kinetics of softening of foods, Rao and Lund (1986) reported that first order kinetic expressions are suitable for expressing the degree of softening at a constant temperature. A study on the postharvest quality of peaches after delays in cooling by Garner et al. (1987) found that delays of up to two hours resulted in better firmness than did greater delays. Boyette et al. (1993) have advocated a delay of 4 hours or less after harvest for blueberries.

Postharvest cooling lowers the respiration rate, slows the ripening process, and reduces the decline in quality (Kays, 1991). According to Thompson et al. (2001), cooling delays following harvest cause reduced product quality for three main reasons: 1) allowing respiration and associated normal metabolism to continue at high rates, consuming sugars, acids, vitamins, and other constituents, 2) fostering water loss, and 3) increasing decay development. Temperature has a pronounced effect on the metabolic rate of a harvested product (Kays, 1991). As the product temperature increases, reaction rates increase, and the product consumes stored photosynthates faster. Thompson et al.

(2001) reported that cooling products from high-summer field-temperatures to room temperature, 21° to 24 ° C, significantly slows respiration.

Thompson et al. (2001) and Kays (1991) both report the importance of water loss on post-harvest fruit and vegetable quality. The loss of water due to improper control of the relative humidity to which the product is exposed can result in serious textural quality losses. Shriveling and the loss of fresh glossy appearance are two of the most noticeable effects of cooling delays.

Bourne (1982) reported that most fruits and vegetables showed decreasing firmness with increasing temperature, although there were some exceptions. He concluded that both researchers and marketers should be aware that it is possible to change the apparent grade of fruit by adjusting the temperature by a sufficient amount in the right direction.

In a study by Thai et al. (1989) on tomato color and firmness concluded the following: Assuming Q is a quality attribute that we would like to model with respect to time and temperature, the following type of relationship was found to apply:

$$F(Q) = F(Q_o) + \rho * \text{time} \qquad (2.1)$$

where ρ is a reaction rate depending on temperature, Q_o is the initial quality attribute at time = 0, and F is a function of Q in this case for tomato color. Using this equation to model blueberry firmness losses would yield:

$$FM_t = FM_o - \rho * t \qquad (2.2)$$

where FM_t is the firmness of any blueberry at any time t, ρ is the negative reaction rate and FM_o is the firmness of any blueberry at time zero.

In this thesis, equations of this nature were used to model the deterioration in blueberry firmness and mass loss. This research also applied these models to determine the effects of delay of cooling on blueberry firmness and moisture loss.

CHAPTER 3

OBJECTIVES

The overall purpose of this study was to identify any changes in operation or design that could improve the firmness results obtained from FirmTech II instruments as well as to determine the effects of delays of postharvest cooling on firmness and mass loss on blueberry fruit. Specific objectives were to:

1. Identify basic parameters and procedures necessary for obtaining repeatable results from FirmTech II instruments at different times and locations.
2. Determine the amount of error in FirmTech II output that results from not including fruit radii in the firmness values and from ignoring the three-halves power of the deformation term.
3. Determine overall repeatability and accuracy of firmness values from a FirmTech II instrument compared with modulus of elasticity values calculated from Hertz contact theory.
4. To develop models for rates of deterioration for blueberry mass and firmness at different temperatures with respect to different delays of cooling and to use the models to predict firmness and mass values over time.

CHAPTER 4

FACTORS AFFECTING BLUEBERRY FIRMNESS MEASUREMENTS BY FIRMTECH II AND APPLICATION OF HERTZ CONTACT THEORY[1]

[1]Tetteh M. K., S. E. Prussia, B. P. Verma and D. S. NeSmith. To be submitted to Transactions of the ASAE.

ABSTRACT

A FirmTech II instrument was evaluated to determine the effects of instrument settings, berry orientation and berry size on firmness values of blueberries. Blueberry firmness values (g/mm) measured by a FirmTech II depended on calyx orientation (up, down, or horizontal). In addition, large changes in firmness readings resulted from different minimum and maximum instrument settings. We propose a recommended standard is to use only the first measurement, with the calyx horizontal, at 50-g minimum and 150-g maximum force. Applications of Hertz contact equations (ASAE standard S368.4) showed a need for including the radius of the fruit and the 3/2th power on the deformation value in the FirmTech II output.

INTRODUCTION

The firmness of blueberries, cherries, grapes, and other small fruit is an important postharvest attribute related to fruit quality. A recently developed instrument, the FirmTech II manufactured and marketed by BioWorks Inc, has been utilized to determine berry firmness. The firmness of 25 fruit can be rapidly obtained by placing each fruit in one of 25 pockets on a rotating plate. The firmness value (g/mm) of each item is determined as the slope of a force/deformation curve between a predetermined minimum and maximum force.

Preliminary tests showed that firmness values depended on several factors. For a single blueberry, firmness values increased as the minimum or maximum force setting was increased. Differences in firmness values were also noted when the calyx was horizontal, up, or down. After several measurements at high maximum force settings berry firmness decreased due to visible bruising. Observations also showed that some berries moved into the supporting pockets more than others when the load cell applied force. Movement of the berries would cause lower firmness values. Tests also showed that the first measurement was lower than subsequent values when the maximum force was at non-destructive levels. These preliminary tests showed the need for controlled experiments to establish standard settings and procedures to enable comparison of results from one test to the next and among different users of the instruments.

A study is also needed to evaluate the possible influence of fruit radii on the firmness output obtained from the FirmTech II. The current output gives firmness values (slope = g/mm) that do not include fruit radius in the calculation. It is expected from Hertz contact theory that two berries with the same modulus of elasticity (E) would give different FirmTech II firmness values if they have different radii. Consequently, a good berry could be rejected as a soft fruit if the slope from the FirmTech II output was below a threshold value. Likewise, a berry with the same E but with a different diameter could be accepted. Application of Hertz contact theory would enable calculations to predict the amount of error expected by not including the radius of fruit in firmness values.

Likewise, the firmness measurement from the FirmTech II does not depend on the 3/2 th power on the deformation term in the equations for calculating E from force/deformation plots.

OBJECTIVES

The overall purpose of this study was to identify any changes in operation or design that could improve the firmness results obtained from FirmTech II instruments. Specific objectives were to:

1. Identify basic parameters and procedures necessary for obtaining the same firmness measurements from the FirmTech II at different times and locations.
2. Determine the amount of error in FirmTech II output that results from not including fruit radii in the firmness values and ignoring the 3/2th power on the deformation term.
3. Determine overall repeatability and accuracy of firmness measurement values from a FirmTech II instrument compared with similar firmness measurement values calculated from parallel plate tests- (Hertz contact theory).

REVIEW OF LITERATURE

The firmness of blueberries, cherries, grapes and other small fruit is an important postharvest attribute related to fruit quality. Accurate firmness measurements of blueberries (and other fruit) are needed both for fresh market channels and for processed fruit. Whole batches of fruit are disposed of based on the results from a small sample. Incorrect firmness determinations can result in the rejection of a good shipment as well as accepting a shipment that is too soft.

Bourne (1967) showed that human determination of the firmness of a product varies among people and under repetitive tests the same person will obtain different results for the same product. Voisey and Crete (1973) also determined that males applied more force and at a higher compression rate than females for firm products like onions. In squeezing tomatoes, males tended to apply higher forces at a considerably lower rate than the females. This is an indication of the variability associated with hand testing the firmness of food products.

A firmness instrument provides the opportunity to remove human subjectivity from fruit firmness measurements. The FirmTech II was specifically designed for assessing the firmness of small fruit such as blueberries, cherries, and grapes (Timm et al., 1996). Fruit are placed into twenty-five shallow pockets on an aluminum turntable that automatically rotates and aligns each fruit in segments under a load cell attached to a linear stepper motor (Figure 4.1). This motor moves the load cell downward to compress the fruit and upward after compression. The hardware components (the load cell and the turntable motors) are linked to a computer through data acquisition cards and are controlled by a computer program.

The software for the FirmTech II includes a configuration file with settings for the maximum and minimum forces, the load-cell travel speed, the turntable speed, the compression mode, and other functions. The equipment comes with a 250g mass, which is used to calibrate the load-cell before the instrument is used.

Sherman (1972) advocated a rational selection of test conditions for any instrumental tests on food products, and such an assessment has not been reported for the FirmTech II.

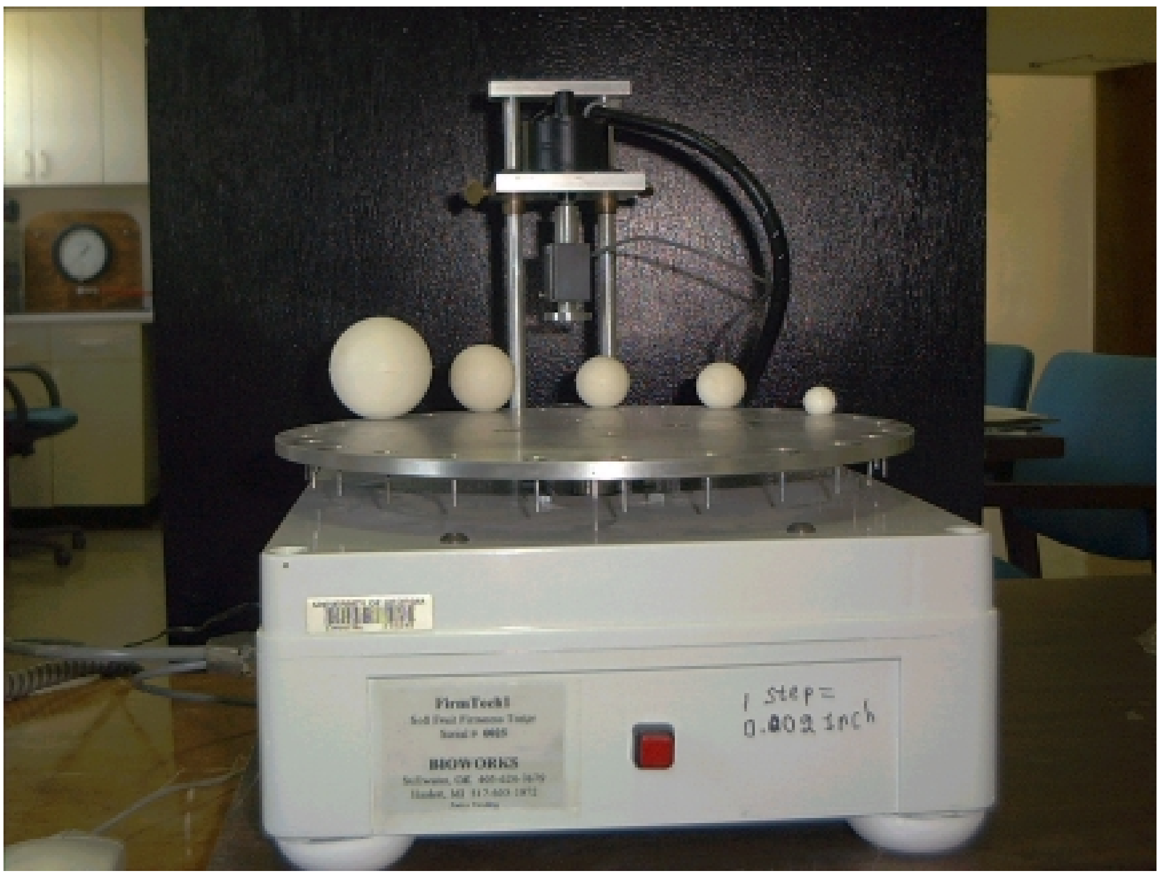

Figure 4.1: FirmTech II instrument with pockets for holding small fruit and a load cell connected to a stepping motor (The photo is of a FirmTech I that was upgraded to a FirmTech II).

The FirmTech II instrument developed by BioWorks, Inc. is an update (improved load cell and software) of their previously available FirmTech I. Mitcham et al. (1998)

compared an Instron universal testing machine to the FirmTech I and two other instruments for measuring cherry firmness. The Instron was determined to be the most precise, followed by the FirmTech I. The FirmTech I was also determined to have the greatest promise for wholesale commercial usage and ranked best for ease of use. Donahue and Work (1998) used a FirmTech I on highbush blueberries. They recommended that blueberries be harvested when they yield a high peak force (after ripening), and after a recent rainfall when the blueberries are plump in order to maintain good conditioning for shipping. NeSmith et al. (2002) used the FirmTech II to determine the firmness losses of rabbiteye blueberries during different harvesting and handling procedures.

Although FirmTech II instruments have been used for several fruit crops and at various locations, we could not find published information with guidance for selecting instrument settings or procedures related to fruit interactions with the instrument. Similarly, information is not available on how the firmness values change when changes are made in operating conditions. Preliminary tests showed that changes in firmness values resulted from repeated tests on an individual item for different operating conditions involving:

1. Orientation of the product tested.
2. Minimum and maximum force setting.
3. Large maximum forces that cause damage.
4. The second measurement is often larger than the first one (possibly due to movement into the pockets supporting the item measured).

FirmTech II instruments do not include the radius of the item tested in computing the firmness value recorded. No published reports could be found that show the error in firmness values based on direct use of the slope of a force deformation plot compared to using a physical property such as modulus of elasticity. Mohsenin (1970) and Finney and Norris (1968) advocated the use of the engineering definitions of firmness, (Modulus of Elasticity) to characterize the texture (firmness) of plant tissue.

Donahue and Work (1998) found that a linear relationship existed between the "texture" sensory attribute and the elastic modulus. This essentially means that firmness determination by hand and the elastic modulus correlated well. Finney and Norris (1968) also defined the firmness of fruits and vegetables as the modulus of elasticity of the flesh under small strain conditions that is, below the point of cell damage. A universal testing machine is typically used for obtaining the force-deformation data needed for calculating modulus of elasticity. Universal testing machines also enable other measurements such as shear resistance, compressibility, extensibility and deformation under a set load (Ryall and Lipton, 1978).

The American Society of Agricultural Engineers publishes a standard (ASAE S368.4) for determining the Modulus of Elasticity, E, and other mechanical attributes of food texture from quasi-static force-deformation tests of materials of convex shapes such as fruits and vegetables (ASAE Standards, 2001). Equations from the ASAE standard are used in the following theoretical development section to show the influence on FirmTech II firmness values from changes in radius and the power on the deformation term.

THEORETICAL DEVELOPMENT

Engineering properties of the materials tested provide a method for evaluating the accuracy of firmness values obtained from FirmTech II instruments. The modulus of elasticity is a widely used material property that has applications to food materials such as blueberries. Hertz contact theory is the basis for the standard (ASAE Standards, 2001) available for determining the apparent modulus of elasticity of food materials of convex shapes. Four equations are available for different loading conditions. The two equations needed for this study are for parallel plate contact given by equation 1 where all the deformation measured is from both the upper and lower contact points of contact:

$$E = \frac{0.338F(1-\mu^2)}{D^{3/2}}\left[Ku\left(1/Ru + 1/Ru'\right)^{1/3} + K_L\left(1/R_L + 1/R_L'\right)^{1/3}\right]^{3/2} \text{------}(4.1)$$

and by equation 2 for single plate contact where all the deformation is from the upper contact point:

$$E = \frac{0.338FK_u^{3/2}(1-\mu^2)}{D^{3/2}}\left[1/R_U + 1/R_U'\right]^{1/2} \text{--------------------}(4.2)$$

where:

E = apparent modulus of elasticity, MPa

D = deformation at a force of F on a force/deformation curve, m

μ = Poisson’s ratio (dimensionless)

F = force, at a deformation of D on a force/deformation curve, N

R_u, R_u' = minimum and maximum radii of curvature at point of contact for the upper convex surface, m

R_L, R_L' = minimum and maximum radii of curvature at the point of contact for the lower convex surface, m

K_u = Constant depending on geometry of upper contact point

K_L = Constant depending on geometry of lower contact point

FirmTech II instruments provide a Firmness Measurement (FM) obtained from a force-deformation curve between predetermined set points for minimum force (F_{min}) and maximum force (F_{max}). The FM is defined as the slope of a line intercepting the force – deformation curve at F_{min} and F_{max}:

$$FM = \frac{F_{max} - F_{min}}{D_{max} - D_{min}} \quad (4.3)$$

where D_{min} and D_{max} are the deformations at F_{min} and F_{max} respectively. Equation 1 can be simplified for a spherical ball with equal upper and lower radii of curvature ($R_u = R_u' = R_L' = R_L = R$) by defining a constant, $C_1 = 0.338(1-\mu^2)\,K^{3/2}(4) = 2.2124(1-\mu^2)$ when k is 1.3514 for normal contact (ASAE S368.4):

$$E = \frac{F * C_1}{D^{3/2}\sqrt{R}} \quad (4.4)$$

Solving for D_{max} and D_{min} gives:

$$D_{max} = \left(\frac{F_{max} C_1}{E\sqrt{R}}\right)^{2/3} \quad (4.5)$$

$$D_{\min} = \left(\frac{F_{\min} C_1}{E\sqrt{R}} \right)^{2/3} \text{-----------------------------} (4.6)$$

Substituting equations 4.5 and 4.6 into equation 4.3 gives an equation relating FM to E for FirmTech II measurements if the berry has a single point of contact at the bottom of the pocket (parallel plate equation 1):

$$FM = \frac{F_{\max} - F_{\min}}{\left[\frac{F_{\max} C_1}{E\sqrt{R}} \right]^{2/3} - \left[\frac{F_{\min} C_1}{E\sqrt{R}} \right]^{2/3}} \text{---------------------} (4.7)$$

Simplifying gives:

$$FM = \frac{F_{\max} - F_{\min}}{\left(F_{\max}{}^{2/3} - F_{\min}{}^{2/3} \right) \left(C_1{}^{2/3} \big/ \left(E\sqrt{R} \right)^{2/3} \right)} \text{-------------------} (4.8)$$

Solving for E gives:

$$E = \frac{FM^{3/2}}{\left[\frac{F_{\max} - F_{\min}}{F_{\max}{}^{2/3} - F_{\min}{}^{2/3}} \right]^{3/2}} \left(\frac{C_1}{\sqrt{R}} \right) \text{---------------------} (4.9)$$

The ability to calculate modulus of elasticity from FM provides an output that correctly measures firmness at selected force settings (and resulting deformations) and for various size fruit. Equation 4.9 can be simplified for the special case when $F_{\min} = 0$ and by substituting equations 4.3 into and 4.9:

$$E = FM\left[\frac{C_1}{\sqrt{D*R}}\right] ---------------------------- (4.10)$$

Equation 4.10 shows the multiplier correction factor (error) needed because FM is not raised to the 3/2 th power and from not including a value for the fruit radius. Equations 4.9 and 4.10 can be applied to the situation where the FirmTech II pockets prevent compression at the bottom of the fruit by replacing C_1 with C_2 where

$C_2 = 0.338\ (1-\mu^2)\ K^{3/2}\sqrt{(2)} = 0.7509\ (1-\mu^2)$.

For some situations, it is useful to compare the FirmTech II outputs for fruit with different radii. A relationship can be found by considering two spherical balls of the same modulus of elasticity but with different radii. The terms in equation 4.9 can be given subscripts 1 and 2 for balls 1 and 2 respectively and set equal since they have the same value for E. The constant terms cancel giving:

$$E = E_1 = E_2 = \frac{FM_1^{\ 3/2}}{\sqrt{R_1}} = \frac{FM_2^{\ 3/2}}{\sqrt{R_2}} -------------------- (4.11)$$

Solving for FM_1 and simplifying gives a relationship between the two measurements for either radius (R) or diameter (d):

$$FM_1 = FM_2\left(\frac{R_1}{R_2}\right)^{1/3} = FM_2\left(\frac{d_1}{d_2}\right)^{1/3} ------------------ (4.12)$$

Equation 4.12 shows that two balls with the same modulus of elasticity will have different FM values from the FirmTech II if they differ in size.

MATERIALS AND METHODS

Materials: The FirmTech II and a universal testing machine (Instron 5544) were the primary instruments used in this study. Other instruments and materials were a digital Mitutoyo vernier caliper, and a fabricated FirmTech II type support with a single pocket like on the FirmTech II. Objects tested included pure gum rubber balls of five different diameters (nominally 15, 25, 28 38 and 51 mm) and blueberries harvested from the horticultural experimental blueberry farm on the Griffin Campus of the University of Georgia.

