



UNIVERSITI PUTRA MALAYSIA

**FACTORS AFFECTING GLUTEN PRODUCTION AND
ITS RHEOLOGICAL CHARACTERIZATIONS**

DAYANG NORULFAIRUZ BINTI ABANG ZAIDEL

FK 2007 61

**FACTORS AFFECTING GLUTEN PRODUCTION AND
ITS RHEOLOGICAL CHARACTERIZATIONS**

By

DAYANG NORULFAIRUZ BINTI ABANG ZAIDEL

**MASTER OF SCIENCE
UNIVERSITI PUTRA MALAYSIA**

2007



**FACTORS AFFECTING GLUTEN PRODUCTION AND
ITS RHEOLOGICAL CHARACTERIZATIONS**

By

DAYANG NORULFAIRUZ BINTI ABANG ZAIDEL

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfilment of the Requirements for the degree of Master of Science**

December 2007



To my mother and father...
Thank you for your love and support.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment
of the requirement for the degree of Master of Science

**FACTORS AFFECTING GLUTEN PRODUCTION AND
ITS RHEOLOGICAL CHARACTERIZATIONS**

By

DAYANG NORULFAIRUZ BINTI ABANG ZAIDEL

December 2007

Chairman : Chin Nyuk Ling, PhD

Faculty : Engineering

In this thesis, focus was given upon three factors affecting gluten production and development during dough mixing namely mixing time, salt levels and water levels. Gluten production was examined in terms of quantity and quality of gluten. Quantity of gluten was measured in terms of wet and dry gluten content. Wet gluten content was determined by weighing the gluten obtained from the dough washed under running tap water. The wet gluten was dried using air oven drying method to obtain dry gluten content. The quality of gluten was determined from the analysis of volume expansion, extensibility and rheological characterization. The volume expansion analysis was performed by frying the wet gluten in hot oil at 170°C in deep fryer for 15 minutes. The volume of fried gluten was measured using mustard seed displacement method and the difference between the volume of fried gluten and the volume of wet gluten is measured as volume expansion of gluten.

The main problem encountered in performing gluten and dough extensibility test is to hold the sample so that it does not break at the jaws that hold the sample. Thus it is one of the objectives in this study to build a simple set-up of tensile test to determine gluten extensibility, which is one of the most common measurements employed in determining the quality of gluten. A simple set-up of tensile test which is attached to Instron 5566 has been build to determine gluten extensibility. Gluten strip of about 10 mm x 10 mm x 70 mm was clamped at two ends using plastic clips and extended at the centre by hook at speed of 300 mm min⁻¹. Extensibility parameters such as original gluten length, gluten length at fracture, measured force, actual force acting on the gluten strips, strain and stress were obtained using the formulas derived from the results of tensile test. The tensile test set-up was successful in terms of providing the gluten extensibility measurements and also the gluten did not fracture at the clamping area. Rheological characteristics of gluten, K and n , were obtained by fitting stress-strain curve following an exponential equation, $\sigma = Ke^{n\epsilon}$. Two types of flour, strong and weak, were used as a comparison. Correlation between two analyses measurements of the gluten quantity and quality are determined at the end of this thesis.

An adequate polynomial equation model which fits the data was produced from Design Expert V.6.0.4. P-value, R^2 and lack-of-fit value were determined to verify the fitness of the polynomial model equation to the actual data and thus can be used as a good prediction of the data. The results from Design Expert were then transferred to Microsoft Excel file where the graph of the response was plotted against the three factors studied.

