ABSTRACT

KOC, HICRAN. Sensory Texture of Model Foods Based on Oral Processing and Food Material Properties Considerations. (Under the direction of Dr. E. Allen Foegeding.)

Food structure design, for specific textural properties, can only be achieved by understanding how food structure is transformed into the cognitive representation of food texture by oral processing. Different structural properties in biopolymer gels can be obtained by changing polymer concentration, solution conditions (i.e., pH, salt), and process conditions (time, temperature, shear). Another way to alter structure is by forming multicomponent gels. To understand transformation of food structure in texture perception by oral processing, polysaccharide based soft solid gels were used as model foods. The response of human senses to food structure was investigated via assessments of material properties (rheological/fracture characteristics), sensory perception and oral processing.

Initially, fundamental mechanical properties (fracture stress and fracture strain) of agar and κ-carrageenan-locust bean gum gels varied by changing polymer concentrations. When model foods became stronger and more deformable, more chewing cycles and relatively greater muscle activity were required to prepare samples for swallowing. Chewing frequency remained the same, indicating a consistent rhythmic jaw movement. Model foods showed differences in sensory perception of hardness, deformability, size of breakdown particles, rate of breakdown, particle mouthcoating and number of chews. Hardness, fracture stress, stress intensity factor, and muscle activities are closely associated and are the best indicators of number of chews. Moreover, fracture strain, fracture surface energy, deformability and occlusal durations exhibited strong correlations. Fracture modulus was closely associated with jaw vertical movements. Relations among sensory attributes,

material properties and oral processing were established by model foods with well defined physical properties.

In the next phase of study, emulsion filled gels were used as model foods to understand textural changes in foods by fat reduction. Agar gels had a brittle fracture pattern while κ-carrageenan-locust bean gum gels displayed elasto-plastic (ductile) fracture based on fracture mechanics considerations. Agar gels and κ-carrageenan-locust bean gum gels, at similar strengths but different deformability, were filled with various phase volumes of corn oil. Corn oil droplets (approximately 1 μm) were stabilized by surfactants that had no charge (Tween 20), negative (β-lactoglobulin) or positive (lactoferrin) charge at neutral pH. Increasing the phase volume of oil droplets decreased fracture stress and stress intensity factor of both filled gels, while the main effect on fracture strain was observed for the highly deformable κ-carrageenan gels. The key factor determining physical properties of filled gels were filler-network interactions and relative mechanical properties of filler droplets compared to the gel network. Oil droplets stabilized with β-lactoglobulin reduced sensory springiness, increased adhesiveness and cohesiveness of agar gels but not κ-carrageenan-locust bean gum gels. Increased adhesiveness and cohesiveness coincided with a greater degree of coalescence of oil droplets during compression. Sensory hardness of both networks was significantly reduced by oil droplets, while deformability decreased only for the κ-carrageenan-locust bean gum gels. The number of chews and muscle activities were mastication parameters affected by textural changes caused by oil droplets, while jaw movements mainly reflected the type of gel. Sensory adhesiveness and particle mouthcoating were related to digastrics activity and anterior posterior jaw movements. Inactive oil droplets significantly affected sensory properties and oral processing of

polysaccharide gels and that this may be related to the fracture pattern of the networks and combined effect of mechanical properties.

Sensory textures of model foods are adequately reconciled taking into consideration food mechanical properties and alterations in oral processing. Investigations of model foods with different material properties demonstrated that the key element controlling the oral breakdown of structure and sensory perception is the properties of the continuous gel network. Moreover, oral processing adaptation to different structures is controlled by sensory input and is related to a combination of food material properties.

Sensory Texture of Model Foods Based on Oral Processing and Food Material Properties Considerations

by
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DEDICATION

Dedicated to the most beautiful people in my life;

My parents- Orhan and Nekariye Koc

My siblings- Imran, Gokhan, and Kubra Koc

And dedicated to the memories of our science teacher in the middle school;

Fikret Caglar

In Turkish:

Doktora tezim, haklarını asla ödeyemeyeceğim, her şeyden çok sevdiğim, canım annem ve babam, Nekariye ve Orhan Koç'a ve canım kardeşlerim İmran'a, Gökhan'a ve Kübra'ya adanmıştır. Aynı zamanda, hayata çok erken veda eden ortaokul fen bilgisi öğretmenim sevgili Fikret Çağlar'ın anısına adanmıştır.