Experiments:

Test 1.a - Effect of Orientation of blueberry on firmness:

The purpose of this test was to determine the differences in firmness values with orientation of blueberries. Berries were hand-harvested and transferred into a 25 X 40 cm plastic tray. Three sets of twenty-five blueberries were randomly selected and placed in the pockets on the FirmTech II with their calyx facing in the horizontal direction. The maximum force threshold was set at 150g with the minimum set at 50g. After one measurement with the calyx in the horizontal position, the firmness of the same berries was then measured calyx down and then with calyx up.

Test 1b - Force required to cause visible damage:

Three sets of ninety hand-harvested blueberries were placed on the FirmTech II in order to evaluate the force necessary to cause visible damage. The minimum force was set at 50g for a series of tests while the maximum force was in 50g decrements from 500g to 100g. After each test, the blueberries were carefully observed to see if flattening was detectable. The berries were held at room temperature for 24 hours, cut and examined visually, and the percentage bruise damage was assigned on a scale as follows:

1 = no bruise at all,

2 = bruise less than a third of the area of the semi-circle of blueberry after being cut,

3 = damage of about a third of the semi-circle area,

4 = bruise greater than a third of area of semi-circle,

5 = bruising covering the total semi-circle of the berry.

The statistical procedure used here grouped the firmness averages at every maximum force that had the same visual score. The average firmness of the group was then computed to give the corresponding visual score.

Test 1c: Influence of maximum and minimum force on firmness:

One white spherical pure gum rubber ball, 2.54 mm in diameter, having a 45-50 Shore A Durometer value, was compressed once between parallel plates on the Instron to a maximum force of 500 g to obtain a typical force-deformation curve. Slopes (g/mm) were calculated for different combinations of maximum and minimum forces. A three-dimensional response surface was generated to simulate the firmness values that would be obtained from repeated tests with the FirmTech II for the same combinations of minimum and maximum force.

Test 2a: Error Due to Differences in Fruit Radii:

Equation 4.12 shows that FM_2 must be multiplied by the correction factor $(R_1 / R_2)^{1/3}$ to make it equal to FM_1 as necessary for two balls with the same modulus of elasticity. Data were plotted to help visualize the size of the corrections necessary for balls with different radii. Correction factors due to radii were applied to obtain a table to show the effect of different radii on berries with the same moduli.

Test 2b: Composite Error due to both radii and three-halves power on deformation term:

Equation 4.10 gives the correction factor necessary to incorporate the radii and 3/2 th power and to compute the Young's Modulus from the FirmTech II's firmness values. The minimum force in this equation is assumed to be zero. A plot shows the correction factors needed for different deformations and radii was generated to help visualize trends in the correction factors needed in the FirmTech II software to enable calculation of E from the fruit firmness measurements.

Test 3a - Error caused by the support pockets:

Rubber balls (same as described in test 1c) with five different radii were tested for firmness on the Instron, first under parallel plate deformation and then using a plate with the FirmTech II type pockets. Three replications of the same test were performed. Force-Deformation curves were plotted using spreadsheets for both tests. FirmTech II type firmness values were computed from the plots for each ball using settings of 50g minimum and 150 g maximum. In addition, repeatability was evaluated by making multiple tests on the same 15 mm diameter pure gum rubber ball after removing it and placing it back into the pockets and between the parallel plates on the Instron.

Test 3b - Overall comparison between FirmTech II and Instron:

Seventy-five randomly selected blueberries were tested on the FirmTech II set at a maximum force threshold of 150 g and a minimum at 50 g. The same berries were then tested on the Instron to a maximum force of 150 g and at the same load cell speed as on the FirmTech II. Moduli of elasticity values were computed from the force-deformation plots using equation 4.1 (A value of 0.4 was assumed for the Poisson's ratio, μ). Equation 4.9 was applied to real blueberry FirmTech II firmness values and the corrected E-values plotted against the actual calculated E-values from parallel plate compression (equation 4.1). On the same plot, actual FirmTech II firmness values simulating single plate deformation were plotted for comparison.

RESULTS AND DISCUSSION

Test 1.a - Effect of Orientation on Blueberry Firmness:

Significant differences in FirmTech II values were obtained with respect to berry orientation (Table 4.1). The calyx up orientation gave the highest average firmness, followed by the calyx down, and the lowest value was obtained with the calyx horizontal. This difference is probably caused by the structure of the blueberry, which is softest across the "cheeks" and firmest along the calyx (longitudinal). The differences due to orientation provide strong evidence that comparisons should not be made from tests using different orientations. Therefore, we recommend the common practice of testing blueberries in the calyx-horizontal orientation. It should be noted, however, that since the order of testing (calyx-up, down, horizontal) was the same each time, there could be a bias in the result.

Table 4.1: Effect of orientation on blueberry firmness

Orientation	Mean, g/mm
Calyx Up	292 a
Calyx Down	262 b
Calyx Horizontal	211 c

Note: Means with the same letter are not significantly different ($p < 0.05$).

While conducting the orientation test we noted a consistent trend for second and consequent tests to give higher firmness values if the berries were not disturbed (moved), between tests. A replicated test then showed the average firmness readings for blueberries taken from a second test were up to 23 % higher than the first readings (Figure 4.2). A possible explanation is the first test is lower because some of the deformation measured was from movement of the berry into the pocket. Therefore, it is critical that users are consistent when recording firmness from either the first or the second tests. Users should be aware that a repeated test on a set of berries would give higher values of firmness if the berries are not moved and replaced in the pockets.

Close observations showed that some berries moved more than others resulting in some of the variation recorded compared with the second test because less movement of the whole berry resulted after it had conformed to the shape of the pocket.

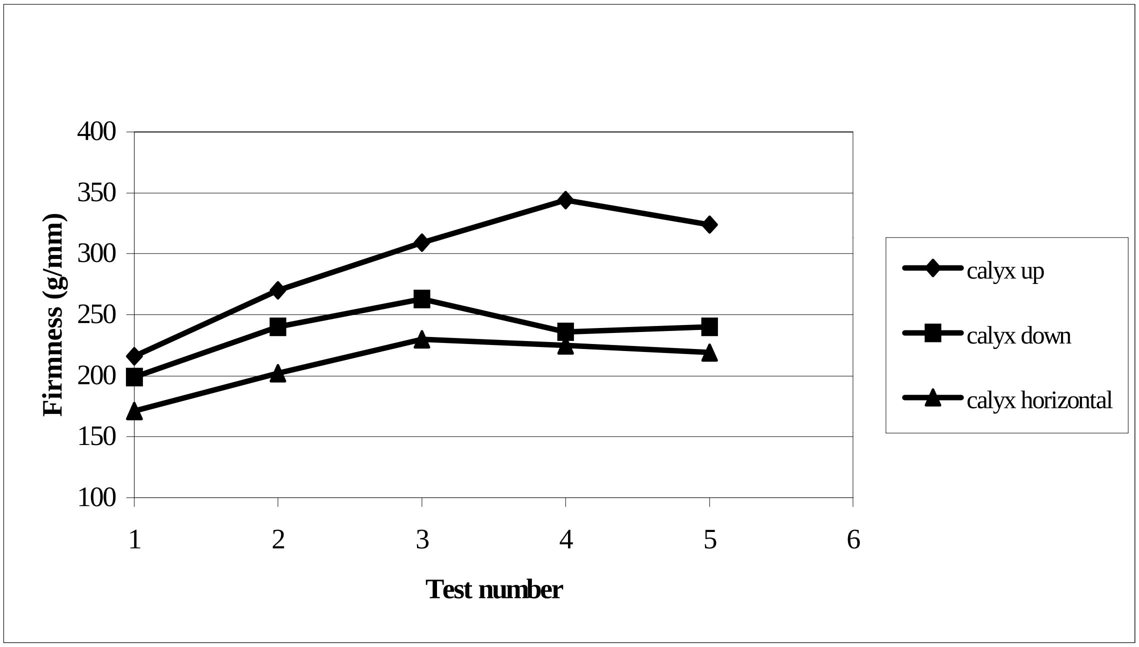

Figure 4.2: Effects of Multiple Test Runs on Berries

Test 1b - Force to cause damage:

Table 4.2 indicates that forces of up to 182 g did not cause any visible damage. An average force of 291 g was necessary before any bruising became visible. The bruising in the berries showed in a shape of a triangle spreading out from the center of the fruit. This was possibly due to the point of contact of the load cell or the pockets in which the berries were supported. Therefore, a maximum setting of 150 g is recommended for blueberries if non-destructive tests are desired. A minimum force of 50 g is recommended based on the need for the berries to conform to the shape of the holder.

Table 4.2: Mean Force giving bruise ratings from no visible damage (with a score of 1) to bruising covering half of cut blueberry (score of 5).

Mean Force, g	Bruise Rating	N
457 a	4	43
399 b	3	54
291 c	2	73
182 d	1	100

Note: Means with the same letter are not significantly different ($p < 0.05$).

Test 1c - Influence of maximum and minimum force on firmness:

An understanding of a typical force versus deformation plot is valuable for the results obtained from both the FirmTech II instrument and the Instron (Figure 4.3).

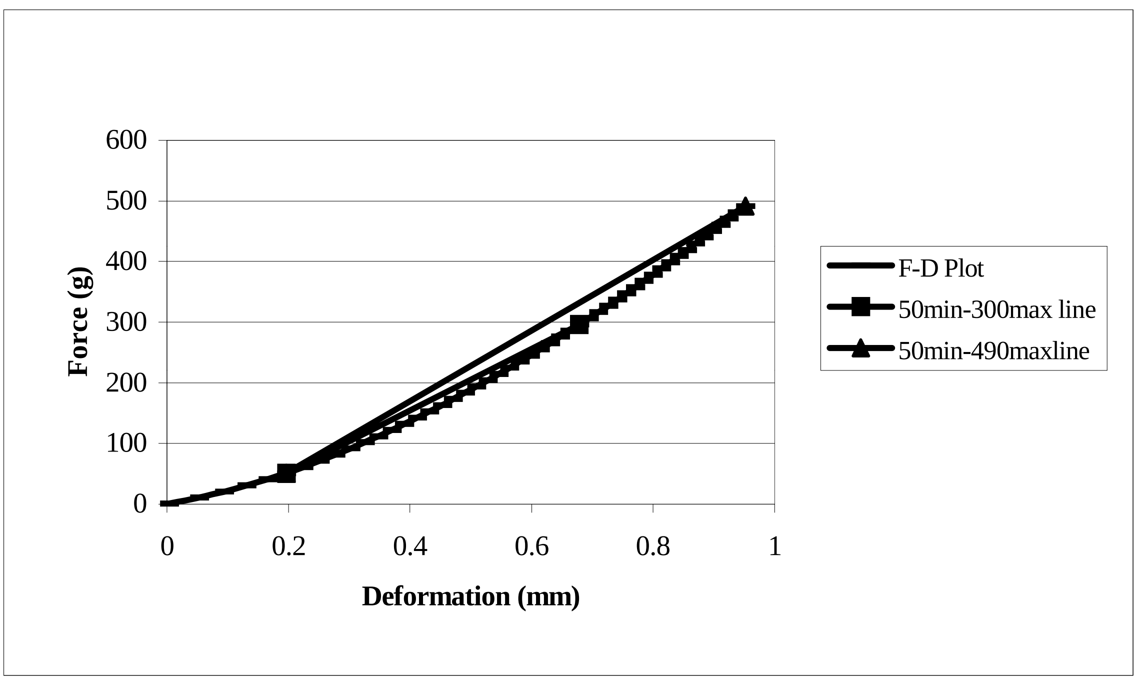

Figure 4.3: A typical force-deformation curve with slopes for selected minimum and maximum force setting.

The curve in figure 4.3 is from a parallel plate test using an Instron on a rubber ball. The two straight lines represent the firmness values (slope in g/mm) to simulate results from the FirmTech II at a minimum force setting of 50 g and maximum settings of 300 and 490 g. The differences in the slopes indicate that one ball would give different firmness values for the FirmTech II if minimum or maximum force settings are changed. The plot also shows the curvilinear nature of the force versus deformation data as expected from equations 1 or 2.

A three-dimensional plot (figure 4.4) of firmness (g/mm) against the maximum and minimum forces was obtained from a single force-deformation plot (figure 4.3) by determining the slope for different combinations of minimum and maximum force. The plot indicates that the variation of the two variables can have a large effect on the output of firmness reported by the instrument for the same rubber ball. The equation of the paraboloid surface was:

$$\text{Firmness} = 279 + 1.531\ \text{Min} + 0.753\ \text{Max} - 0.00532\ (\text{Min})^2 - 0.000516(\text{Max})^2 \quad \ldots\ldots\ldots(4.13)$$

where: Firmness is in g/mm units

Min = Minimum force (g)

Max = Maximum force (g)

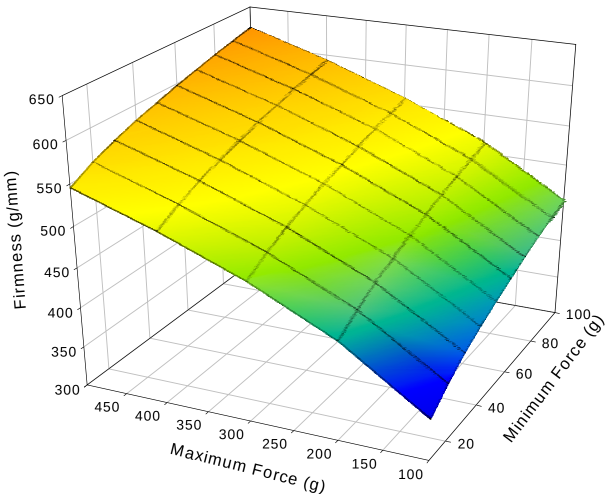

Figure 4.4: Response surface showing effect of changing minimum and maximum forces setting on the FirmTech II instrument.

The good correlation (R^2 = 0.997) indicated a very consistent relationship among the variables. The surface in figure 4.4 shows a large increase in the firmness value would be obtained from one item when either the minimum or maximum force setting is increased. The shape of the surface and equation 4.13 reveals that firmness values are more sensitive to the minimum than maximum forces. Figure 4.4 and equation 4.13 shows the absolute necessity for standardizing the minimum and maximum force settings when using the FirmTech instruments. Results cannot be directly compared if the tests were not done at the same settings. Based on this research the recommended procedure is to use only the first measurement from blueberries tested with their calyx horizontal at a minimum force of 50 g and a maximum force of 150 g.

Test 2a: Error Due to Differences in Radii:

Figure 4.5 is the plot generated from equation 4.12 showing the multiplier correction factor necessary to make FM_2 equal to FM_1 for balls with equal modulus of elasticity.

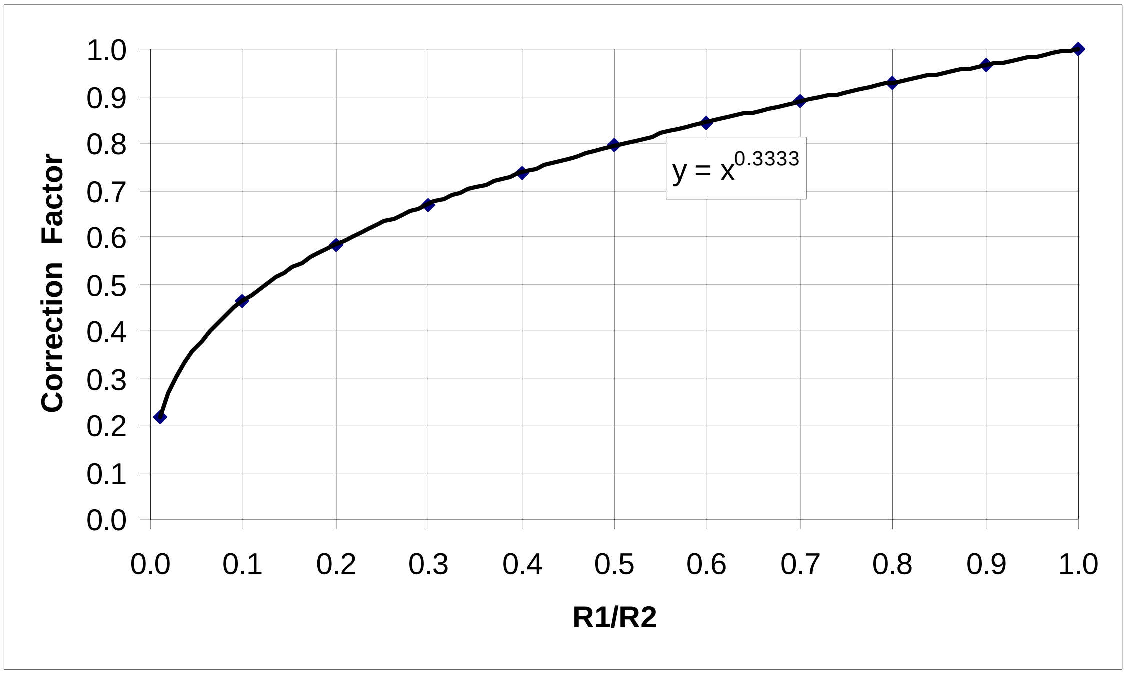

Figure 4.5: Correction factors needed when radii differ for two items with the same modulus of elasticity.

As expected, when R_1 equals R_2 the correction factor is 1.0. Using this data, the firmness measurement from the FirmTech II for a 20-mm diameter (10-mm radius) blueberry would need to be multiplied by 0.8879 to equal the firmness measurement from a 14-mm diameter (7-mm radius) blueberry. Likewise, if R_1 is one half of R_2, the firmness measurement for blueberry one will be 79.37 percent of blueberry two. The correction factor changes rapidly for ratios less than 0.2.

It is important to note that larger blueberries give a higher firmness measurement than they should compared to smaller blueberries. This is illustrated in Table 4.3 for a 10mm diameter blueberry with a firmness value of 70 g/mm. The equivalent FM indicates the FM values needed for a blueberry to have the same firmness E, as the 10-mm diameter berry. Note that a 5mm reduction in size gives a 14-g/mm change while a 5-mm increase gives only a 10-g/mm change.

Table 4.3: Variation in firmness values due to different diameters

Diameter , mm	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Equivalent FM	56	59	62	65	68	70	72	74	76	78	80	82	84	85	87	88

Test 2b: Composite error due to no radius term and the 3/2 th power on deformation term:

Equation 4.10 can be used for computing correction factors needed for converting FM values to values of E. Figure 4.6 shows a response surface of correction factors for selected combinations of deformations and radii. The graph shows the effect of the neglect of radii and the 3/2th power on deformation. Higher values for correction are needed for small deformations and small radii blueberries.

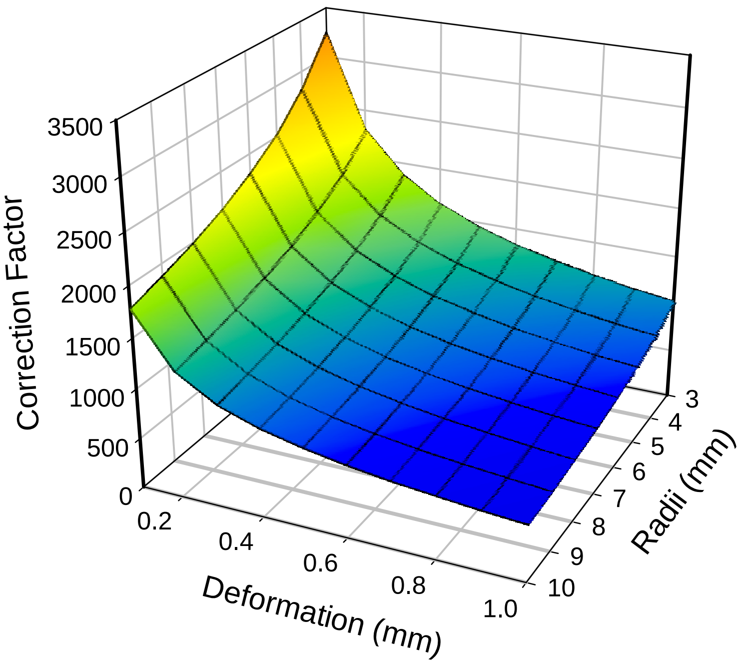

Figure 4.6: Graph showing relation between the deformation, radii and correction factor needed to compute E.