Results suggested that from the three factors studied, salt gave the most significant effect ($0.0001 < P < 0.02$) on the gluten quantity and quality. As salt level increases, it decreases the wet and dry gluten content. The volume expansion of gluten and the extensibility seem to decrease with increasing salt level. This indicates that gluten network strength reduces and it does not mix into elastic dough as salt level increases. The next significant factor was water level ($0.0001 < P < 0.67$). Mixing time was the least significant factor among the three ($0.0001 < P < 0.95$). For all factors studied, the results for strong flour were higher than the weak flour in the quantity, volume expansion and also extensibility. This demonstrates that the quality of gluten is affected by the protein content of the flour. All correlations between two analyses of quantity and quality measurements show positive coefficient of correlation (R). Strong correlation between (i) gluten quantity and volume expansion ($R > 0.75$), (ii) gluten quantity and extensibility ($R > 0.80$) and (iii) volume expansion and extensibility of gluten ($R > 0.60$) were obtained for strong flour compared to weak flour ($R > 0.45$; $R > 0.50$; $R > 0.30$, respectively). These results indicate that the quality of gluten is influenced by the protein content of the flour and the extensibility and volume expansion of gluten is positively correlated. These correlations could be used in the food industry to improve the gluten quantity and quality in the future.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

**FAKTOR – FAKTOR MEMPENGARUHI PENGHASILAN GLUTEN
DAN SIFAT – SIFAT REOLOGINYA**

Oleh

DAYANG NORULFAIRUZ BINTI ABANG ZAIDEL

Disember 2007

Pengerusi : Chin Nyuk Ling, PhD

Fakulti : Kejuruteraan

Dalam tesis ini, tumpuan diberikan kepada tiga faktor yang mempengaruhi penghasilan dan perkembangan gluten semasa pengadunan doh iaitu masa pengadunan, kandungan garam dan kandungan air. Penghasilan gluten ditentukan dari segi kuantiti dan kualiti gluten. Kuantiti gluten diukur dari segi kandungan basah dan kering gluten. Kandungan basah gluten diperolehi daripada doh yang dibasuh di bawah air paip yang mengalir. Gluten basah dikeringkan menggunakan kaedah pengeringan angin-ketuhar untuk memperoleh kandungan kering gluten. Kualiti gluten dinilai menerusi analisis pengembangan isipadu, kekenyalan dan sifat reologi. Pengembangan isipadu gluten dijalankan dengan menggoreng gluten di dalam minyak panas pada suhu 170°C menggunakan periuk penggoreng selama 15 minit. Isipadu gluten yang digoreng ditentukan dengan menggunakan kaedah

sesaran biji sawi dan perbezaan di antara isipadu gluten yang digoreng dan gluten basah diambil sebagai pengembangan isipadu gluten.

Masalah utama yang dihadapi semasa menjalankan ujian kekenyalan doh dan gluten ialah bagi mengepit sampel supaya ia tidak putus pada kawasan pengepit. Oleh itu, salah satu daripada objektif tesis ini adalah untuk membina sebuah alat penguji tensil yang ringkas untuk menguji kekenyalan gluten, yang merupakan satu cara untuk menentukan kualiti gluten. Sebuah alat penguji tensil yang ringkas untuk dipasangkan kepada Instron 5566 telah dibina untuk menentukan kekenyalan gluten. Kepingan gluten yang berukuran 10 mm x 10 mm x 70 mm dikepit pada hujung kedua-dua belah menggunakan klip plastik dan ditarik di tengah-tengah dengan menggunakan cangkuk pada kelajuan 300 mm min^{-1} . Ukuran kekenyalan seperti panjang asal gluten, panjang gluten semasa putus, daya ukuran, daya sebenar bertindak pada gluten, tegangan dan regangan dikira dengan menggunakan rumus yang diperolehi melalui ujian tensil. Alat penguji tensil ini berjaya dari segi menghasilkan ukuran kekenyalan gluten dan juga gluten tidak putus pada kawasan apitan. Sifat reologi gluten, K dan n , diperolehi dengan memadankan lengkungan tegangan-regangan mengikut persamaan eksponensial, $\sigma = Ke^{ne}$. Dua jenis tepung, kuat dan lemah, digunakan sebagai perbandingan. Korelasi antara dua ukuran bagi kuantiti dan kualiti gluten ditentukan di akhir kajian ini.

Model persamaan polinomial yang menepati data telah dihasilkan daripada Design Expert V.6.0.4. Nilai P , R^2 dan *lack-of-fit* ditentukan bagi mengesahkan kesesuaian model persamaan polinomial tersebut terhadap data sebenar dan seterusnya akan digunakan sebagai ramalan yang bagus untuk data tersebut. Keputusan daripada Design Expert kemudian dipindahkan ke fail Microsoft Excel di mana graf respon diplot melawan tiga faktor yang dikaji.