"*Imagination is the highest form of research.*"

Albert Einstein

BIOGRAPHY

Hicran was born in Eregli-Konya, Turkey in August 1st, 1981. She was raised in Istanbul where she has been in love with and where her family and friends live. She received her B.S. degree in Food Engineering from Istanbul Technical University (2004) and M.S. degree in Grain Science & Industry from Kansas State University (2007). She has used near-infrared chemical imaging and mid-infrared microspectroscopy techniques to study wheat germination in Microbeam Molecular Spectroscopy Laboratory at K-State. In 2008, she moved from Little Apple (Manhattan, KS) to Raleigh and started her Ph.D. in the Department of Food, Bioprocessing and Nutrition Sciences at North Carolina State University. Her current research focuses on food materials science approach to understand sensory texture perception of foods by examining food structure, mechanical properties and oral processing.

"I have no special talent. I am only passionately curious."

Albert Einstein

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with "love of wisdom"

Hicran

TABLE OF CONTENTS

LIST OF TABLES ..... **ix**
LIST OF FIGURES ..... **xii**

CHAPTER 1. Literature Review: Understanding Texture of Soft Solids by Oral Processing, Sensory Analysis, and Rheological Characteristics **1**
1. Introduction 2
2. Food Texture 3
3. Creating and Modifying Texture 4
   3.1. Gelation of Biopolymers 5
   3.2. Agar Gels and Carrageenan Gels 8
   3.3. Multicomponent Gels (Composite Food Gels) 10
   3.4. Food Structure 12
4. Oral Processing and Food Breakdown 14
5. Oral Processing Analysis of Texture 17
6. Sensory Analysis of Texture 21
   6.1. Descriptive Analysis 21
   6.2. Descriptive Analysis Combination with Time-Intensity Methods 23
7. Rheological Analysis of Texture (Material Properties) 27
   7.1. Experimental Techniques 28
      7.1.1. Fundamental Rheological Methods 30
8. Relationship among Rheology, Sensory, Oral processing 44
   8.1. Sensory and Rheology 45
   8.2. Sensory and Oral Processing 54
9. Conclusion 56
References 57

CHAPTER 2. Alteration of Oral Processing with Increased Fracture Stress and Fracture Strain of Model Foods **85**
Abstract 86
Practical Applications 87
1. Introduction 88
2. Materials and Methods 92
   2.1. Model Foods 92
   2.2. Large Deformation Rheological Tests 94
   2.3. Subject Selection 98
   2.4. Masticatory Recordings 98
   2.5. Data Anaysis 100
   2.6. Statistical Analysis 102
3. Results 102
   3.1. Rheological Measurements of Gels 102
   3.2. Mastication 104

4. Discussion 109
5. Conclusions 111
References 114

CHAPTER 3. Sensory Texture of Model Foods Based on Large Deformation Rheological Properties and Oral Processing 131
Abstract 132
1. Introduction 133
2. Materials and Methods 136
2.1. Materials 136
2.2. Sample Preparation 136
2.3. Large Deformation Rheological Tests 137
2.3. Masticatory Recordings and Data Analysis 138
2.4. Descriptive Sensory Analysis 138
2.5. Statistical Analysis 139
3. Results 139
3.1. Descriptive Sensory Analysis 139
3.2. Sensory Texture Related to Large Deformation Rheological Properties 142
3.3. Sensory Texture in Relation to Oral Processing 144
4. Discussion 146
5. Conclusions 148
References 150

CHAPTER 4. Effect of Filler Type and Concentration on Small and Large Strain Rheological Properties of Emulsion Filled Polysaccharide Gels 165
Abstract 166
1. Introduction 167
2. Materials and Methods 171
2.1. Materials 171
2.2. Sample Preparation 172
2.2.1. Emulsion formation and particle size analysis 172
2.2.2. Gel preparation 173
2.3. Small Strain Rheology 174
2.4. Large Strain Rheology 174
2.5. Confocal Scanning Laser Microscopy 175
3. Results and Discussion 176
3.1. Emulsion Stability and Droplet size 176
3.2. Small Strain Rheology 177
3.3. Large Strain Rheology 180
4. Conclusions 185
References 186