From the FirmTech II instrument as it stands, the power term can easily be incorporated into the software. The plot shows less necessity to include the radius as previously thought since changes in radii did not cause large changes in the correction factor within typical values for radii and deformations.

Test 3a - Error caused by the support pockets:

Tests to estimate the amount of error that could be caused by the interaction of the support pockets and items tested were completed with an Instron universal testing machine in order to minimize any errors that might result from the load cell or deformation measurements using the FirmTech II.

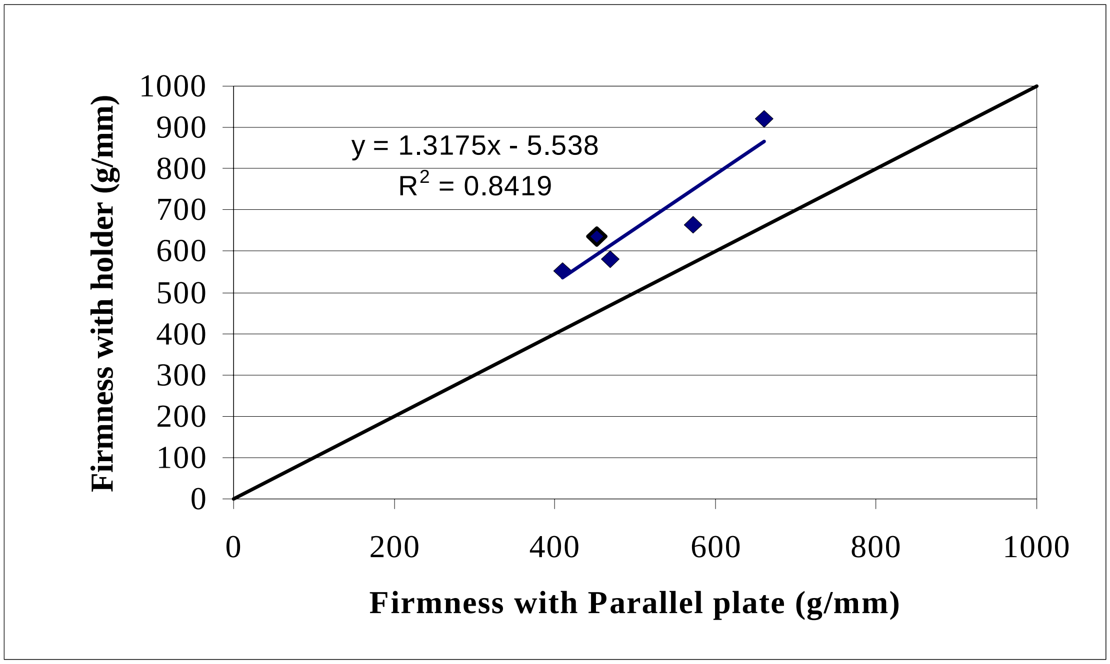

Figure 4.7: Effect of support pockets on firmness values

The five rubber balls that were tested showed different firmness values (slope at 50 g minimum and 150 g maximum force) for parallel plate tests than for the pockets. All the firmness values from the pockets were higher than the parallel plate tests by an average 31 %. A regression line through the points shows the slope differs from unity, indicating the error increases as firmness increases. The points would be on the 45-degree line if there were no differences between the two support methods. Higher firmness values with the holder indicate smaller deformations due to distribution of the force over a larger contact area. Therefore, force-deformation plots from measurements with the FirmTech II type support are a combination of parallel plate (equation 4.1) and single plate (equation 4.2) compression.

In a related test, repeated tests on the same 15 mm diameter pure gum rubber ball 9 times with and without the pockets confirmed the plot above, with the pockets giving a firmness 42 % higher than the parallel plate. The different sized balls, however, gave different percentage differences, the smallest ball giving the highest, 40%, and the largest ball, giving the smallest difference, 16 %. The standard deviations obtained from the Instron for parallel plate and the FirmTech II type holder on the same 2.54-mm pure gum rubber ball were 2.35 and 6.44 g/mm respectively. Figure 4.7 and the repeatability tests show that the pockets need to be redesigned to hold the blueberries better, or better still to use the parallel plate loading with a means of stabilizing the blueberries. This would reduce the errors introduced by the holder.

Test 3b - Overall comparison between FirmTech II and Instron:

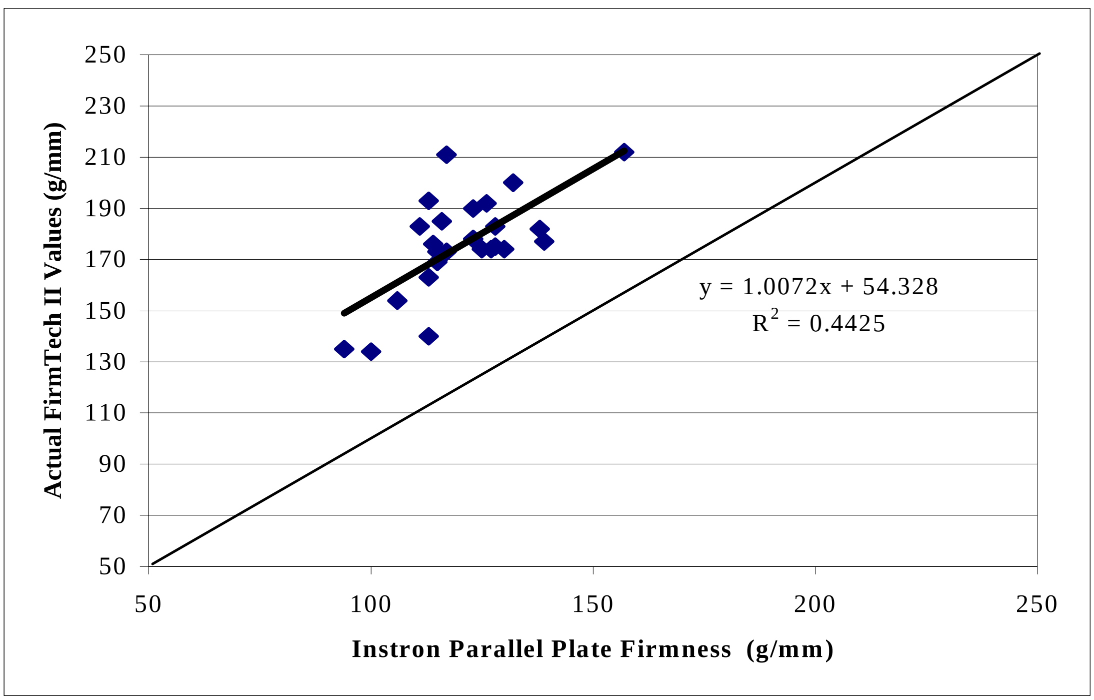

Figure 4.8: Comparison of 25 blueberry firmness values from FirmTech II with similar measurements obtained from Instron data.

Tests with 25 blueberries showed a rather poor overall correlation ($R^2 = 0.4425$) between the actual FirmTech II firmness measurements and the computed values from the Instron

(Figure 4.8). The blueberry data is in a similar location relative to the 45 ° line as the rubber ball data in figure 4.7 indicating similar movements in the support pocket. As expected, the slope was nearly unity, although the FirmTech II values showed an average 45 % higher than the Instron computed firmness values. This high percentage difference indicated that there was more error with the small radii blueberries and balls due to the holder than the bigger ones.

In much the same way, the correction factors computed using equation 4.9 were applied to the actual FirmTech II firmness values from figure 4.8, and the values obtained plotted against the actual E-values from Instron parallel plate data as shown in figure 4.9 below.

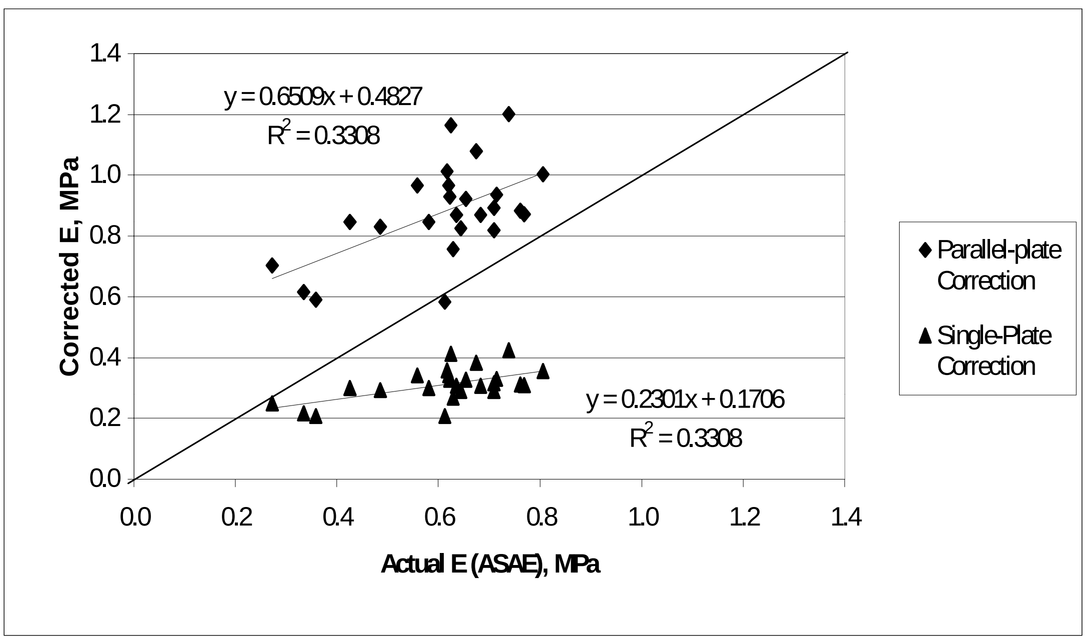

Figure 4.9: Comparison of Corrected E-value against actual computed E-values.

The data points above the 45 ° line were calculated using equation 4.9 with constant C_1 which assumes the FirmTech II compresses the berries between parallel plates. The data below the 45 ° line uses the constant C_2 which assumes single plate compression.
The correlation between both parallel and single plate corrected E-values and the actual computed values were low (R^2 =0.3308). Figure 4.9 shows that the FirmTech II operates somewhere between parallel plate and single plate compression. Based on where the regression lines intersect the 45 ° line, the plots show that at low E-values (soft fruit), the FirmTech II approximates a single plate compression while for higher values of E, it approximates the parallel plate compression. Ideally, both plots should have been parallel to and close to the 45 ° line but they do not due to errors inherent in the instrument's operation. The errors associated with these two plots were most likely be due to differences in berry shape, load cell resolution and precision of the deformation measurements. Another important source of error is the holder. The use of equation 4.1 assumes a parallel plate deformation, therefore assuming the FirmTech II was also parallel plate. However, small blueberries that sit in the holder can approximate to parallel plate while larger ones will actually deform according to equation 2, the single plate deformation.

CONCLUSIONS

1. Controlled studies have verified that measurement conditions must be specified to enable comparisons of results from firmness measurements made with FirmTech II instruments. Recommendations for nondestructive measurements on blueberries are: to

use only the first measurement, to position the calyx horizontally, and to use force settings of 50 g minimum and 150 g maximum.

2. Differences in blueberry radii cause larger berries to appear firmer than smaller berries with the same modulus of elasticity. The firmness measurement of a blueberry with twice the radius of a smaller berry must be multiplied by 0.79 to give the equivalent value.

3. Neglect of radius and power term introduces some errors. 3-D Plot indicated more errors at smaller values of radii and deformation.

4. The actual FirmTech II firmness measurements of blueberries had a poor correlation (R^2 = 0.4425) with computed firmness measurements determined by parallel plate measurements from the Instron. A similar low correlation value (R^2 = 0.3308) was obtained for the actual ASAE E-values compared with E-values calculated from both single-plate and parallel plate compression tests. The FirmTech II's operation lies between the two.

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CHAPTER 5

MODELLING THE EFFECT OF POSTHARVEST COOLING DELAYS ON THE RATE OF FIRMNESS AND MASS LOSS OF BLUEBERRIES[1]

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[1]Tetteh M.K., S.E. Prussia, D.S. NeSmith and B.P. Verma. To be submitted to the Transactions of the ASAE.

ABSTRACT

Blueberry mass and firmness losses in a postharvest environment were tested to determine dependence on delays of cooling and ambient field temperatures. Models were generated from the slopes from plots of firmness and mass against time for four temperatures (4, 21, 27 and 32 ° C). The models were evaluated by holding blueberries at three temperatures (21, 27 and 32 ° C) and at high relative humidity of 95 %. Fruit were then subjected to delays of 0, 2, 4, 8, 12 and 24 hours before they were cooled to 4 ° C. Predicted versus observed data showed that it is possible to model the mass and firmness losses of blueberries at different temperature and cooling delays. Impact of delays was most obvious at 32° C and less at 21° C.

INTRODUCTION

Blueberries, being living things, continue to respire after they have been harvested. They are becoming an increasingly important fruit crop in the Southeastern U.S. Current strategies of farmers are to cool their berries as rapidly as possible after harvest. On-farm portable coolers have been used to cool the fruit just as they are taken off the bushes. In addition, (Boyette et al., 1993) have advocated harvesting when it is cool (i.e., late afternoons and early mornings) and advise that delays in cooling should not exceed four hours.

Thai et al. (1989) studied the quality changes of tomatoes by quantifying changes in tomato color and firmness. Exponential equations were found to closely model changes in color as individual fruit ripened. However, the similar models for firmness changes were less successful (lower values for R^2) due to the unavailability of a non-destructive firmness instrument for following firmness changes of each fruit.

For this study, the non-destructive ability of the FirmTech II enabled repeated measurements of firmness on the same blueberry. Likewise, changes in mass can be monitored during storage of blueberries at different temperatures. Analyses of the resulting data should provide relationships for better understanding the consequences of delays in cooling blueberries.

The overall purpose of this study was to develop models for rates of deterioration for blueberry mass and firmness at different temperatures with respect to different delays of cooling and to use the models to predict firmness and mass values over time.

LITERATURE REVIEW

Postharvest cooling rapidly removes field heat from freshly harvested commodities such as blueberries before shipment, storage, or processing and is essential for many perishable crops (Boyette et al. 1993). Proper postharvest cooling is known to have a number of effects:

- It suppresses enzymatic degradation and respiratory activity (softening)
- Slows or inhibits water loss (wilting)
- Slows or inhibits the growth of decay-producing micro-organisms and
- Reduces the production of ethylene (a ripening agent) or minimizes the products reaction to ethylene.

Many consumers purchase fresh fruit such as blueberries on impulse and are prompted primarily by the perception of quality. Wholesale buyers also associate appearance and firmness with fruit quality and freshness. In addition, price and particularly reputations (of farmers) depend largely on quality (D. Morris, personal communication, Baxley, Georgia, 27 June 2001).

Blueberries left at ambient temperature after harvest rapidly loose firmness due to high respiration rates (Boyette et al. 1993). At 27°C, blueberries can produce as much as 22,000 Btu per ton per day from heat of respiration (Hardenburg, et al. 1986). Unless this heat is removed by cooling, it can cause up to a 6 °C rise in temperature (Boyette et al. 1993). Cooling lowers the respiration rate, slowing the ripening process and accompanying decline in quality. The respiration rate of blueberries held at 27°C, is nearly 20 times the rate of those held at 4.4°C. In other words, blueberries held at 4.4°C have nearly 20 times the shelf life of those held at 27°C (Boyette et al. 1993).

A review of the kinetics of thermal softening of foods by Rao and Lund (1986) concluded that first order kinetic expressions are suitable for expressing the degree of softening at a constant temperature. The effect of temperature on softening can be expressed by an Arrhenius relationship (Huang and Bourne, 1983; Toledo, 1991). Bourne (1982), in studies on the effect of temperature on fruits and vegetables, found that the firmness-temperature relationship was approximately linear. Thai et al. (1989) obtained an exponential relationship between tomato firmness changes and time. In a delay of cooling study by Garner et al. (1987) on peaches, it was observed that delays of up to two hours was acceptable after storage under warehouse conditions. In addition, they reported that more mature fruit had to be cooled earlier than less mature fruit.

A study by Jackson et al., (1999) concluded that minimizing delays (before storage) is the best option for maximizing fresh low-bush blueberry quality. The same study suggested that before-storage delays beyond 21 hours resulted in a marked loss of firmness, particularly at pre-packing temperatures above 25°C. Nesmith et al. (2002) reported a firmness decrease of rabbiteye blueberries of about 3 to 8 % in pre-storage firmness when fruit was kept at ambient temperature for 24 hours after harvest. In a similar study on table grapes, Crisosto et al. (2001) reported that table grapes suffer water loss and stem browning during cooling delays.

Sanford et al. (1991) determined that increasing the storage temperature of low - bush blueberries resulted in higher levels of split, shriveled and decayed berries. The storage temperature was found to have a greater impact than bruise damage on fruit firmness. In preliminary delay of cooling studies on blueberries in June of 2000, we observed that softening was followed by increasing firmness during prolonged storage, apparently due to loss of moisture from the fruit.

ANALYSIS

The temperature dependence of a reaction rate constant can be expressed by the Arrhenius equation:

$$\ln K = \ln A - E_a/RT \Rightarrow K = A * e^{[-Ea/RT]} \text{------------------------------ (5.1)}$$

(Huang and Bourne, 1982), where K is the reaction velocity constant, E_a is the activation energy, R is the universal gas constant, A is the rate constant and T is the temperature (in degrees Kelvin). This relates reaction velocity, or rate constant to the absolute temperature. This equation can be used to describe the rate of change of firmness of the blueberry fruit since firmness depends on the temperature of the fruit of the ambient environment Toledo, (1991). In studies by Thai et al., (1990 and 1989), the following was observed:

If Q is a quality attribute, for example, firmness in this case, to model with respect to time and temperature, the following type equation was found to apply:

$$f(Q) = f(Q_o) + \rho t \text{ -- (5.2)}$$

Where ρ = reaction rate or slope depending on temperature,

t = time

Q_o = initial quality attribute at time = 0

f = function of Q, say firmness F.

Thai et al. (1989) used an exponential for reaction rate (ρ) in equation 5.2 to fit their data of firmness of tomatoes, however, they had to use the averages of groups of tomatoes since the firmness tests were destructive. A poor correlation was obtained for the fit, and hence they suggested that a non-destructive firmness instrument needed to be used in order to obtain the predictive equation desired. The FirmTech II fits the profile of this non-destructive instrument and it was used in this study. A linear variation of equation 5.2 was used to model the firmness and mass losses of blueberries in this study.

MATERIALS AND METHODS

Blueberry Studies:

Blueberries of the cultivar Tifblue were hand-harvested at typical commercial harvesting maturity level at the Horticulture Experimental Farm in Griffin, Georgia. The fruit were harvested into plastic clamshells and transported to the Postharvest Systems Laboratory within 10 minutes of harvest. Firmness was measured with the FirmTech II firmness instrument marketed by BioWorks Inc. The mass of each blueberry was measured with a Mettler-Toledo PR 503 balance. Large walk-in coolers (made by International Cold Storage Company) were set at the different temperatures needed for this study. The berries were placed in plastic bags to maintain high relative humidity during storage.

Test 1: Modeling Mass and Firmness Changes for Different Constant Temperatures

Blueberries were randomly selected and placed into individually numbered plastic cups (one for each blueberry) and 20 of these cups were placed into custom wooden trays. The FirmTech II was set at a maximum force of 150g and a minimum of 50g. Blueberries were tested for firmness during storage at temperatures of 4, 21, 27 and 32° C, and at every 4 hours for the next 48 or more hours. The berries were also weighed immediately after each firmness test to determine mass.

Test 2: Modeling Mass and Firmness Changes for Different Cooling Delays and Holding Periods

A set of 6 trays (each containing 2 sets of 10 randomly selected blueberries making a total of 120 berries) were tested for firmness and mass initially and then delayed 0, 2, 4, 8, 12 and 24 hours at 4, 21, 27 and 32 ° C before cooling. They were then tested every 4 hours after cooling to 4 ° C for the next 48 to 100 hours. Testing for firmness and weighing were done concurrently.

GENERATION OF MODELS

Linear slopes adequately described the rates of mass and firmness deterioration at the different temperatures as indicated by the example for mass in figure 5.1.