Keputusan menunjukkan di antara tiga faktor yang dikaji, garam memberikan kesan yang paling signifikan ($0.0001 < P < 0.02$) terhadap kuantiti dan kualiti gluten. Dengan peningkatan kandungan garam, ia mengurangkan kandungan basah dan kering gluten. Isipadu pengembangan dan kekenyalan gluten menurun dengan peningkatan kandungan garam. Ini menunjukkan bahawa kekuatan rangkaian gluten berkurangan dan ia tidak diadun menjadi doh yang kenyal apabila kandungan garam bertambah. Faktor yang signifikan berikutnya ialah kandungan air ($0.0001 < P < 0.67$). Masa pengadunan adalah faktor yang paling kurang signifikan di antara tiga faktor tersebut ($0.0001 < P < 0.95$). Untuk semua faktor yang dikaji, keputusan bagi jenis tepung yang kuat adalah lebih tinggi berbanding tepung yang lemah dari segi kuantiti, isipadu pengembangan dan juga kekenyalan. Ini menunjukkan bahawa kualiti gluten dipengaruhi oleh kandungan protein tepung. Semua korelasi di antara kuantiti dan kualiti menunjukkan nilai pekali hubungkait (R) yang positif. Korelasi yang tinggi di antara (i) kuantiti gluten dan pengembangan isipadu gluten ($R > 0.75$), (ii) kuantiti gluten dan kekenyalan gluten ($R > 0.80$) dan

(iii) pengembangan isipadu dan kekenyalan gluten ($R > 0.60$) diperolehi bagi tepung yang kuat dibandingkan dengan tepung yang lemah ($R > 0.45$; $R > 0.50$; $R > 0.30$, masing-masing). Keputusan ini menunjukkan bahawa kualiti gluten dipengaruhi oleh kandungan protin tepung dan kekenyalan dan pengembangan isipadu gluten adalah berkorelasi secara positif. Korelasi – korelasi ini boleh digunakan dalam industri makanan bagi meningkatkan kuantiti dan kualiti gluten pada masa hadapan.

ACKNOWLEDGEMENTS

In the name of Allah, The Most Gracious and The Most Merciful.

Alhamdulillah. I would like to thank my supervisor, Dr. Chin Nyuk Ling, for her guidance, helpful advice, generous encouragement and motivation, never-ending patience, kind attention and willingness to assist me throughout this research. I have learnt a lot of useful knowledge from her throughout this research. Thank you also to my supervisory committee members, Prof. Russly Abdul Rahman and Dr. Roselina Karim, for their advice and guidance.

I am also grateful to Encik Nazri Meor Razlan, Encik Raman Morat and Encik Kamarul Zaman from Process and Food Engineering Department laboratory for providing technical support and guidance throughout my laboratory works. My sincere appreciation also goes to all Process and Food Engineering Department staffs and master and PhD students year 2005-2007, who have helped and guided me throughout my studies. I would like to thank Malayan Flour Mill (M) Sdn. Bhd. for supplying the flour for this study. Thank you to other individuals who I have not mentioned but have helped me in any possible way.

Last but not least, I would like to express heartiness gratitude and love to my parents, family and friends for their love, encouragement and support.

THANK YOU ALL!!!

I certified that an Examination Committee has met on 18 December 2007 to conduct the final examination of Dayang Norulfairuz binti Abang Zaidel on her Master of Science thesis entitled “Factors Affecting Gluten Production and its Rheological Characterizations” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulation 1981. The Committee recommends that the student be awarded the degree of Master of Science.