CHAPTER 5. Sensory Texture of Emulsion Filled Polysaccharide Gels Explained by Microrheology and Oral Processing.....203
Abstract.....204
1. Introduction.....205
2. Materials and Methods.....208
2.1. Materials.....208
2.2. Sample Preparation.....208
2.3. Descriptive Sensory Analysis.....209
2.4. Microrheology.....210
2.5. Oral Processing.....210
2.6. Statistical Analysis.....211
3. Results and Discussion.....211
3.1. Descriptive Sensory Analysis.....211
3.2. Microrheology.....217
3.3. Oral Processing.....218
4. Conclusions.....219
References.....221

LIST OF TABLES

CHAPTER 1

Table 1. Early classification of textural parameters (adopted from Szczesniak (1963)[a], Civelle and Szczesniak (1973)[b] 72

Table 2. Gel texture attributes, evaluation techniques and definitions 73

CHAPTER 2

Table 1. Mastication parameters extracted from oral processing analysis and their definitions 119

Table 2. Correlation coefficients between rheological parameters....120

Table 3. Minimum and maximum mean values obtained from all subjects while 3% (w/w) agar gels were chewed 121

Table 4. Effects of increased fracture stress of agar gels on mastication parameters. Mean values for the treatments and standard error (SE) are presented together with the results of ANOVA and Tukey mean separation test ($p<0.05$). Different letters in the same row showed that treatments were different effects on parameters. Mean values were calculated from the data of 14 subjects chewing 3 replicates of each treatment in a single session (n= 42 for each level of hardness) 122

Table 5. Effects of increased deformability of κ-carrageenan –locust bean gum gels on mastication parameters. Mean values for the treatments and standard error (SE) are presented together with the results of ANOVA and Tukey mean separation test. Different letters in the same row showed that treatments were different effects on parameters. Mean values were calculated from the data of 14 subjects chewing 3 replicates of each treatment in a single session (n= 42 for each level of hardness) 123

Table 6. Significant correlation coefficients between rheological and mastication parameters ($p<0.05$)....124

Table 7. Significant correlation coefficients between rheological and mastication parameters of different phases ($p<0.05$) 125

CHAPTER 3

Table 1. Evaluation techniques and definitions of sensory texture attributes.....153

Table 2. Mean values of sensory texture attributes of agar gels and κ-carrageenan-locust bean gum gels. (Samples with the same letter within a row are not significantly different, $p<0.05$).....154

Table 3. Correlation coefficients among sensory attributes ($p<0.05$).....155

Table 4. Fracture properties of agar (1A, 3A, 5A) and κ-carrageenan-locust bean gum gels (1C, 3.1C, 1.1C) (data from Koc et al., 2012a). Each data point is the average of minimum eight samples.....156

Table 5. Correlation coefficients between sensory attributes and rheological parameters....157

Table 6. Significant correlation coefficients between rheological and mastication parameters averaged over a complete chewing cycle ($p<0.05$). Significant correlation coefficients in parenthesis are between first compression sensory attributes and average mastication parameters for initial phase of chewing (first three cycles) ($p<0.05$).....158

Table 7. Significant correlation coefficients between rheological and mastication parameters averaged over a complete chewing cycle ($p<0.05$). Significant correlation coefficients in parenthesis are between mastication sensory attributes and average mastication parameters for middle phase of chewing (middle three cycles) ($p<0.05$).....159

Table 8. Significant correlation coefficients between rheological and mastication parameters averaged over a complete chewing cycle ($p<0.05$). Significant correlation coefficients in parenthesis are between residual sensory attributes and average mastication parameters for last phase of chewing (last three cycles) ($p<0.05$).....160

CHAPTER 4

Table 1. Average median, modal diameters and surface area of the particles stabilized with different emulsifying agents (each data point is the mean value of 2-4 replicates).....189

Table 2. Recoverable energies for agar (A) and κ-carrageenan-locust bean gum gels (B). Tables on the top represent RE when compression was done to 90% of the original height, tables at the bottom represents RE during compression to 80% of the height 190