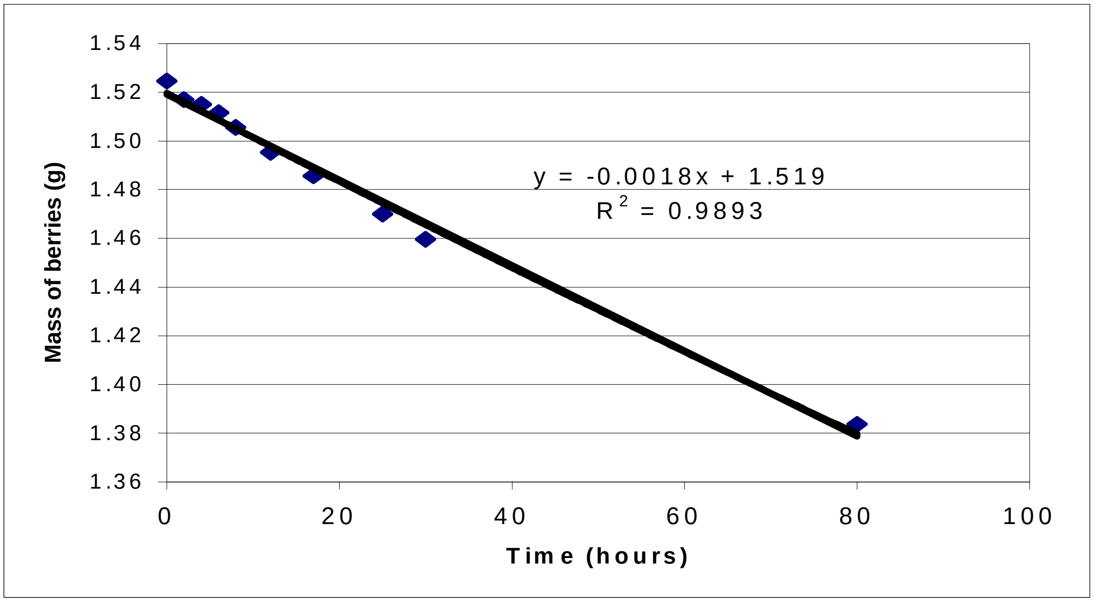

Figure 5.1: Sample plot showing linearity of mass deterioration at 21 C

The slopes from similar mass versus time plots for other temperatures are plotted in figure 5.2 for mass and figure 5.3 for firmness. The high correlation for both mass and firmness confirm exponential relationship expected between the slopes and temperature, T as shown from equation 5.1.

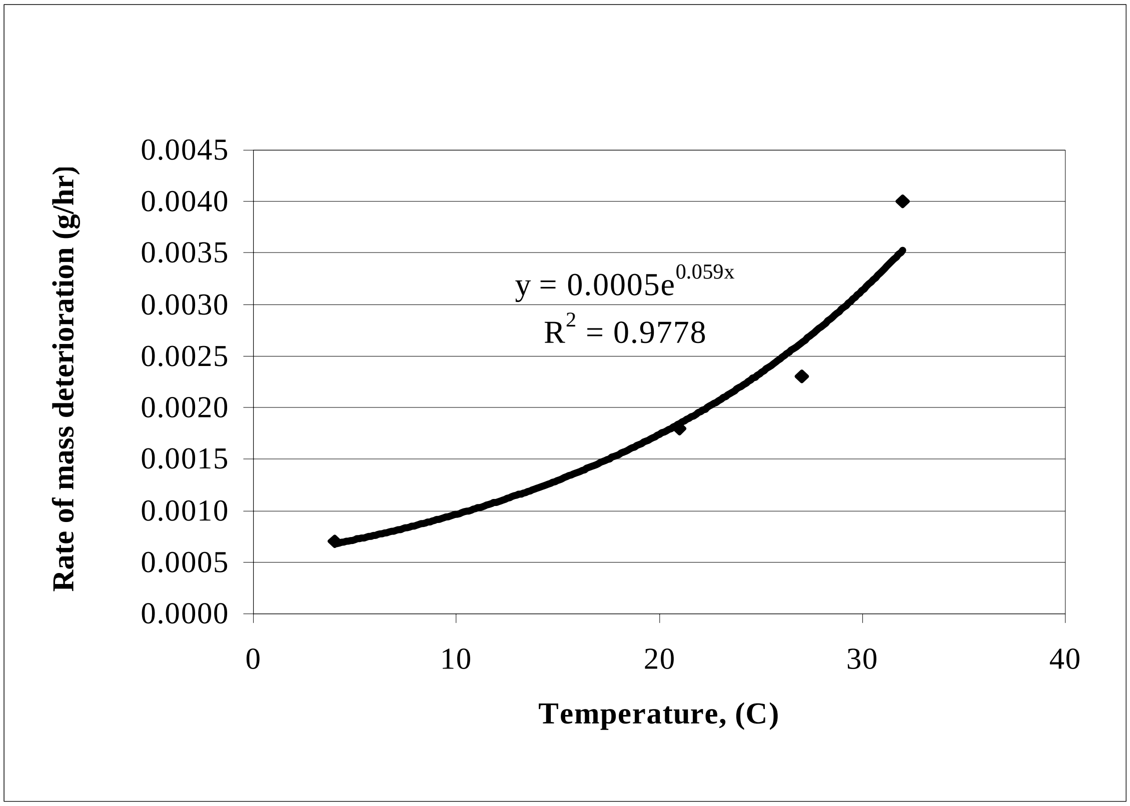

Figure 5.2: Rate of blueberry mass deterioration showing an exponential increase with increasing temperatures

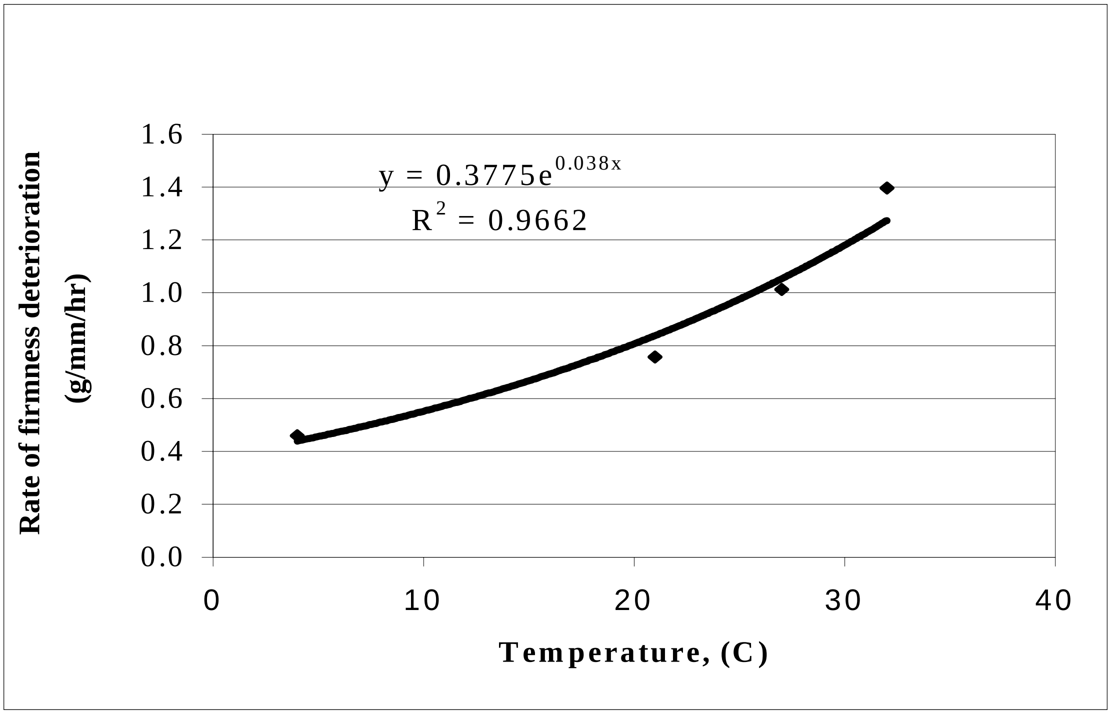

Figure 5.3: Rate of blueberry firmness deterioration showing an exponential increase with increasing temperature.

Figures 5.2 and 5.3 provide the basis for the model formulation and can be used to predict different conditions of postharvest cooling delays. A general linear equation for reduction of firmness is given by:

Firmness $_{(t=t)}$ = Initial Firmness $_{(t=0)}$ – slope * time (t)---------------------------------(5.3)

Equation 5.3 was obtained from equation 5.2 with the negative sign indicating the negative slope obtained from firmness deterioration plots such as in figure 5.1 for mass deterioration. The expression for the slope as a function of temperature can be obtained from Figure 5.3, which means equation (5.3) can be re-written as:

$$\text{Firmness}_{(t=t)} = \text{Initial Firmness}_{(t=0)} - \left[0.3775 * e^{0.038\text{Temp}}\right] * \text{time (t)}\text{-------------}(5.4)$$

Similarly, for mass the model obtained from equation 5.2 and the slope from figure 5.2 is given by:

$$\text{Mass}_{(t=t)} = \text{Initial Mass}_{(t=0)} - \left[0.0005 * e^{0.059\text{Temp}}\right] * \text{time (t)}\text{----------------------}(5.5)$$

In equations 5.4 and 5.5, changing the values of the temperatures and times will simulate different field temperatures and different cooling delays or changes during storage. These equations can be expanded to predict firmness for selected temperatures for the combined periods before cooling and during storage by using the firmness value calculated from equation 5.4 as the initial firmness and using equation 5.4 again to calculate firmness during storage:

$$F = F_H - t_D\,[0.3775 e^{0.038T_D}] - t_S\,[0.3775 e^{0.038T_S}]\text{ --------------------------------------}(5.6)$$

Where: F = Firmness, g/mm

F_H= Firmness at harvest, g/mm

t_D = time delay between harvest and cooling, hours

T_D= temperature during delay before cooling, ° C

t_S = time stored after cooling, hours

T_S = Temperature during storage, ° C

A similar equation can be written from equation 5.5 for mass:

$$M = M_H - t_D\,[0.0005e^{0.059T_D}] - t_S\,[0.0005e^{0.059T_S}] \text{ ---------------------------------------(5.7)}$$

Where: M = Mass, g

M_H= mass at harvest, g/mm, and all other symbols are the same as for equation 5.6.

RESULTS AND DISCUSSION

Examples of blueberry mass and firmness predictions from the models developed (equations 5.6 and 5.7) are shown by Figures 5.4 and 5.5 below, along with observed values.

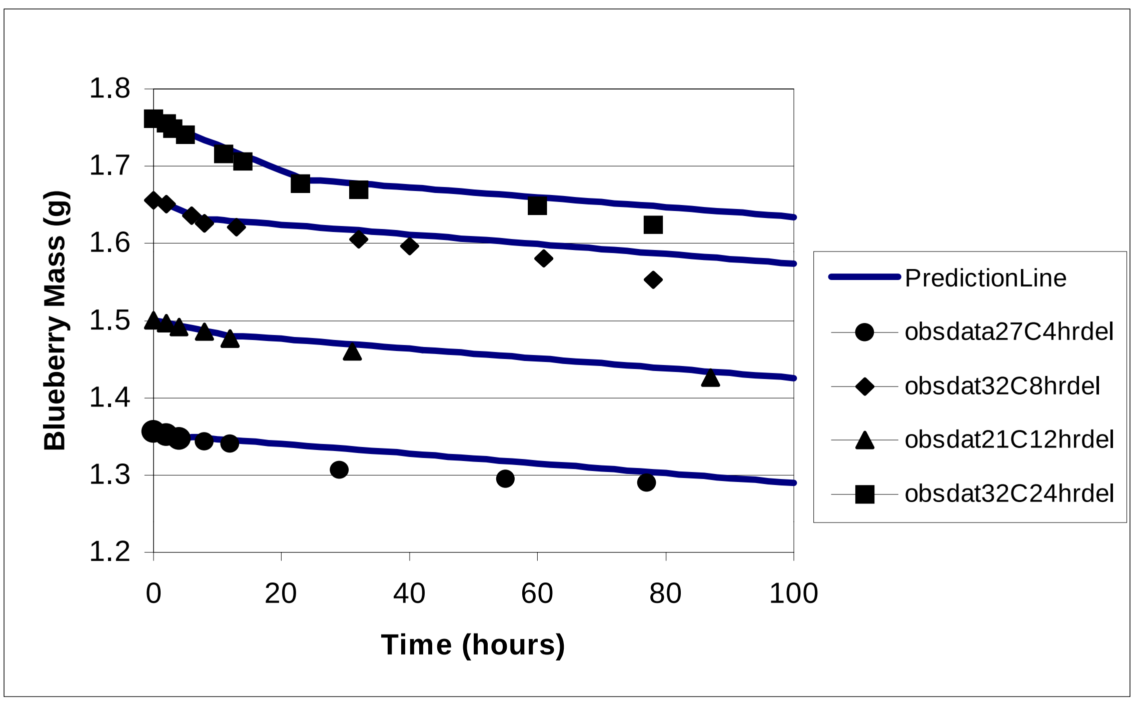

Figure 5.4: Graph showing validation of the mass loss model.

The legend shows the symbols used for prediction lines and observed data (for example 21 °C, with a 12-hour delay shows on graph as obsdata21C12hrdel). The delays in cooling were followed by storage at 4 °C. The plots indicate that the rates of mass and firmness loss during storage of the berries were similar regardless of the length or temperature of delays before cooling. Apparently, little or no residual damage due to temperature stresses occurred. In other words, predisposing fruit to different prestorage temperatures did not affect rate of deterioration during storage.

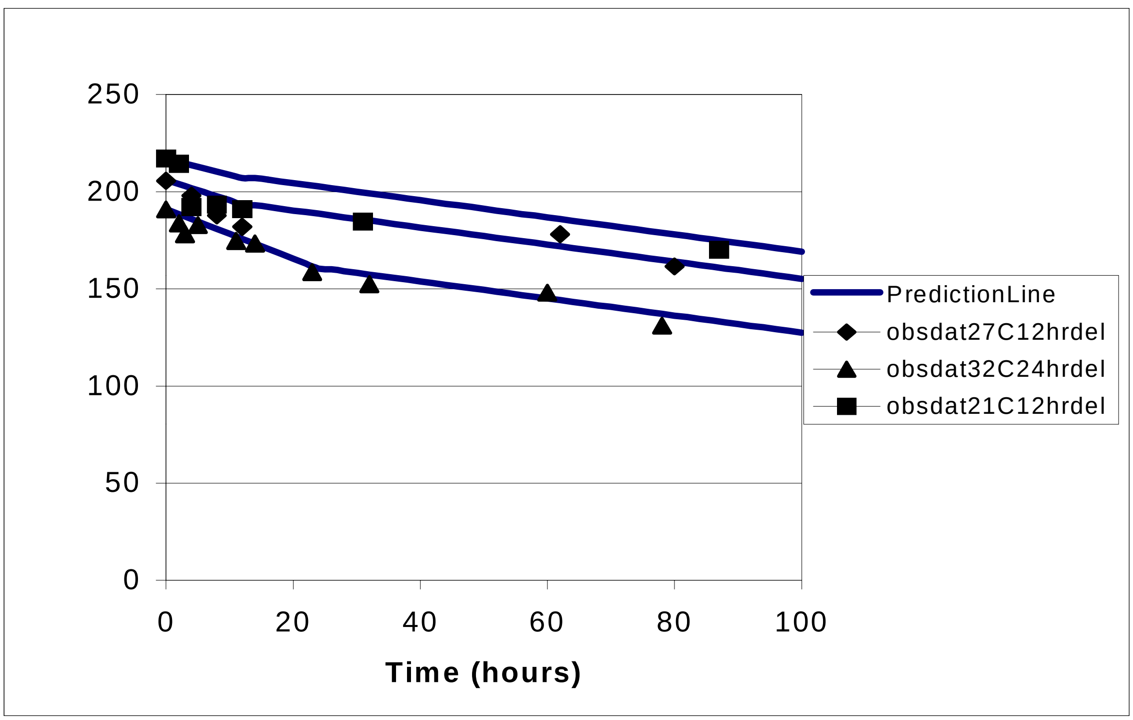

Figure 5.5: Graph showing validation of the firmness loss model.

In addition, duration of prestorage temperature exposure did not affect the rate of deterioration during storage. The interactions of prestorage ambient temperatures and the storage temperature can therefore be modeled using equations 5.6 and 5.7.

Plots of predicted against observed values for the data points representing all temperatures and delays and storage times (including those in figures 5.4 and 5.5) showed a strong correlation ($R^2 = 0.9393$ and $R^2 = 0.7213$) to the predictions obtained with the model. Overall the model predicted blueberry mass and firmness losses, however, there were some under-predictions and over-predictions. The pattern of variability is to be expected with agricultural and biological data. The mass data provided a better fit than the firmness data. This could be due to a combination of instrument errors and general noise in the firmness data as discussed in chapter 4.

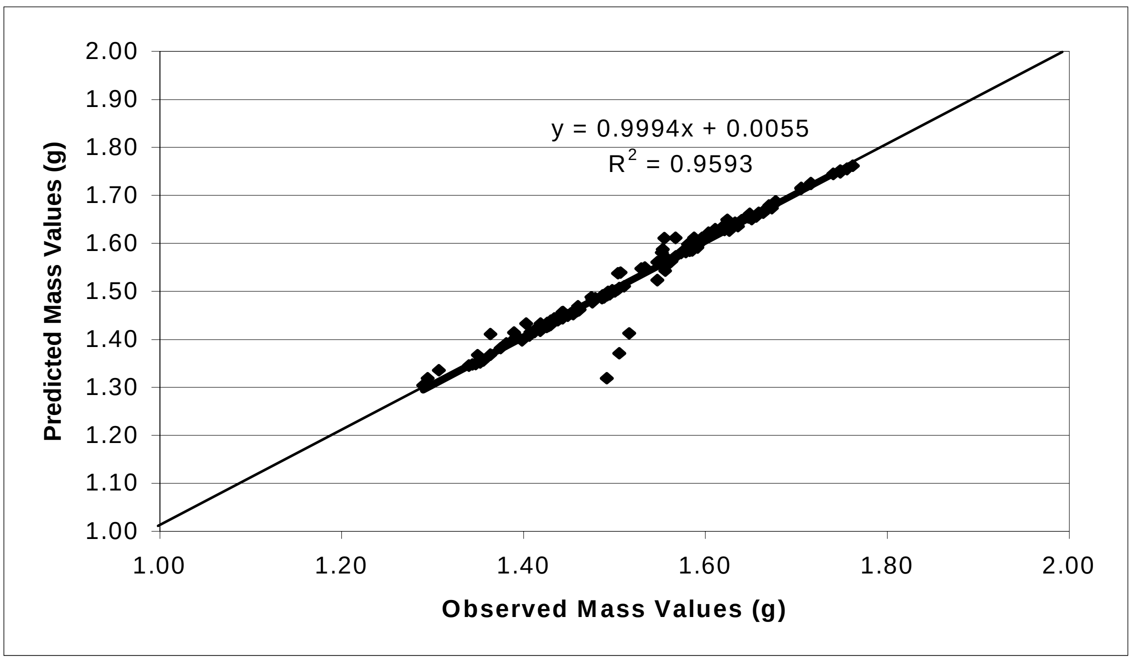

Figure 5.6: Plot showing predicted versus observed mass values (n=146 data points).