Members of the Examination Committee were as follows:

Mohd. Nordin Ibrahim, PhD

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Siti Mazlina Mustapa Kamal, PhD

Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Ling Tau Chuan, PhD

Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Ida Idayu Muhammad, PhD

Senior Lecturer
Faculty of Chemical and Natural Resources Engineering
Universiti Teknologi Malaysia
(External Examiner)

HASANAH MOHD. GHAZALI, PhD

Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 29 January 2008



This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Chin Nyuk Ling, PhD

Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Russly Abdul Rahman, PhD

Professor
Faculty of Food Science and Technology
Universiti Putra Malaysia
(Member)

Roselina Karim, PhD

Lecturer
Faculty of Food Science and Technology
Universiti Putra Malaysia
(Member)

AINI IDERIS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 21 February 2008



DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

**DAYANG NORULFAIRUZ BINTI
ABANG ZAIDEL**

Date: 4 January 2008

TABLE OF CONTENTS

	Page
DEDICATION	ii
ABSTRACT	iii
ABSTRAK	vi
ACKNOWLEDGEMENTS	x
APPROVAL	xi
DECLARATION	xiii
LIST OF TABLES	xvi
LIST OF FIGURES	xvii
LIST OF APPENDICES	xxvi
LIST OF ABBREVIATIONS	xxvii
NOMENCLATURE	xxviii
CHAPTER	
1 INTRODUCTION	1
1.1 Gluten Uses and Properties	1
1.2 Significance of This Study	4
1.3 Objectives	5
1.4 Scope of Work and Thesis Outlines	5
2 LITERATURE REVIEW	8
2.1 Introduction to Wheat Gluten	9
2.1.1 Wheat Flour Composition	9
2.1.2 Gluten Networks Development during Flour-Water Mixing	11
2.1.3 Gluten Preparation and Washing Method	14
2.1.4 Current Uses of Wheat Gluten in Food Industry	16
2.2 Gluten Quantity	18
2.3 Gluten Volume Expansion	19
2.3.1 Frying Method	19
2.3.2 Volume Displacement Method	23
2.4 Rheology of Gluten	24
2.4.1 Basic Concepts of Rheology	25
2.4.2 Introduction to Food Texture Analysis	31
2.4.3 Rheological Properties of Gluten	32
2.5 Gluten Extensibility	34
2.5.1 Tensile Test	35
2.5.2 Derivation of Extensibility Parameters	40
2.6 Factors Affecting Gluten Properties	43
2.6.1 Effect of Flour Composition	43
2.6.2 Effect of Processing Factors	44
2.6.3 Effect of Ingredient Factors	46
2.7 Summary	48



3 RESEARCH DESIGN AND METHODOLOGY	49
3.1 Raw Materials	49
3.1.1 Flour	49
3.1.2 Water and Salt	50
3.2 Methods for Quantity Analysis of Gluten	51
3.2.1 Dough Preparations	52
3.2.2 Gluten Preparations	55
3.2.3 Gluten Analysis	56
3.3 Methods for Quality Analysis of Gluten	59
3.3.1 Dough Preparations	60
3.3.2 Gluten Preparations	60
3.3.3 Gluten Analysis	63
3.4 Experimental Design	73
3.4.1 Preliminary Experiment	73
3.4.2 Response Surface Methodology	74
3.4.3 Data Analysis	77
3.5 Summary	79
4 RESULTS AND DISCUSSION	80
4.1 Dough and Gluten Preparations	81
4.2 Quantity Analysis of Gluten	82
4.2.1 Preliminary Experiment	82
4.2.2 Wet Gluten Content Analysis	84
4.2.3 Dry Gluten Content Analysis	91
4.3 Quality Analysis of Gluten	98
4.3.1 Preliminary Experiment	98
4.3.2 Gluten Volume Expansion Analysis	103
4.3.3 Extensibility Analysis	111
4.3.4 Stress-Strain Curve-Fitting Analysis	123
4.4 Correlation between Quantity and Quality Measurements	154
4.5 Summary	160
5 CONCLUSIONS AND RECOMMENDATIONS	163
5.1 Introduction	163
5.2 Summary of the Works	164
5.3 Recommendations for Future Work	167
REFERENCES	168
APPENDICES	175
BIODATA OF THE AUTHOR	196