CHAPTER 5

Table 1. Gel texture attributes, evaluation techniques and definitions for filled gels 223

Table 2. Mean values of sensory texture attributes of agar gels and κ-carrageenan-locust bean gum gels. (Samples with the same letter within a row are not significantly different, $p<0.05$).....224

Table 3. Significant correlation coefficients between sensory attributes ($p<0.05$).....225

Table 4. Significant correlation coefficients between sensory attributes and rheological parameters ($p<0.05$).....226

Table 5. Oral processing parameters.....227

LIST OF FIGURES

CHAPTER 1

Figure 1. Mechanical spectra for dilute solution (5% dextrin), concentrated solution (5% λ-carrageenan) and gel (1% agar) (reprinted from Steffe (1996)-drawn based on data from Ross-Murphy (1988)-Small deformation measurements, In: Food Structure-Its creation and evaluation).....74

Figure 2. Structure of agarose polymer (top) (reprinted from Wikipedia) and model for agarose gelation (bottom) (showing double helices and assocation of double helices into junction zones (reprinted from Clark and Ross Murphy(1987)) 75

Figure 3. Structure of κ-carrageenan (top) (reprinted from Wikipedia) and model for its gelation (reprinted from Morris et al. (1980)) 76

Figure 4. Behaviors of proteins and polysaccharides when they are mixed (reprinted from de Kruif and Tuinier (2001)) 77

Figure 5. Model for in mouth processing of food (reprinted from Hutchings and Lillford (1988)).....78

Figure 6**.** Mandibular movement during a complete feeding sequence (reprinted from Okada et al. (2007)).....79

Figure 7. An example of stress-strain plot showing three regions of deformation: Linear, nonlinear and fracture. Solid line represents strain-hardening behavior, dotted line represents strain-weaking behavior (reprinted from Foegeding (2006)) 80

Figure 8. General Foods texturometer curve (reprinted from Friedman et al. (1963)) showing force versus time curve for double compression. A_1- first compression A_2- second compression 81

Figure 9. Different fracture modes in compression (top) and in torsion (bottom) testing (reprinted from Daubert, C.-Food Rheology class notes).....82

Figure 10. Normalized force versus normalized true strain curves after fracture point of WPI mixed gels. Low crumbly gels are represented with bold curves without marker symbols. Crumbliness scores are presented in the brackets next to sample name (reprinted from van der Berg et al. (2008)).....83

Figure 11. a. Schematic showing fracture process zone and plastic deformation zone in a notched tension test (reprinted from Hashemi (1997)), b. Schematic showing brittle fracture (top) and elasto-plastic (bottom) fractures (reprinted from Zhang et al.(2006)) 84

CHAPTER 2

Figure1. Fracture properties of agar (1A, 3A, 5A) and κ-carrageenan-locust bean gum gels (1C, 3.1C, 1.1C). Each data point is the average of eight samples.....126

Figure 2. Example of a chewing sequence showing changes through the sequence. Interpose swallow (in circle), and clearance and swallowing section (in rectangle), C:Close, O:Open, A:Anterior, P:Posterior, R:right, L:left.....127

Figure 3. Mean values obtained for muscle activities for agar gels.....128

Figure 4. Mean values obtained for muscle activities for κ-carrageenan-locust bean gum gels 128

Figure 5. Changes in muscle activities along the chewing sequence. (A) Agar gels (B) κ-Carrageenan-locust bean gum gels. Mean values for 14 subjects and 3 replicates were used**.** Changes along the sequence were represented with first 3 cycles (F1-F3), middle 3 (M1-M3) and last 3 cycles (L1-L3) of the sequence. Upper case letters indicates differences among different level of treatments, while lower case letters show differences among first, middle, and last sections of same hardness.....129

Figure 6. Changes in vertical movements along the chewing sequence. (A) Agar gels (B) κ-Carrageenan-locust bean gum gels. Mean values for 14 subjects and 3 replicates were used**.** Changes along the sequence were represented with first 3 cycles (F1-F3), middle 3 (M1-M3) and last 3 cycles (L1-L3) of the sequence. Upper case letters indicates differences among different level of treatments, while lower case letters show differences among first, middle, and last sections of same hardness.....130