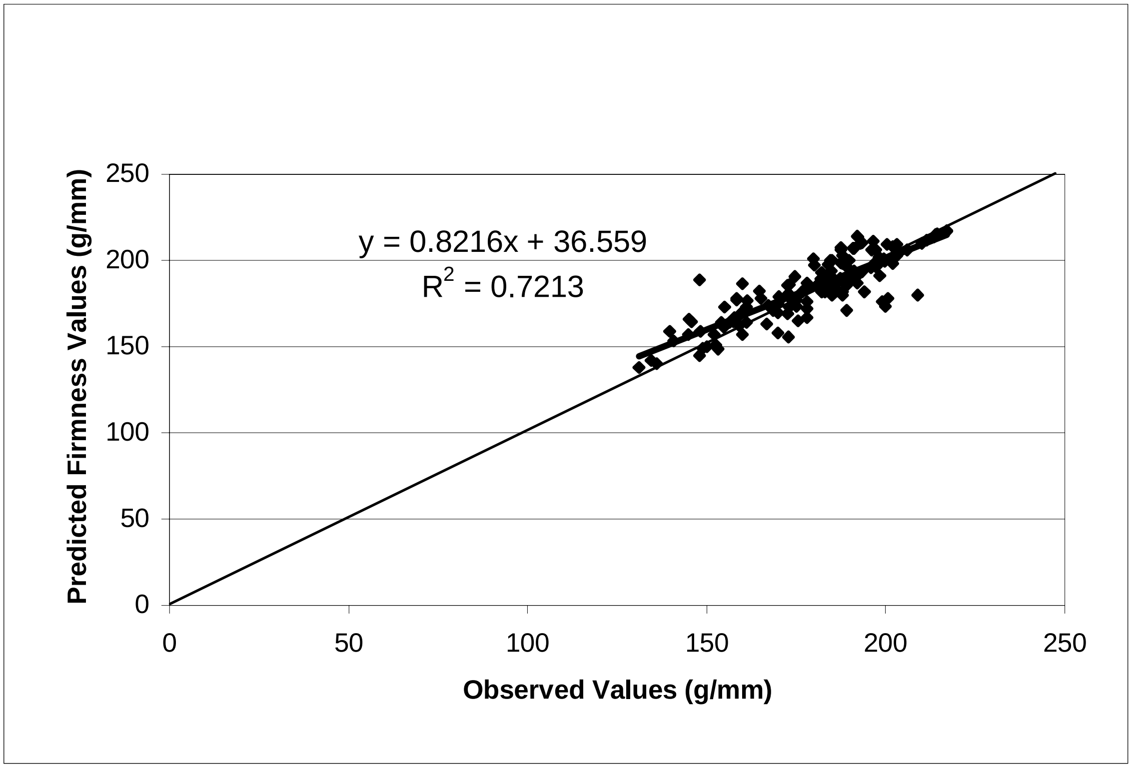

Figure 5.7: Plot showing predicted versus observed firmness values (n=138 data points).

The models developed (equation 5.6 and 5.7) for calculating predicted percentage losses of firmness and mass after a 24 hour period that included delays of cooling at three different temperatures (20, 28 and 35 ° C) followed by cooling at 2 ° C. Starting firmness and mass values of 200 g/mm and 1.6 g were used for these computations.

Table 5.1: Predicted percentage firmness loss after 24 hours.

Temp., °C	0 hr delay	2 hr delay	4 hr delay	8 hr delay	12 hr delay	24 hr delay
35	4.9	5.9	6.9	9.0	11.0	17.0
28	4.9	5.6	6.3	7.6	9.0	13.0
20	4.9	5.3	5.7	6.5	7.3	9.7

Table 5.2: Predicted percentage mass loss

Temp.,°C	0 hr delay	2 hr delay	4 hr delay	8 hr delay	12 hr delay	24 hr delay
35	0.8	1.3	1.7	2.5	3.4	5.9
28	0.8	1.1	1.4	1.9	2.4	3.9
20	0.008	0.01	1.1	1.4	1.6	2.4

Similar data can be obtained for different temperatures and times of interest to growers and packers. The percent loss in firmness of blueberries 24 hours after harvest are shown in Table 5.1 for three ambient temperatures (20, 28, and 35 C) during delays in cooling of 0, 2, 4, 8, 12, and 24 hours (0 = immediate cooling and 24 = no cooling) followed by storage at 2 C. The results show that ambient temperature during delays in cooling has increasing impact on firmness loss as the delay in cooling increases.

At a 4 hour delay the percent firmness losses for 20, 28, and 35 C are only 5.7, 6.3, and 6.9 % respectively while losses for a 12 hour delay increase to 7.3, 9.0, and 11.0 % . Similarly, a 10 % loss in firmness results for a delay of about 10 hours at 35 C, 13 hours at 28 C, and over 24 hours at 20 C. Thus, ambient temperature is less critical if cooling delays are less than 4 hours compared with delays of 8 hours or more.

Similar percent losses in mass at the end of 24 hours are shown in Table 5.2 for the same temperatures, delays in cooling, and storage temperature. The importance of temperature is shown by a 2.5 % loss if cooling is delayed 8 hours at 35 C compared to a similar 2.4 % loss after 24 hours with no cooling if the ambient temperature is 20 C.

The results shown in Tables 5.1 and 5.2 support the need to harvest blueberries in early morning when temperatures are lowest. If temperatures are above about 28 C it is important to cool the fruit in less than 12 hours when evaluations are made after 24 hours. Other scenarios can be obtained from the models for different combinations of times and temperatures to determine how critical cooling delays are for the selected temperatures.

CONCLUSION

The models developed in the study provide a way to evaluate the benefits expected from reducing delays in cooling blueberries. The models obtained for the mass and firmness loss in the blueberries were suitable for predicting the condition of blueberries after a known number of hours at a specified temperature. Such models could also be useful for comparing different harvest situations to determine which is best for different fruit.

These data support previous recommendations that blueberry harvest times be limited to cool times of the day with temperatures below 28 ° C. Higher temperatures can adversely affect the firmness and mass loss of blueberries, depending on the duration of exposure to those temperatures. However, the data suggested predisposing fruit to high temperatures does not adversely affect the rate of mass and firmness loss after cooling.

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CHAPTER 6

SUMMARY

Users of the FirmTech II instrument need to have a standard procedure for their use of the equipment. For the most accurate firmness values, they need to select blueberries that are of a similar size to reduce errors in firmness measurements. For blueberries, they need to set the minimum force at 50 g, in order to have the necessary pre-load that will make the berries sit adequately in their holders. A maximum force of 150 g is recommended if the test needs to be non-destructive. Users of the FirmTech II should not mix first and second readings, since they turn out to be different. The recommended orientation by the manufacturer is the calyx horizontal position. Although placing the berries in this position was the most difficult and unstable, we recommend it because all literature to date was reported in that position.

Modeling of the loss of firmness and mass of the blueberries followed the Arrhenius law as indicated in the literature review. For the loss of mass, it was shown that cooling reduced the rate of loss to similar levels irrespective of the delay of cooling at any ambient temperature. Higher temperatures showed an increase in the rate of loss of both mass and firmness. It is therefore our conclusion that, at 32 ° C, growers must try to cool as soon as possible, since even a delay of 4 hours can cause damage. At field temperatures of about 21 to 27° C however, cooling as quickly is of less concern. Growers can delay for up to at up to 12 hours with little detrimental effect on quality.

Further studies should be conducted to obtain a model that will combine different combinations of temperature and relative humidity to see what the different effects on the overall blueberry quality will be. In addition, the model can be applied to different fruit (by finding rates of loss) in order to predict the behavior of even other quality parameters. In addition, the corrections obtained can be applied to the FirmTech II firmness readings to see how it will impact its overall usage.

CHAPTER 7

CONCLUSIONS

From this study, we conclude the following:

- Standardized procedures must be followed when measuring the firmness of blueberries (or other fruit) with the FirmTech II instrument. Recommendations are to place the calyx horizontal, set maximum force at 150 g, set minimum force 50 g, and use only the first measurement.
- For accurate results when using the FirmTech II, blueberries must all be in the same size range. Differences in berry radii cause larger berries to appear firmer than smaller berries with the same modulus of elasticity.
- Poor correlation (R^2=0.4425) was found between the actual FirmTech II values and the similar computed firmness values from parallel plate compression tests. The slope was a little above unity. Both corrected E (single and parallel plate compression) against actual calculated E also had a low correlation (R^2=0.3308). the FirmTech II was found to compress in-between single and parallel plate compression. The errors can be explained to be due to variations in output from the load cell and stepping motor and to unpredictable movement of blueberries into the holder.
- Models were developed for predicting the effect of temperature on losses of mass and firmness for blueberries. The equations allow prediction of firmness or mass at selected temperatures. Equations of the model were also suitable for modeling losses in blueberry firmness and mass during delays in cooling and during storage. Rate of

loss during storage was not affected by the amount of loss before cooling. Predicted versus observed plots showed high R^2 values (0.9563 for mass and 0.7535 for firmness), therefore showing that the models worked as expected.

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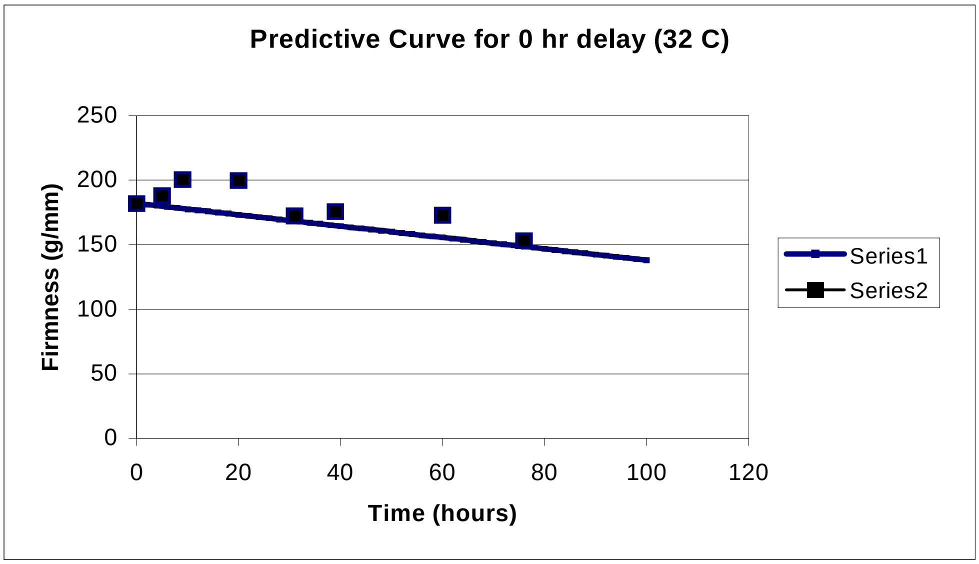
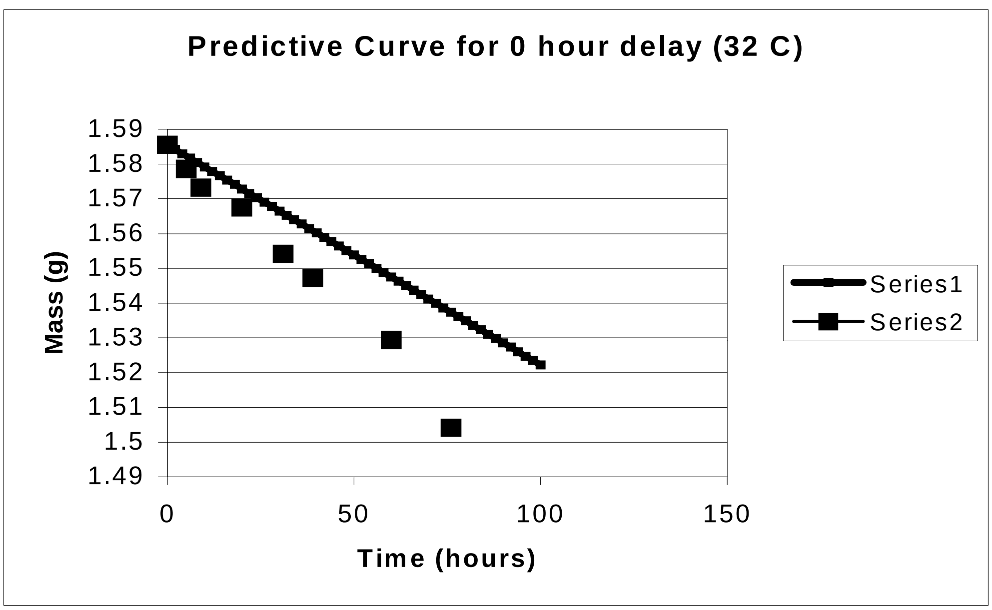
APPENDIX A

GRAPHS OF FIRMNESS AND MASS AGAINST TIME FOR ALL DELAYS AND TEMPERATURES



A1: Series 1= Predictive Curve, Series 2 = Actual Curve



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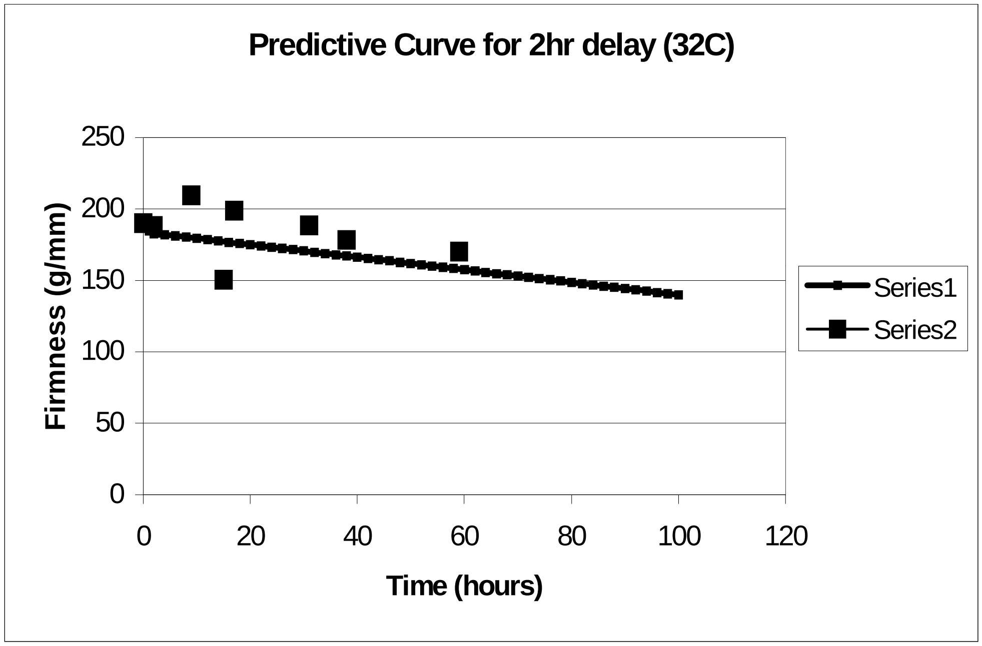

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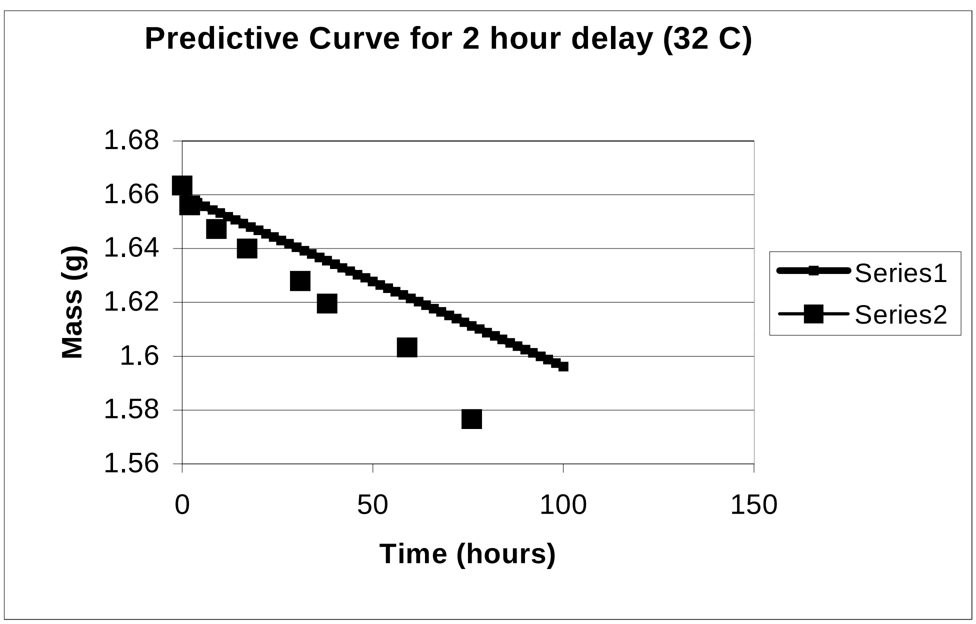

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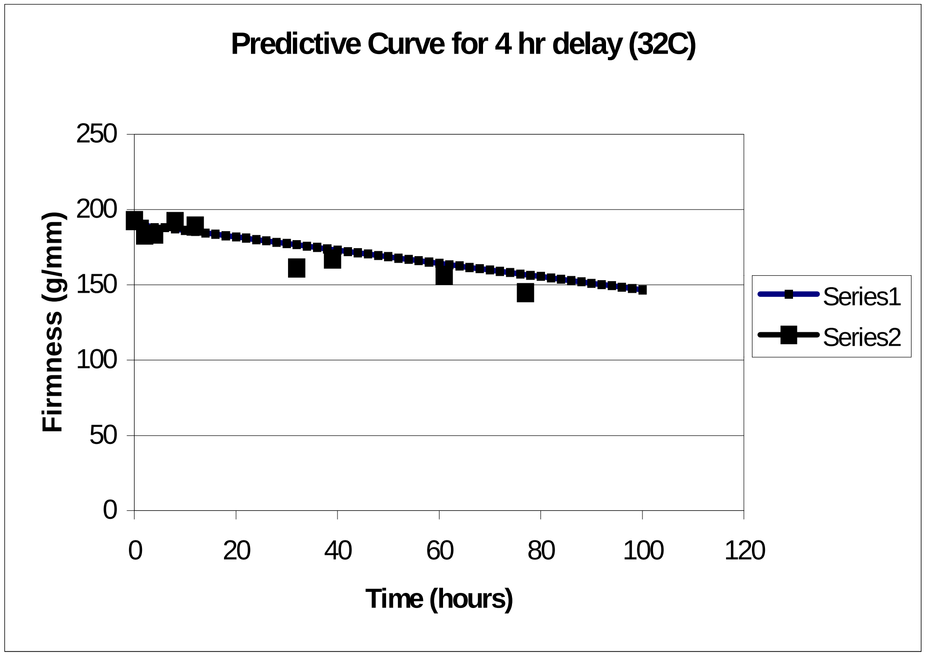

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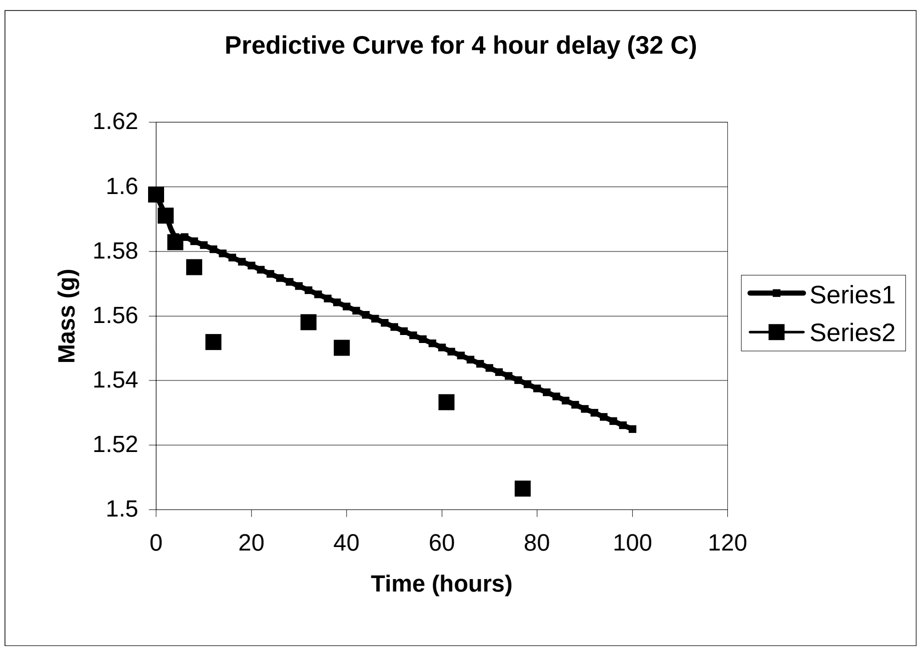