LIST OF TABLES

Table		Page
2.1	Usage of gluten in different regions of the world (as percentage)	16
2.2	Objective methods for measuring food texture (Bourne, 2002b)	31
3.1	Flour analysis for strong and weak flour	50
3.2	Details of water and salt used for dough preparation	51
3.3	Amount of small dough based on 25 g of flour for strong and weak flour	54
3.4	Alpha, low, centre and high points for the experimental design	75
3.5	2^{3-1} fractional factorial central composite design for quantitative analysis	76
3.6	2^{3-1} fractional factorial central composite design for qualitative analysis	76
4.1	Summary of the linear correlation coefficient, R between the quantity and quality measurements	155
4.2	Summary of the coefficient of determination, R^2 between the quantity and quality measurements	155

LIST OF FIGURES

Figure		Page
2.1	A model for the molecular structure of gluten. HMW subunits are approximately by linear polymers, interchain disulphide links are not shown. Other polymers are approximated by spheres (adapted from Belton, 1999)	12
2.2	Molecular interpretation of gluten development (a) beginning of mixing, (b) optimum development and (c) overmixing (adapted from Létang <i>et al.</i> , 1999)	13
2.3	Heat transfer in (a) shallow frying and (b) deep-fat frying (adapted from Fellows, 2000)	20
2.4	(a) Schematic cross-section of a piece of food during deep-fat frying (adapted from Mellema, 2003) (b) cross-section of the crust of fried gluten	21
2.5	Displacement method (adapted from Anon. 2007a)	24
2.6	Mustard seeds used in solid displacement method	24
2.7	Diagrammatic representation of (a) shear and (b) extensional deformation of an isolated macromolecule (adapted from Menjivar, 1989)	26
2.8	Curves for typical time-independent fluids (a) shear stress in function of shear rate and (b) apparent viscosity in function of shear rate (adapted from Steffe, 1996a)	29
2.9	Curves of time-dependent behavior of fluids (a) Shear stress in function of time at constant shear rate and (b) apparent viscosity in function of shear rate showing hysteresis loop (adapted from Steffe, 1996a)	30
2.10	Creep and recovery curves for ideal elastic, ideal viscous and viscoelastic materials (adapted from Steffe, 1996b)	30

2.11	The deformation of polymers resulting from extending the network. (a) The equilibrium configuration. (b) Small extension - only the loops are deformed. (c) Large deformation loops are flattened and the interchain hydrogen bonds are broken so that the chains slip over each other (adapted from Belton, 1999)	34
2.12	Extension test of dough on Brabender extensograph (adapted from Anon., 2007b)	36
2.13	Load-Extension curve obtained from Brabender extensograph	37
2.14	The extension test of a strip of gluten on a Kieffer dough and gluten extensibility rig fitted to a texture analyzer (adapted from Wang, 2003)	37
2.15	Graph of gluten extension from Kieffer dough and gluten extensibility rig (adapted from Tronsmo <i>et al.</i> , 2003)	39
2.16	Attachment for measuring chapati extensibility on Instron (adapted from Gujral and Pathak, 2002)	40
2.17	Schematic diagram of forces acting on gluten and the length of gluten during tensile test (adapted from Dunnewind <i>et al.</i> , 2004)	41
2.18	Typical Farinograph curve (adapted from Létang <i>et al.</i> , 1999)	45
3.1	Flow of methods and preparations for quantitative analysis	52
3.2	Electronic balance (a) Model EL-4100D, Setra Systems Inc., USA used for weighing flour, water, dough and gluten (b) Model ER-120A, A&D Company Limited, Tokyo Japan	53
3.3	(a) Mixer (5K5SS, KitchenAid, Belgium) (b) Dough hook blade	53
3.4	Gantt chart of time period in gluten preparations for strong and weak flour	56
3.5	Aluminium foil numbered and gluten arranged on baking pan before oven drying	57
3.6	Oven (UM200-800, Memmert GmbH+Co.KG, Germany)	58
3.7	Flow of methods and preparations for qualitative analysis	59