CHAPTER 3

Figure 1.Sensory scores of hardness, deformability, particle size and rate of breakdown for agar gels (a) and κ-carrageenan-locust bean gum gels (b).....161

Figure 2. (a)Number of chews and chewing time for agar (filled squares) and κ-carrageenan-locust bean gum gels (unfilled squares) (b) Chewing frequency for agar (filled squares) and κ-carrageenan-locust bean gum gels (unfilled squares).....162

Figure 3. Mean values obtained for muscle activities for agar gels and κ-carrageenan-locust bean gum gels. Significant differences ($p<0.05$) among treatments for each muscle are showed with letters 163

Figure 4. Mean values observed for three dimensional movements of mandibular for agar and κ-carrageenan-locust bean gum gels.....164

CHAPTER 4

Figure 1. Agar gels (top images) and κ-carrageenan-locust bean gum gels (bottom images) with 20% oil droplets stabilized by Tween 20, β-lactoglobulin, lactoferrin (from left to right) 191

Figure 2. a. Storage and loss modulus of agar gels without oil and with 25% oil. Legend: A-Agar, AT-Agar with Tween 20 stabilized fillers, AB-Agar with β-lactoglobulin stabilized fillers, AL-with lactoferrin stabilized fillers, b. Relative changes in storage modulus of agar gels at 1 Hz at different oil concentrations (G′ is storage modulus of filled gel, Gm′ is storage modulus of gel matrix).....192

Figure 3. a. Storage and loss modulus of κ-carrageenan gels without oil and with 25% oil. C-Agar, CT- κ-carrageenan gels with Tween 20 stabilized fillers, CB- κ-carrageenan gels with β-lactoglobulin stabilized fillers, CL- κ-carrageenan gels with lactoferrin stabilized fillers, b. Relative change in storage modulus of κ-carrageenan gels at 1 Hz at different oil concentrations (G′ is storage modulus of filled gel, Gm′ is storage modulus of gel matrix).193

Figure 4. Change in phase angle of agar gels (top) and κ-carrageenan gels (bottom) at 1 Hz at different oil concentrations 194

Figure 5. The effect of oil phase fraction on the ratio of storage modulus of filled gel to matrix of agar gels (top) and κ-carrageenan gels (bottom) at 1 Hz at different oil concentrations. Blue lines show modeling based on van der Poel theory assuming $G'_f=0$, surface tension=6 mN/m and poisson ratio= 0.5 195

Figure 6. Change in Young's modulus with increase oil concentration for agar gels (a) and for κ-carrageenan gels (b), Relation between complex modulus (G*) and Young's Modulus (E) for all gels (c).....196-197

Figure 7. Change in fracture stress with increase oil concentration for agar gels (a) and for κ-carrageenan gels (b).....198

Figure 8. Change in fracture strain with increase oil concentration for agar gels (a) and for κ-carrageenan gels (b).....199

Figure 9. Change in fracture modulus with increase oil concentration for agar gels (a) and for κ-carrageenan gels (b).....200

Figure 10. Change in stress intensity factor with increase oil concentration for agar gels (a) and for κ-carrageenan gels (b) 201

Figure 11. Change in fracture surface energy with increase oil concentration for agar gels (a) and for κ-carrageenan gels (b) 202

CHAPTER 5

Figure 1. Sensory results of agar (top), and κ-carrageenan-locust bean gum gels (bottom).....228

Figure 2. PCA biplot for sensory attributes. Samples were labeled as: 1. Agar , 2. Agar with 10% oil , 3. Agar with 20 % oil, 4. κ-Carrageenan , 5. κ-Carrageenan with 10% oil, 6. κ-Carrageenan with 20% oil 229

Figure 3. Stepwise compression images of filled agar gels (20% oil).....230

Figure 4. Stepwise compression images of filled κ-carrageenan-locust bean gum gel (20% oil).....231

Figure 5. Stress-strain curves of stepwise compression of agar (top), κ-carrageenan-locust bean gum (bottom) gels 232

CHAPTER 1

Literature Review

Understanding Texture of Soft Solids by Oral Processing, Sensory Analysis, and Rheological Characteristics