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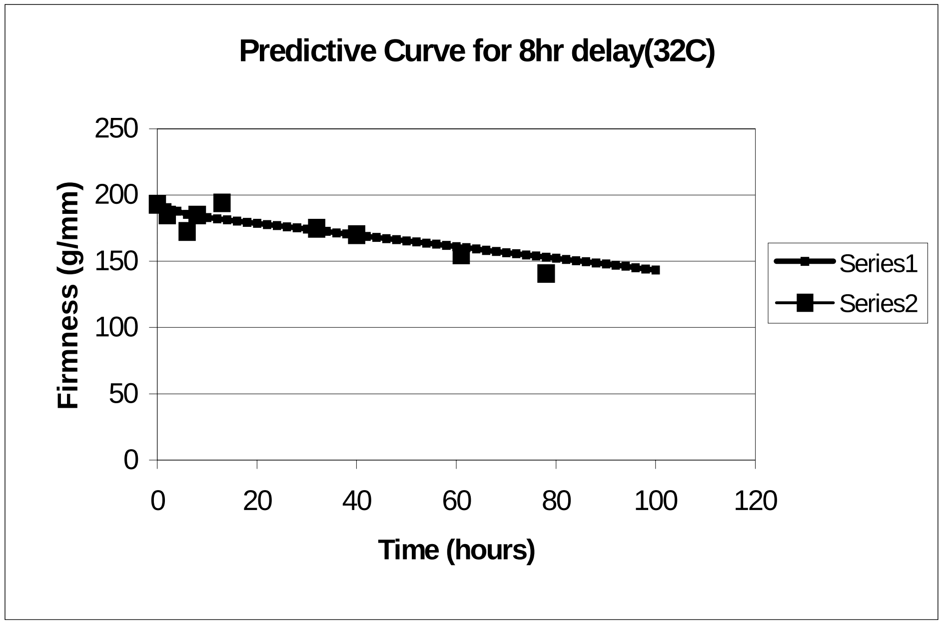

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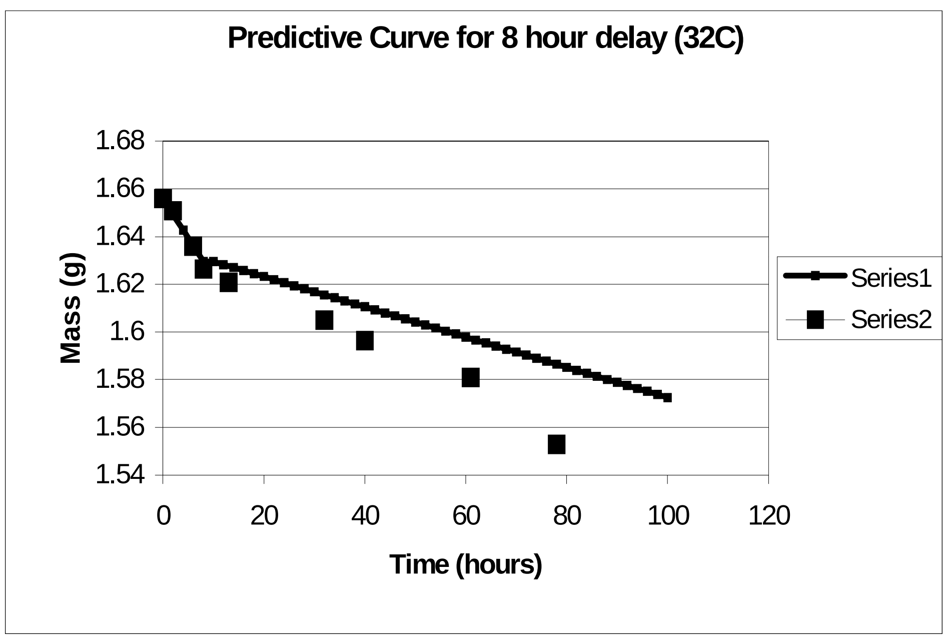

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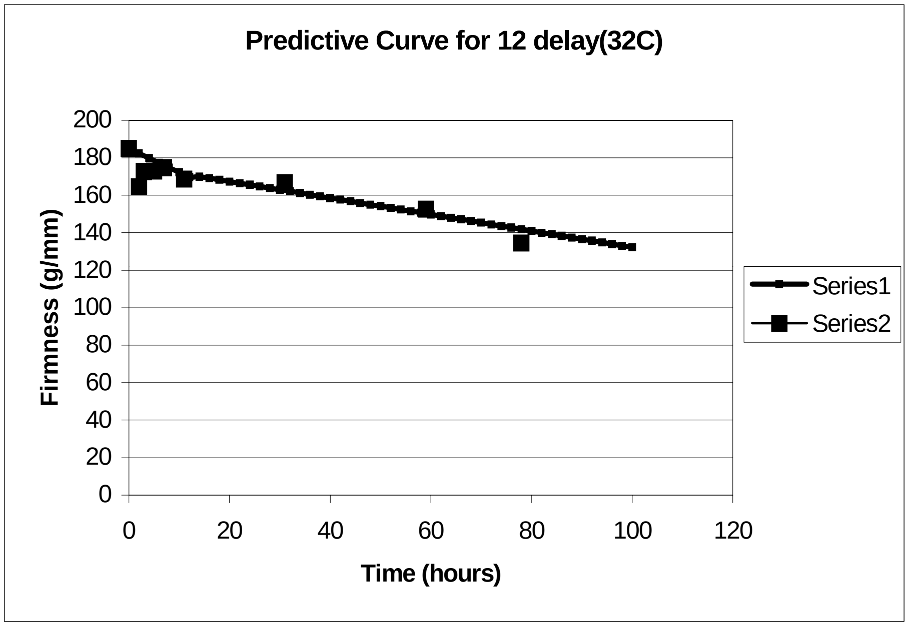

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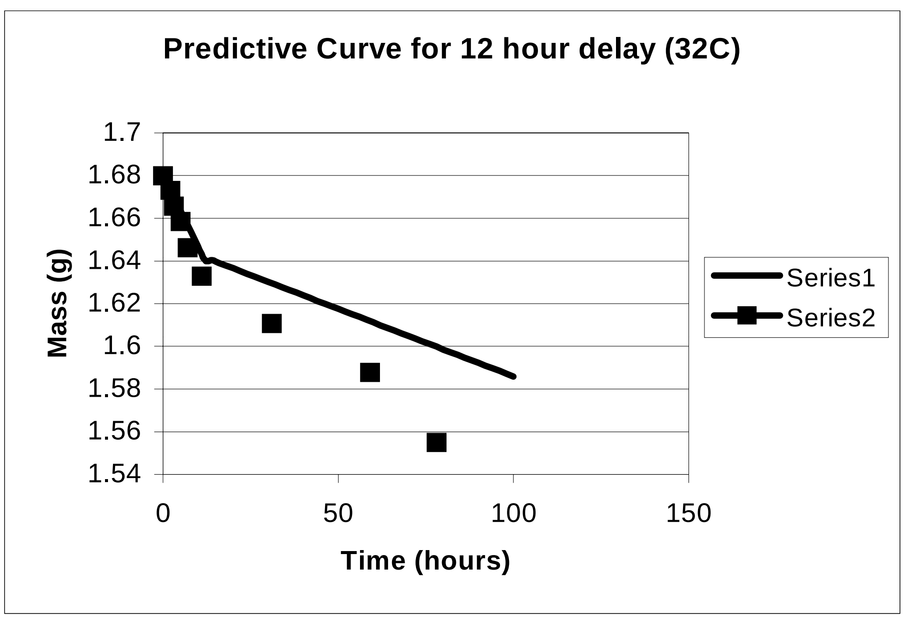

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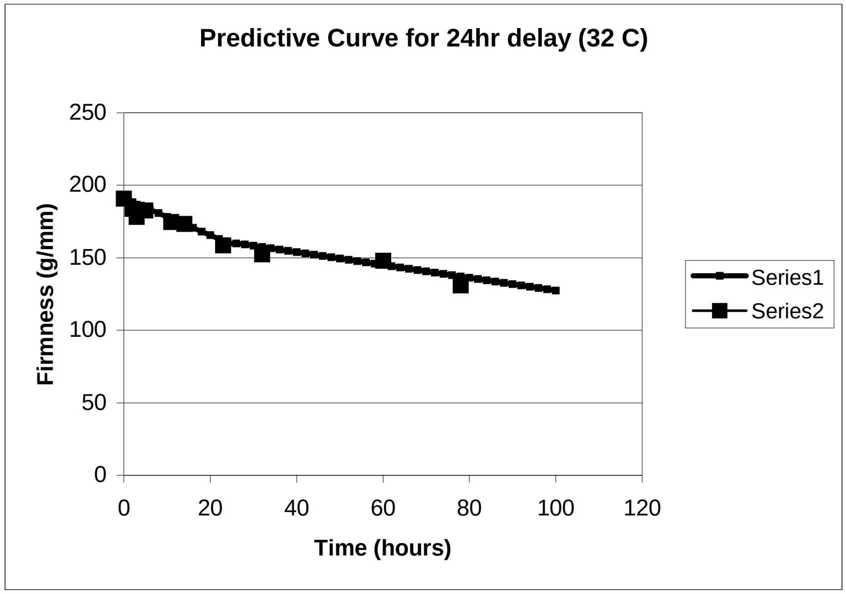

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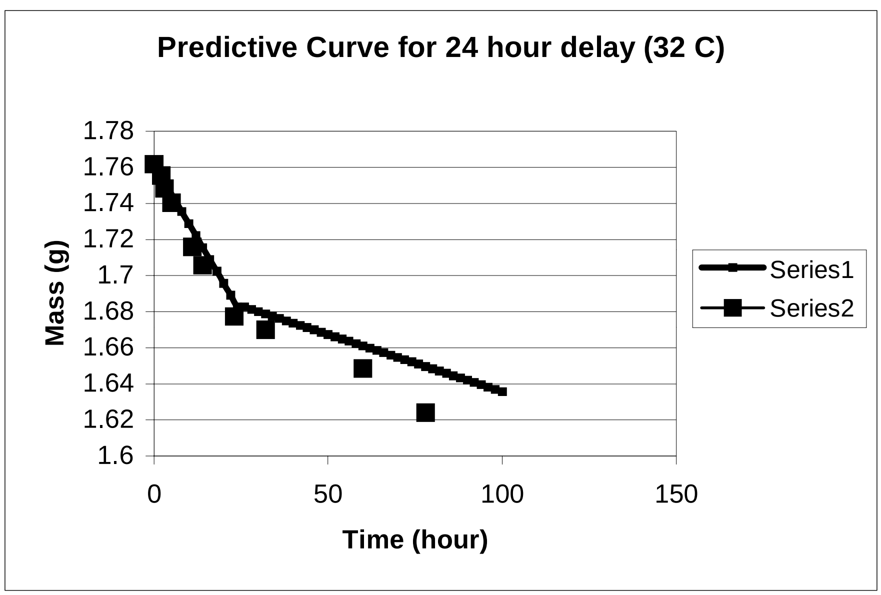

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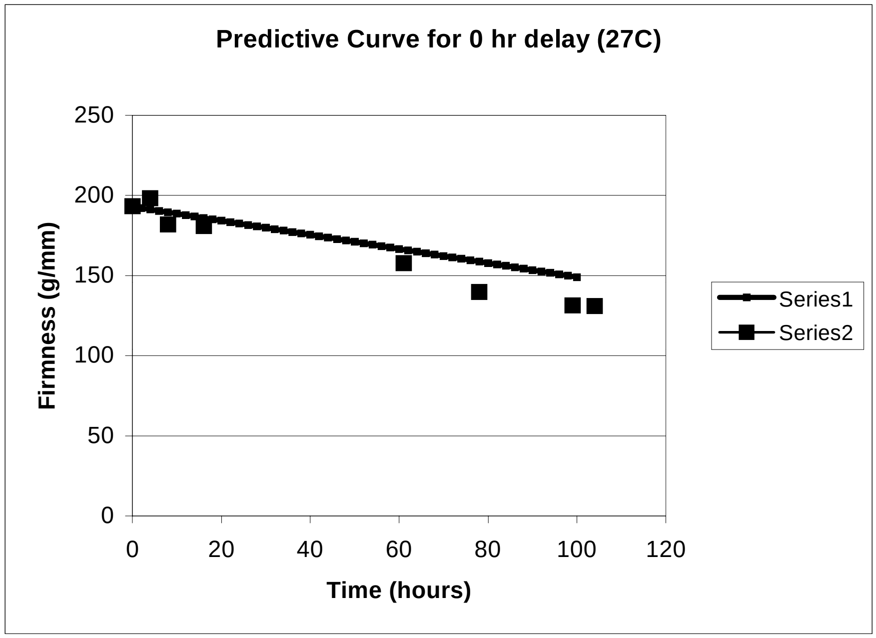

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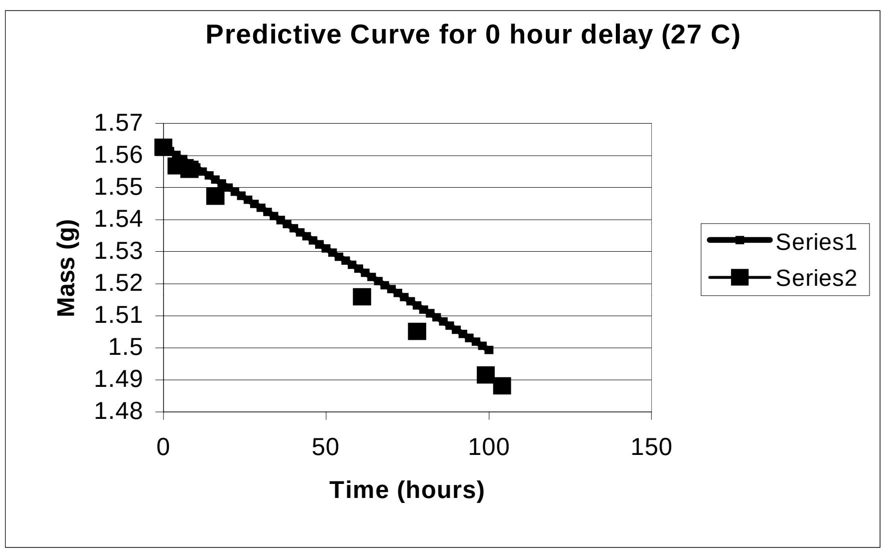

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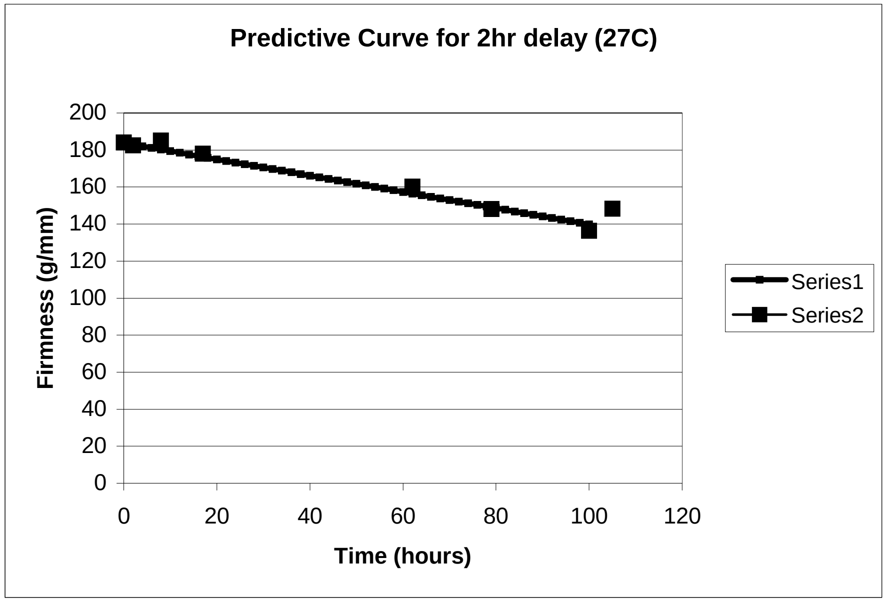

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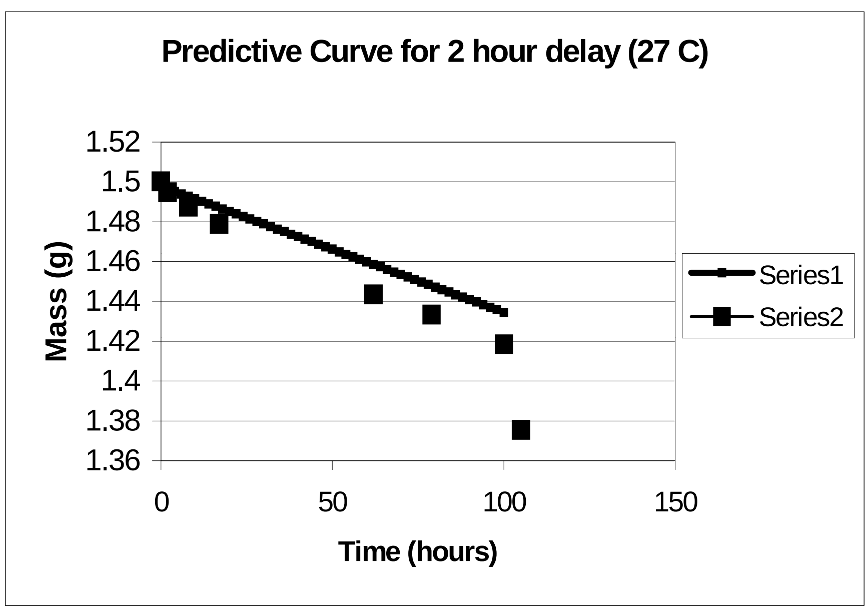

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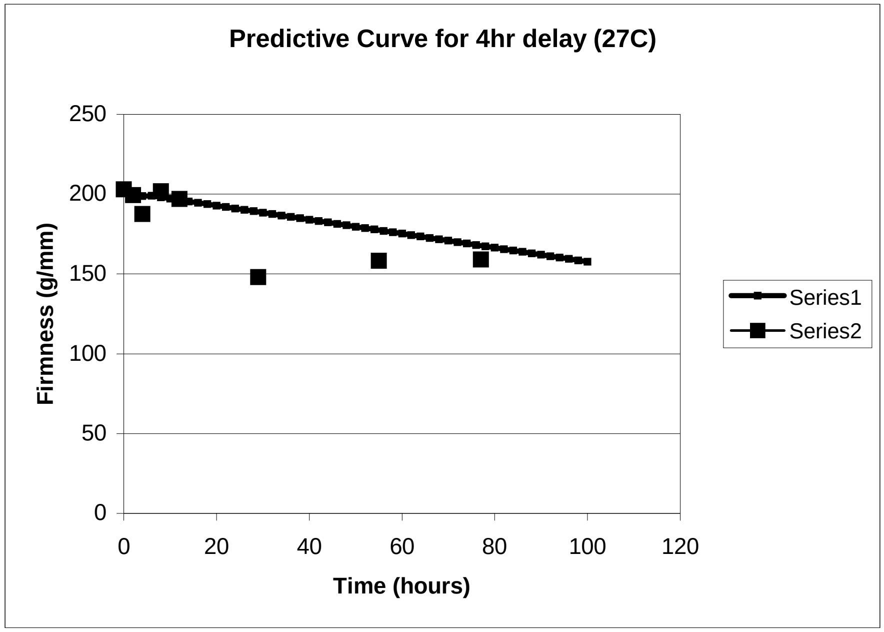