3.8	(a) Paper clip for shaping the gluten at a consistent size and (b) paper cutter used for gluten cutting	62
3.9	Gluten cutting at consistent size using paper clip (a) top (b) cross-sectional view	62
3.10	(a) Deep-fryer (PDF-9989, Pensonic, Malaysia) and (b) the four channel datalogging thermometer (Monarch 309, Monarch Instrument, USA) and thermocouple probe (TP-K01, Monarch Instrument, USA) to monitor the oil temperature	63
3.11	Determination of volume of container, V_1	64
3.12	Determination of volume of displaced seeds, V_2	65
3.13	Instron (5566 series, Instron Corporation, USA) connected to computer software and fitted with gluten extensibility attachment	67
3.14	Gluten extensibility attachment on Instron utilising two plastic clips set at 40 mm distance at each other and a hook attached to the Instron and placed in between the clips	68
3.15	Tensile test set-up diagram from (a) top and (b) side view	69
3.16	Tensile test showing gluten extensibility at various stages: (a) gluten clamped at clips (b) gluten pulled upward by hook (c) gluten became thinner (d) gluten fractured	70
3.17	Force versus hook displacement graph produced by Instron computer software	71
3.18	Graph of actual force versus gluten extension	71
3.19	Curve-fitting of stress-strain curve using exponential equation	72
4.1	Gluten mass obtained after washing of dough	81
4.2	Profile for (a) wet gluten content and (b) dry gluten content at various mixing times for strong and weak flour	83
4.3	Predicted versus actual wet gluten content for (a) strong and (b) weak flour	85

4.4	Wet gluten content at various mixing times for (a) 3 water levels and (b) 3 salt levels for strong flour	86
4.5	Wet gluten content at various mixing times for (a) 3 water levels and (b) salt levels for weak flour	87
4.6	Wet gluten content at various salt levels for (a) 3 mixing times and (b) 3 water levels for strong flour	88
4.7	Wet gluten content at various salt levels for (a) 3 mixing times and (b) 3 water levels for weak flour	88
4.8	Wet gluten content at various water levels for (a) 3 mixing times and (b) 3 salt levels for strong flour	89
4.9	Wet gluten content at various water levels for (a) 3 mixing times and (b) 3 salt levels for weak flour	90
4.10	Wet gluten content at various mixing times for strong (filled symbols) and weak flour (empty symbols) for different salt levels (solid lines 2%, broken lines 5%, dotted lines 8%) and different water levels (rectangular – low, square – middle, round – high level)	91
4.11	Predicted versus actual dry gluten content for (a) strong and (b) weak flour	92
4.12	Dry gluten content at various mixing times for (a) 3 water levels and (b) 3 salt levels for strong flour	93
4.13	Dry gluten content at various mixing times for (a) 3 water levels and (b) 3 salt levels for weak flour	94
4.14	Dry gluten content at various salt levels for (a) 3 mixing times and (b) 3 water levels for strong flour	95
4.15	Dry gluten content at various salt levels for (a) 3 mixing times and (b) 3 water levels for weak flour	95
4.16	Dry gluten content at various water levels for (a) 3 mixing times and (b) 3 salt levels for strong flour	96
4.17	Dry gluten content at various water levels for (a) 3 mixing times and (b) 3 salt levels for weak flour	97



4.18	Dry gluten content at various mixing times for strong (filled symbols) and weak flour (empty symbols) for different salt levels (solid lines 2%, broken lines 5%, dotted lines 8%) and different water levels (rectangular – low, square – middle, round – high level)	97
4.19	Volume expansion of fried gluten for various mixing times for strong and weak flour	99
4.20	Graph of (a) measured force-hook displacement for gluten extensibility from strong and weak flour mixed for 8 minutes and (b) measured and actual force versus hook displacement for gluten extensibility from strong flour	100
4.21	Gluten length at fracture resulting from tensile test at various mixing times for strong and weak flour	101
4.22	Curves of stress-strain for gluten from (a) strong and (b) weak flour mixed for various mixing times	102
4.23	(a) Fracture stress (b) fracture strain (c) coefficient, K and (d) index, n for gluten from strong and weak flour mixed for various mixing times	103
4.24	(a) Fried gluten (b) inside of fried gluten showing the gluten network	104
4.25	Predicted versus actual volume expansion of fried gluten for (a) strong and (b) weak flour	105
4.26	Volume expansion of fried gluten for various mixing times for (a) 3 water levels and (b) 3 salt levels for strong flour	106
4.27	Volume expansion of fried gluten for various mixing times for (a) 3 water levels and (b) 3 salt levels for weak flour	107
4.28	Volume expansion of fried gluten for various salt levels for (a) 3 mixing times and (b) 3 water levels for strong flour	108
4.29	Volume expansion of fried gluten for various salt levels for (a) 3 mixing times and (b) 3 water levels for weak flour	109
4.30	Volume expansion of fried gluten for various water levels for (a) 3 salt levels and (b) 3 mixing times for strong flour	110