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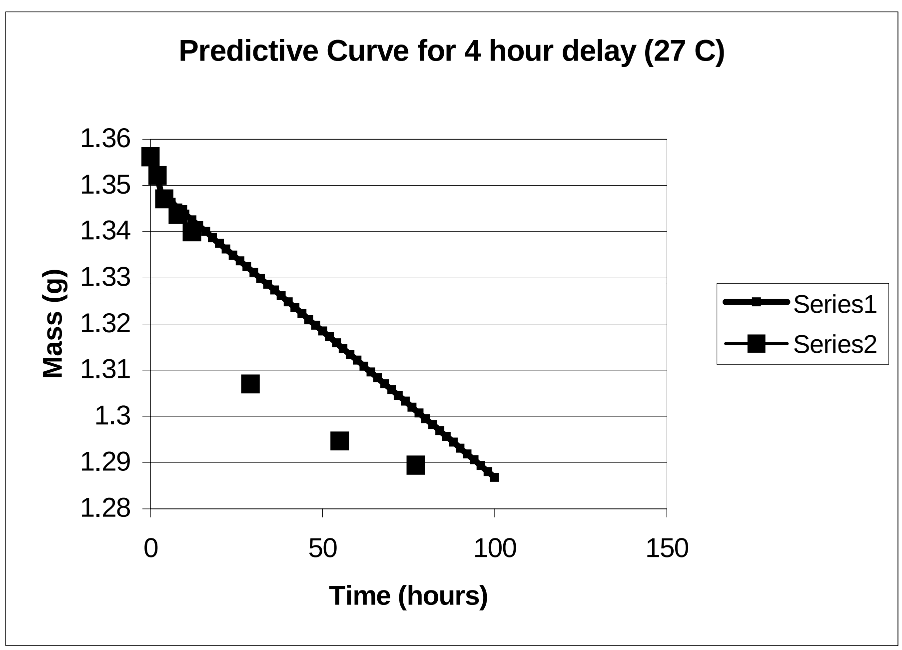

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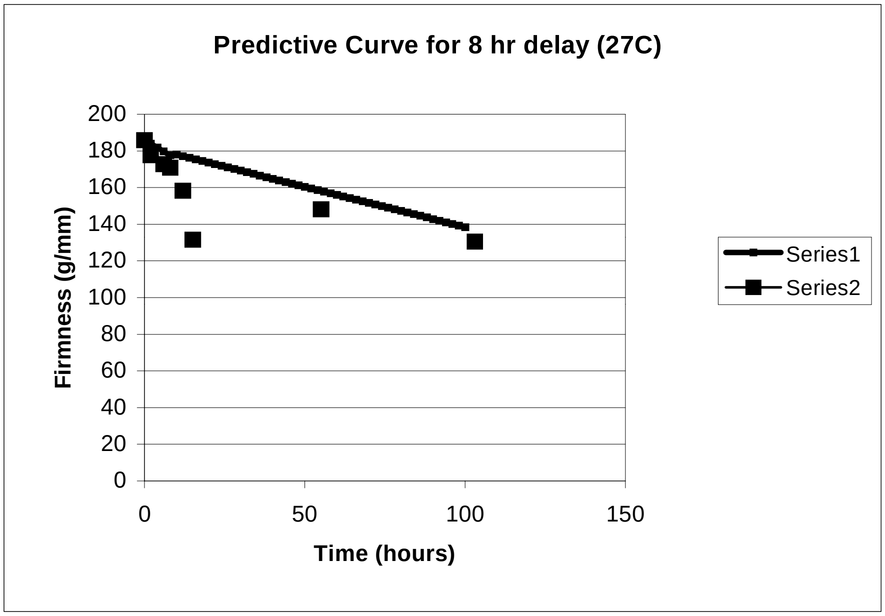

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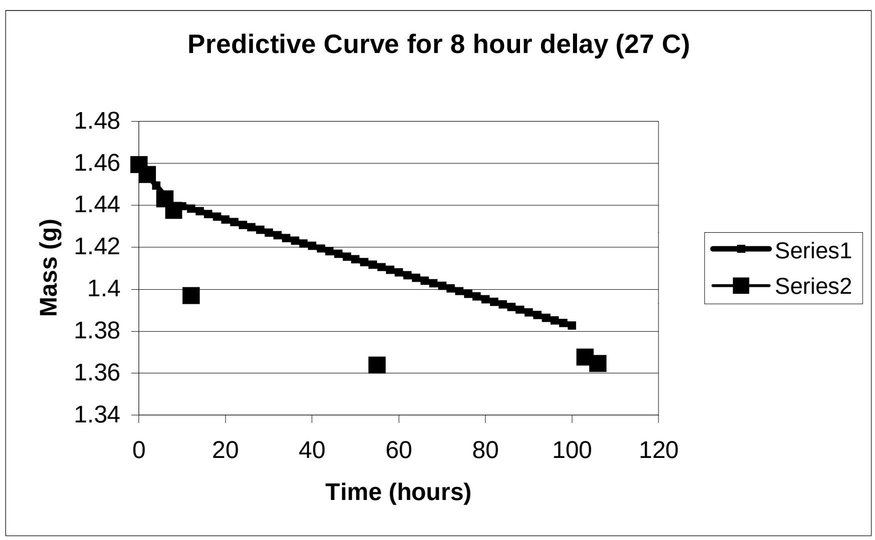

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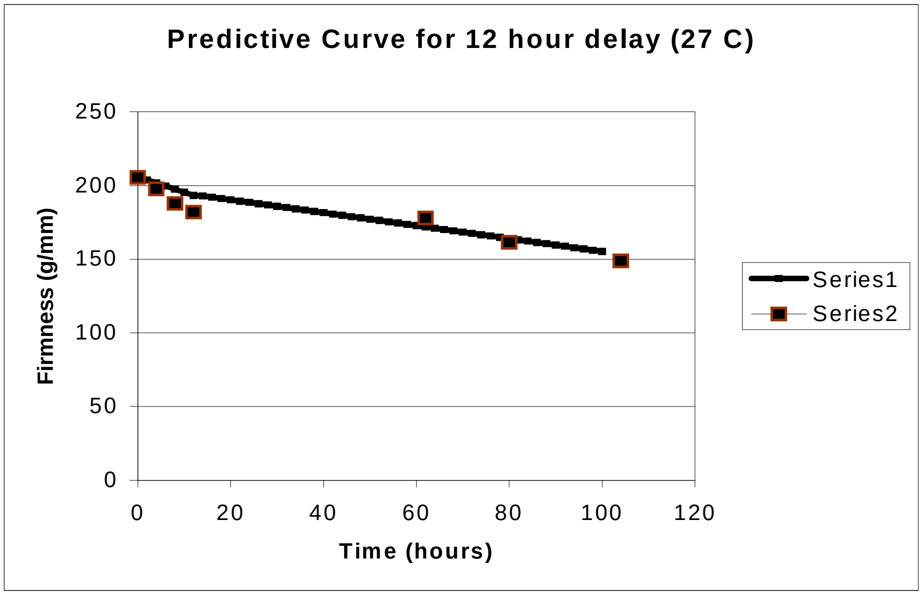

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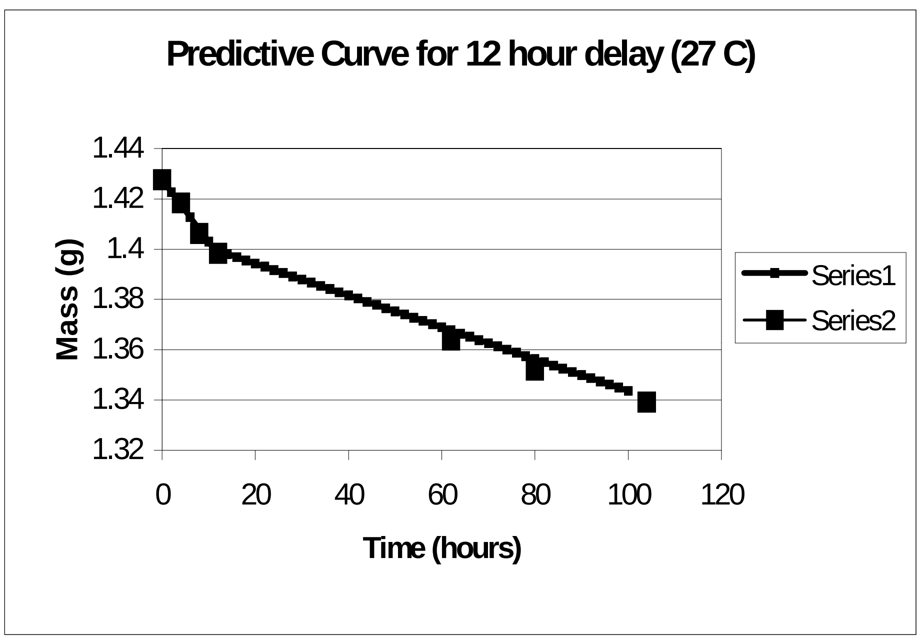

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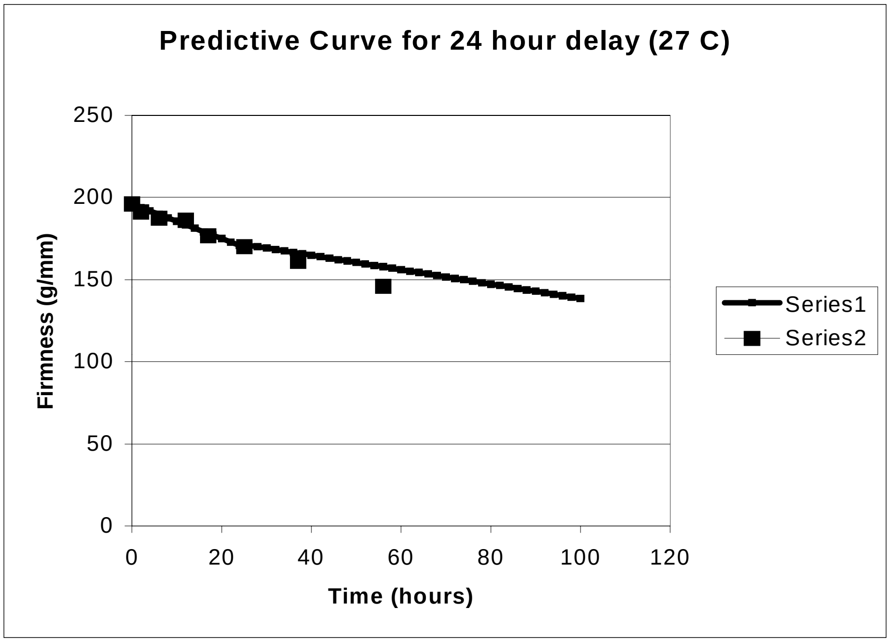

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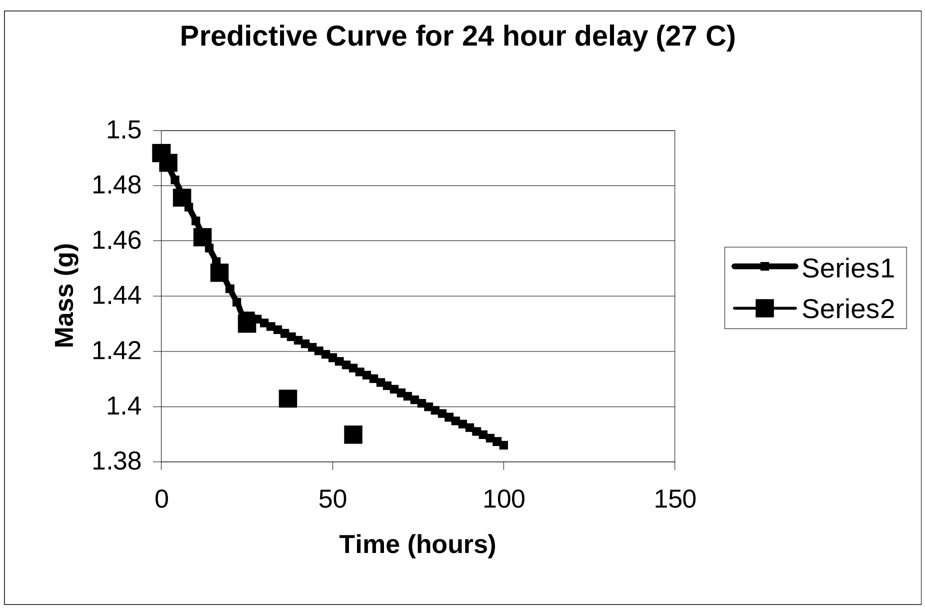

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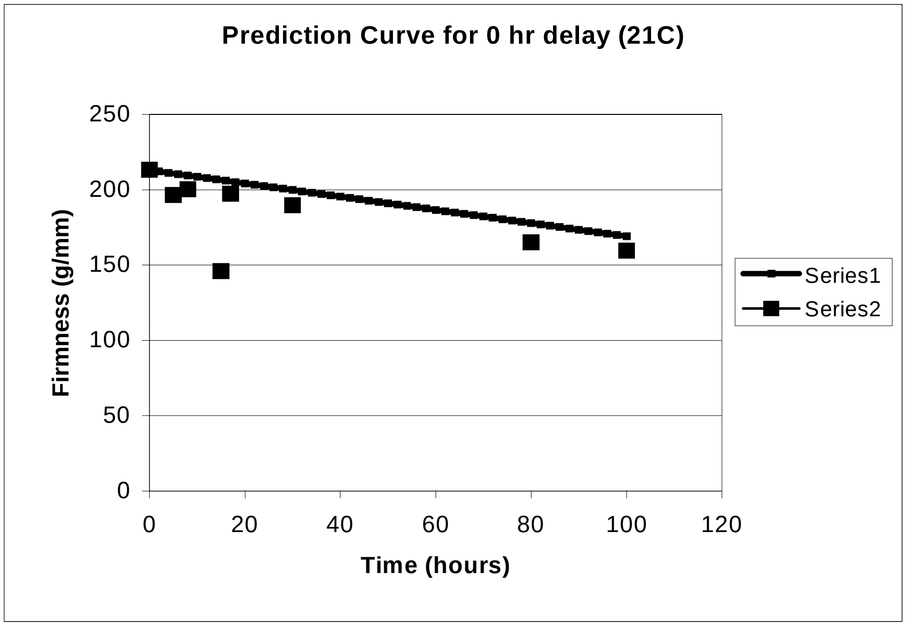
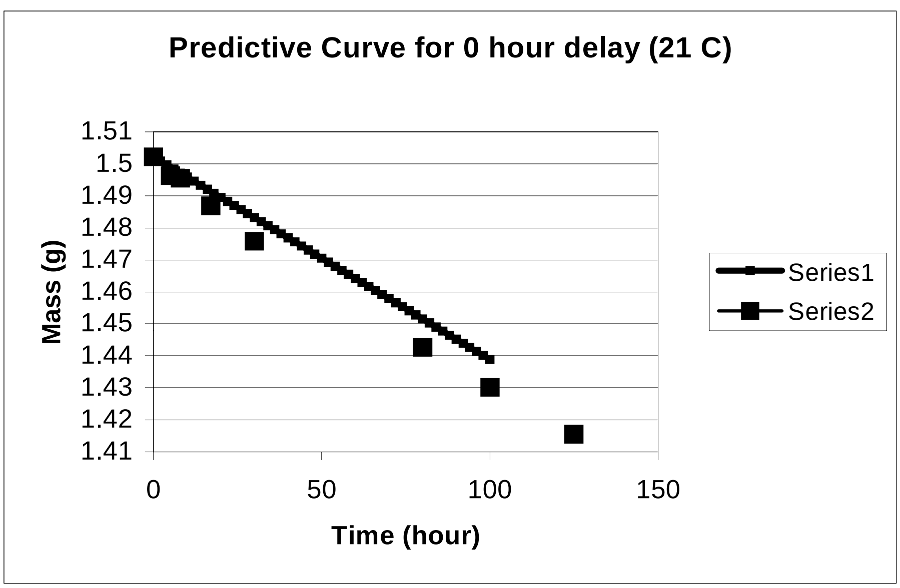
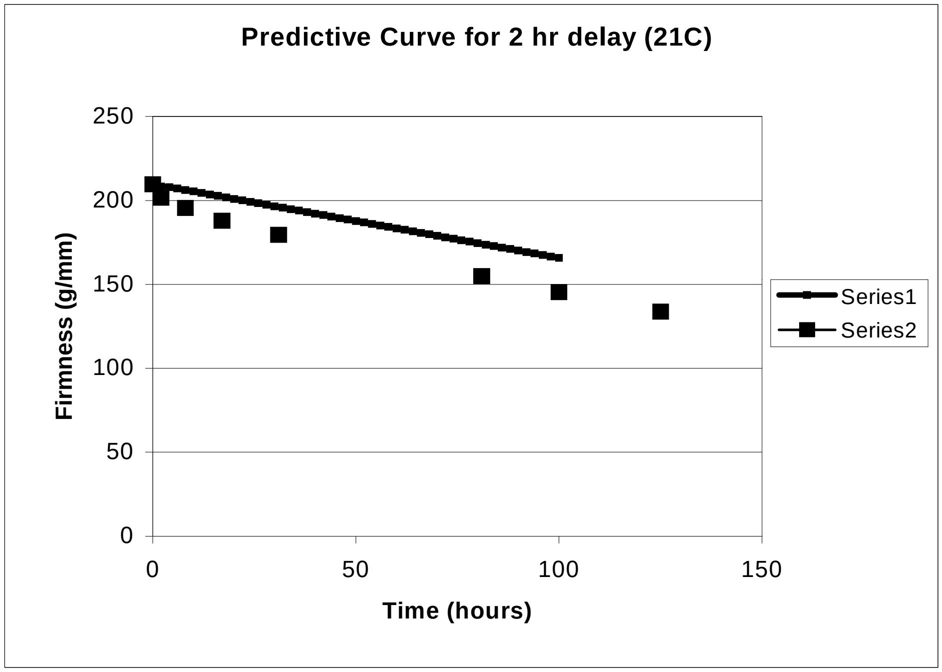


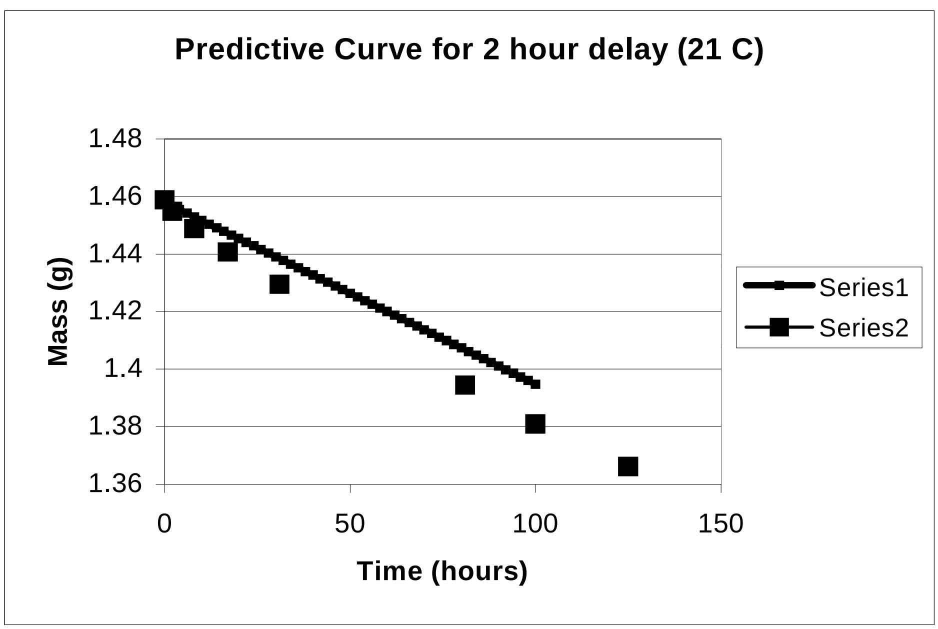
A25: Series 1= Predictive Curve, Series 2 = Actual Curve



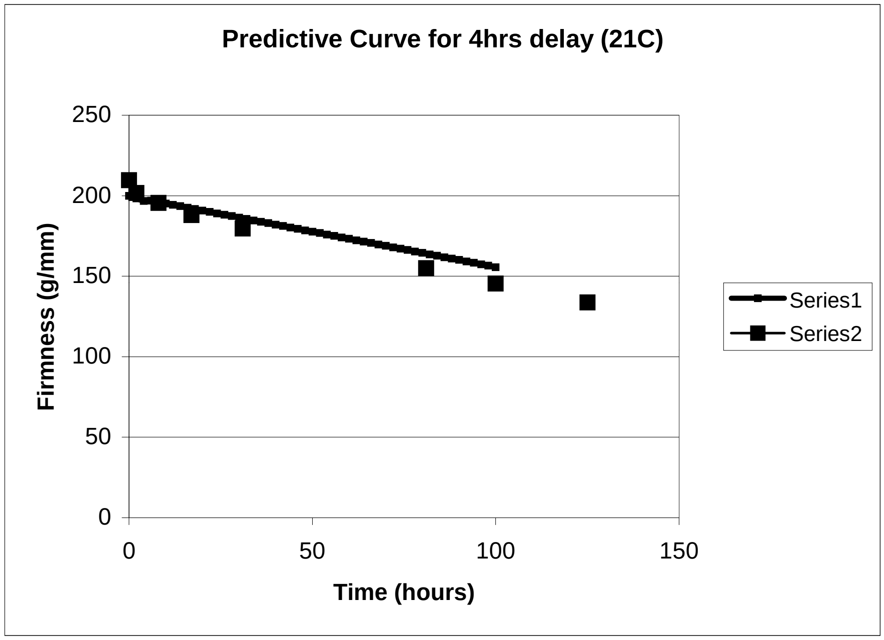
A26: Series 1= Predictive Curve, Series 2 = Actual Curve