4.31	Volume expansion of fried gluten for various water levels for (a) 3 salt levels and (b) 3 mixing times for weak flour	110
4.32	Volume expansion of fried gluten for various mixing times for strong (filled symbols) and weak flour (empty symbols) for different salt levels (solid lines 2%, broken lines 5%, dotted lines 8%) and different water levels (rectangular – low, square – middle, round – high level)	111
4.33	Gluten extensibility (a) gluten became thinner as it pulled upward (b) gluten fractured	112
4.34	Graph of measured force-hook displacement for actual runs obtained from Instron for gluten from (a) strong and (b) weak flour	113
4.35	Measured and actual force versus hook displacement for gluten from (a) strong and (b) weak flour	114
4.36	Predicted versus actual gluten length at fracture for (a) strong and (b) weak flour	115
4.37	Gluten length at fracture for various mixing times for (a) 3 salt levels and (b) 3 water levels for strong flour	116
4.38	Gluten length at fracture for various mixing times for (a) 3 salt levels and (b) 3 water levels for weak flour	118
4.39	Gluten length at fracture for various salt levels for (a) 3 mixing times and (b) 3 water levels for strong flour	119
4.40	Gluten length at fracture for various salt levels for (a) 3 mixing times and (b) 3 water levels for weak flour	120
4.41	Gluten length at fracture for various water levels for (a) 3 salt levels and (b) 3 mixing times for strong flour	121
4.42	Gluten length at fracture for various water levels for (a) 3 salt levels and (b) 3 mixing times for weak flour	122
4.43	Gluten length at fracture for various mixing times for strong (filled symbols) and weak flour (empty symbols) for different salt levels (solid lines 2%, broken lines 5%, dotted lines 8%) and	



	different water levels (rectangular – low, square – middle, round – high level)	123
4.44	Stress-strain curves for gluten from (a) strong and (b) weak flour mixed for various mixing times, salt and water levels.	124
4.45	Predicted versus actual value of fracture strain for (a) strong and (b) weak flour	126
4.46	Predicted versus actual value of fracture stress for (a) strong and (b) weak flour	127
4.47	Predicted versus actual value of coefficient, K for (a) strong and (b) weak flour	128
4.48	Predicted versus actual index, n value for (a) strong and (b) weak flour	130
4.49	Fracture strain for various mixing times for (a) 3 water levels and (b) 3 salt levels for strong flour	131
4.50	Fracture strain for various mixing times for (a) 3 water levels and (b) 3 salt levels for weak flour	132
4.51	Fracture strain for various salt levels for (a) 3 mixing times and (b) 3 water levels for strong flour	133
4.52	Fracture strain for various salt levels for (a) 3 mixing times and (b) 3 water levels for weak flour	133
4.53	Fracture strain for various water levels for (a) 3 mixing times and (b) 3 salt levels for strong flour	134
4.54	Fracture strain for various water levels for (a) 3 mixing times and (b) 3 salt levels for weak flour	135
4.55	Fracture stress for various mixing times for (a) 3 water levels and (b) 3 salt levels for strong flour	136
4.56	Fracture stress for various mixing times for (a) 3 water levels and (b) 3 salt levels for weak flour	137
4.57	Fracture stress for various salt levels for (a) 3 mixing times and (b) 3 water levels for strong flour	138