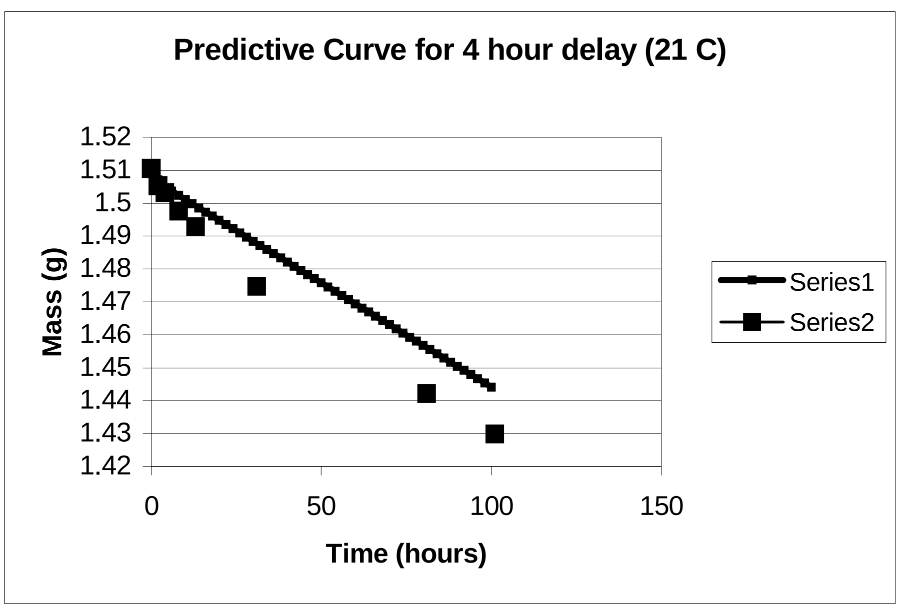
A27: Series 1= Predictive Curve, Series 2 = Actual Curve



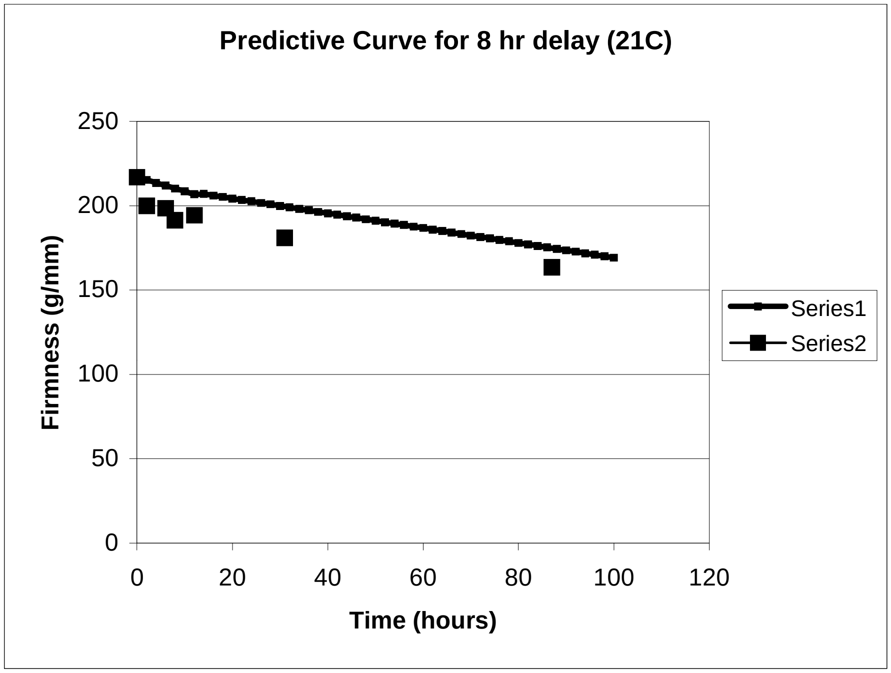
A28: Series 1= Predictive Curve, Series 2 = Actual Curve



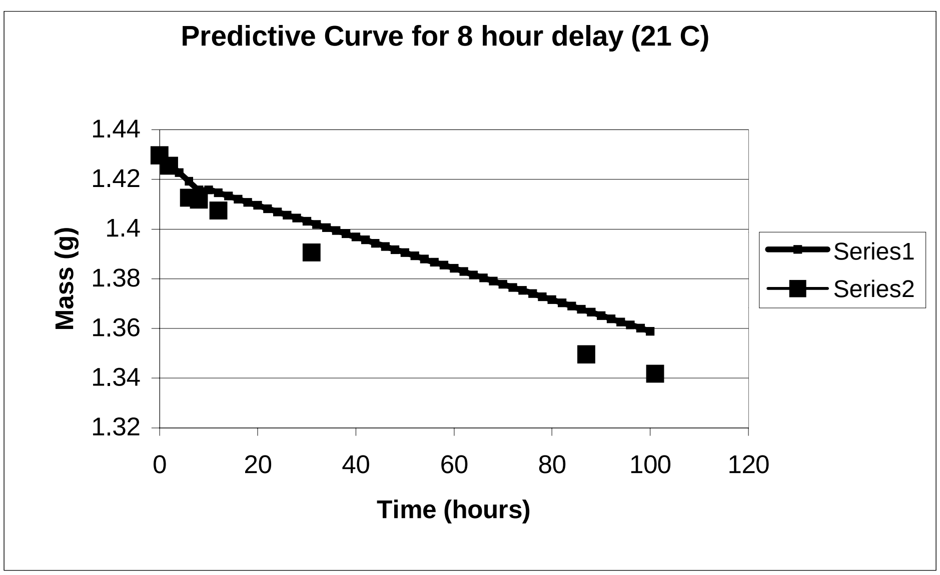
A29: Series 1= Predictive Curve, Series 2 = Actual Curve



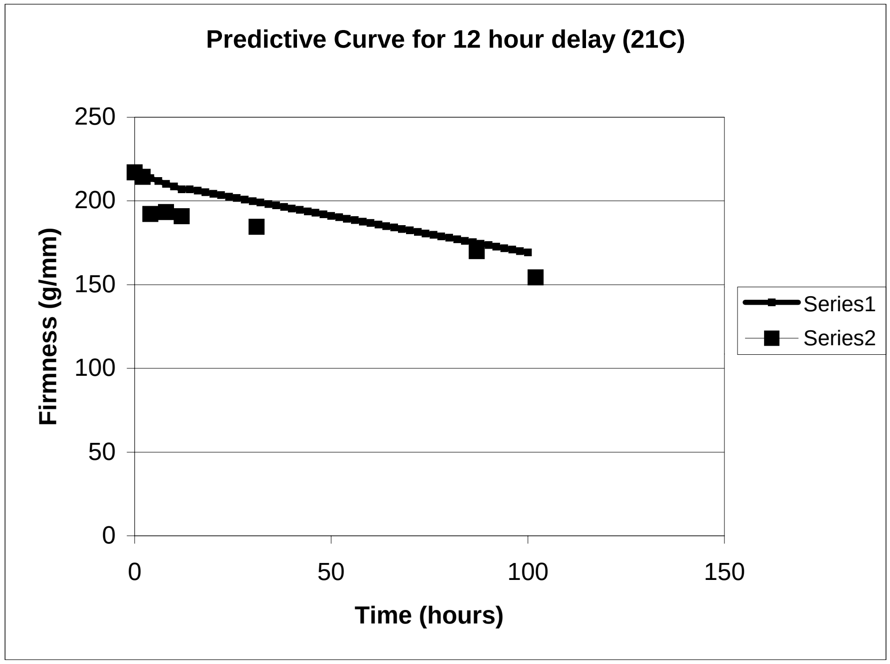
A30: Series 1= Predictive Curve, Series 2 = Actual Curve



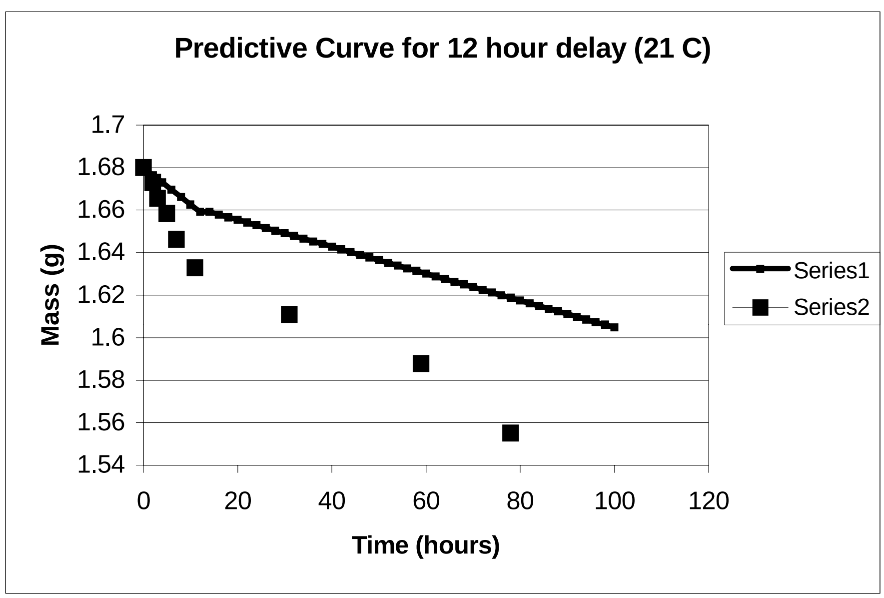
A31: Series 1= Predictive Curve, Series 2 = Actual Curve



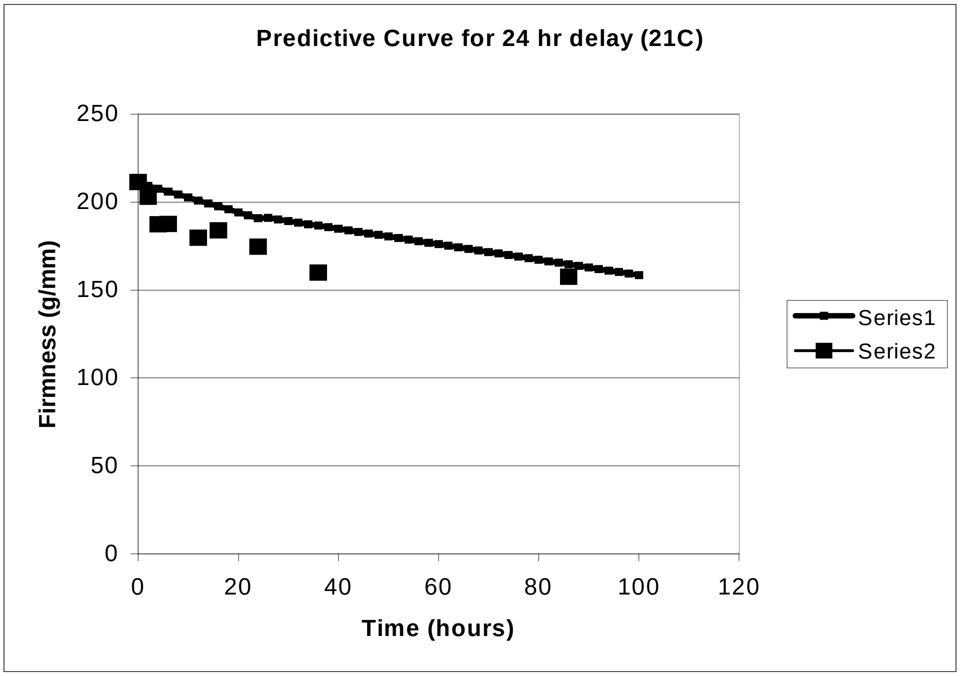
A32: Series 1= Predictive Curve, Series 2 = Actual Curve



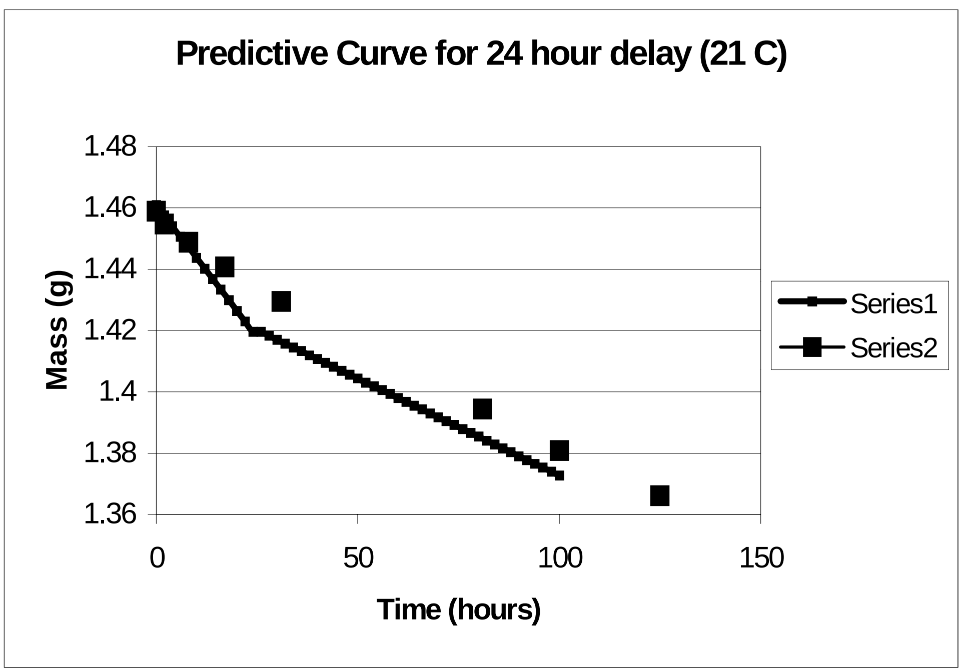
A33: Series 1= Predictive Curve, Series 2 = Actual Curve



A34: Series 1= Predictive Curve, Series 2 = Actual Curve



A35: Series 1= Predictive Curve, Series 2 = Actual Curve



A36: Series 1= Predictive Curve, Series 2 = Actual Curve

APPENDIX B

VALUES PLOTTED FOR PREDICTION GRAPHS

Table B1

Firmness Values for Predictive Plot					
Predicted	Observed	Predicted	Observed	Predicted	Observed
206	206	171	169	185	185
202	198	163	167	182	165
198	188	151	153	181	173
193	182	142	135	179	173
172	178	193	193	176	175
164	161	191	198	201	180
191	191	189	182	198	184
188	184	186	181	191	175
187	178	167	158	187	160
185	183	159	140	165	158
177	175	203	203	210	193
173	173	201	199	207	191
162	159	199	188	200	185
157	152	198	202	175	170
145	148	196	197	211	211
138	131	189	148	209	203
217	217	178	158	208	187
215	214	168	159	206	188
214	192	186	186	210	210
210	193	184	178	208	202
207	191	180	173	206	196
200	185	178	171	203	188
175	170	177	158	197	180
182	182	159	148	173	155
180	188	196	196	166	145
178	200	194	191	184	184
173	200	190	187	182	183

Firmness Values for Predictive Plot(continued)					
Predicted	Observed	Predicted	Observed	Predicted	Observed
169	173	183	186	180	185
165	176	182	177	176	178
156	173	179	170	157	160
149	153	173	161	149	149
193	193	165	146	140	136
190	183	213	213	190	190
188	184	211	197	182	188
187	192	209	200	180	209
185	189	206	197	176	199
177	161	200	190	171	189
174	167	178	165	167	178
164	156	169	160	158	170
157	145	200	200	150	150
193	193	198	197	217	217
190	185	197	197	215	214
185	173	196	189	214	192
183	185	194	185	170	170
182	194	186	173	161	155
173	175	164	154	153	141

Table B2

Mass Values for Predictive Plot					
Predicted	Observed	Predicted	Observed	Predicted	Observed
1.3562	1.3562	1.6118	1.5878	1.5496	1.5333
1.3521	1.3521	1.6112	1.5551	1.5395	1.5066
1.3488	1.3471	1.7619	1.7619	1.6800	1.6744
1.3480	1.3437	1.7552	1.7555	1.6733	1.6731
1.3455	1.3399	1.7519	1.7484	1.6700	1.6656
1.3353	1.3070	1.7453	1.7404	1.6634	1.6584
1.3189	1.2947	1.7255	1.7160	1.6568	1.6463
1.3037	1.2895	1.7156	1.7057	1.6436	1.6329
1.5009	1.5009	1.6859	1.6774	1.6296	1.6108
1.4968	1.4968	1.6788	1.6700	1.4403	1.4368
1.4916	1.4916	1.6611	1.6485	1.4334	1.4280
1.4860	1.4860	1.6497	1.6241	1.4196	1.4130
1.4801	1.4768	1.5627	1.5627	1.4132	1.4089
1.4687	1.4598	1.5528	1.5568	1.3816	1.3745
1.4346	1.4259	1.5430	1.5557	1.4878	1.4748
1.6560	1.6560	1.5233	1.5473	1.4562	1.4422
1.6509	1.6509	1.4126	1.5160	1.4297	1.4297
1.6360	1.6360	1.3708	1.5051	1.4262	1.4255

Mass Values for Predictive Plot (continued)					
Predicted	Observed	Predicted	Observed	Predicted	Observed
1.7440	1.7404	1.3981	1.3985	1.6636	1.6636
1.7242	1.7160	1.3677	1.3638	1.6569	1.6561
1.7143	1.7057	1.3563	1.3519	1.6538	1.6473
1.6878	1.6774	1.4919	1.4919	1.6399	1.6279
1.6774	1.6700	1.4870	1.4883	1.6354	1.6196
1.6597	1.6485	1.4771	1.4758	1.6221	1.6034
1.6483	1.6241	1.4624	1.4614	1.6114	1.567
1.5855	1.5855	1.4501	1.4485	1.6487	1.6401
1.5823	1.5787	1.4329	1.4029	1.5003	1.5003
1.5798	1.5733	1.4139	1.3898	1.4936	1.4949
1.5728	1.5676	1.5022	1.5022	1.4911	1.4875
1.5659	1.5541	1.4990	1.4963	1.4854	1.479
1.5608	1.5472	1.4971	1.4955	1.4569	1.4435
1.5475	1.5294	1.4914	1.4869	1.4436	1.4336
1.5374	1.5041	1.4832	1.4758	1.4329	1.4186
1.5977	1.5924	1.4516	1.4427	1.459	1.459
1.5910	1.5911	1.4389	1.4301	1.4523	1.4549
1.5844	1.5828	1.5106	1.5106	1.4498	1.4489
1.5832	1.5751	1.5071	1.5054	1.4441	1.4408
1.5806	1.5520	1.5036	1.5033	1.4036	1.3944
1.5680	1.5581	1.5024	1.4977	1.3916	1.3809
1.5635	1.5501	1.4992	1.4929	1.4193	1.4127
1.6264	1.6264	1.3192	1.4915	1.4158	1.4120
1.6281	1.6209	1.4593	1.4593	1.4146	1.4076
1.6168	1.6049	1.4544	1.4548	1.4019	1.3906
1.6117	1.5965	1.4445	1.4431	1.3671	1.3495
1.5978	1.5809	1.4396	1.4377	1.4610	1.4610
1.5876	1.5529	1.4111	1.3638	1.4575	1.4560
1.7619	1.7619	1.4276	1.4276	1.4541	1.4522
1.7555	1.7555	1.4178	1.4185	1.4506	1.4457
1.7484	1.7484	1.4079	1.4063		