1. Introduction

Food texture, in harmony with other sensory properties of foods such as appearance, taste and flavor, is one of the most important factors in consumer appreciation and enjoyment of food products. Increased demand to produce foods that are low in fat and salt, high in protein, or targeted for specific diets (gluten free, vegetarian), have led the food industry to use different ingredients and processes to produce traditional products with altered composition. Many of these attempts resulted in less attractive, low quality products with undesirable textures (Wilkinson et al., 2000; Foegeding et al., 2010). Moreover, consumers have not been willing to compromise on texture of foods for health or other factors (Childs and Drake, 2009). Therefore, companies have been challenged with redesigning products with more appealing textures. These developments in the food industry have brought researchers to ask the question, "How does food structure translates into perceived texture?" Our hypothesis is that this question can only begin to be answered by understanding how food structure is transformed into the cognitive representation of food texture by the process of oral processing.

Understanding the response of our senses to food structure and its breakdown requires a multidisciplinary approach including physiological and psychological aspects of perception, physical and chemical factors associated with food structure, and how the food structure changes during mastication (Rosenthal, 1999). In this chapter, food texture will be reviewed starting from how it is defined and how different structures are designed. Oral processing and food breakdown will be discussed. Moreover, different approaches to understand textural properties, focusing on mainly soft solids and model foods, will be

reviewed. Recent developments in sensory analysis, oral processing and rheological/fracture mechanics of foods, and interrelations of these disciplines, will also be considered for a better understanding of texture perception.

2. Food Texture

Food texture is a cognitive property we assign to a food based on how our senses interact with a food. It is defined as "all the mechanical, geometrical and surface attributes of a product perceptible by means of mechanical, tactile and, where appropriate, visual and auditory responses" (ISO, 1992). The texture of a food can be perceived by one of the senses of sight (visual), touch (tactile) and sound (auditory) or by the combination of these senses (Lawless and Heymann, 2010). Szczesniak (1963), a pioneering publication in texture research, classified textural characteristics in three groups: 1) mechanical characteristics are perceived by the forces on teeth, tongue and roof of the mouth when the food is stressed, 2) geometrical characteristics, are related to size, shape and the arrangements of particles in food, 3) other characteristics which are moisture and fat content of food and mouthfeel attributes (Table 1). This classification of textural properties by the scientists at General Food Corporation led to development of Texture Profile Analysis (TPA) used with instrumental (Friedman et al., 1963) and sensory (Brandth et al., 1963) analysis. Moreover, quantitative rating scales for sensory texture profiling were established (Szczesniak et al., 1963). Several modifications of TPA have been made over the years and instrumentation developed. It has been used widely in industry and in academia due to its simplicity and obtaining various textural properties with a two-cycle compression test, although TPA is not

designed to measure any fundamental physical properties of foods (e.g., fracture stress or strain) (Foegeding et al., 2011). In addition to developments in sensory and instrumental approaches to texture evaluation, another important part of the texture puzzle, oral processing, was brought into attention by Hutchings and Lilliford in 1988. They proposed a model explaining the breakdown pathway of food during oral processing which clearly indicated the dynamic and complex nature of texture perception with the continuous changes from food to bolus formation. Therefore, understanding texture perception and progress in this area requires a combination of research in sensory, oral physiology and physics/chemistry (involving rheology, fracture properties, microstructure) (van Vliet et al., 2009). Study of rheological, fracture and microstructural properties of foods, and how ingredients interact to produce food structure, provides information on foods as materials. These material properties aid in understanding how food breaks down under oral conditions by mechanical, thermal and enzymatic actions. Oral physiology investigates physiological signals produced during breakdown of food and how signals modulate oral processing and form the description of texture in the brain. Sensory research provides texture perception of foods based on human assessment and has input from neurophysiology and psychology.

3. Creating and Modifying Texture

Food polymers, proteins and polysaccharides, are key components responsible for building food structures (Tolstoguzov, 2008). Food texture, appearance, stability and sometime flavor release originate from food structure. Therefore, it is very crucial to understand structure-function relationship in food materials to achieve desirable properties

(Aguilera and Lillford, 2008). Gelation of biopolymers is one way to create structures and is critical to modulate texture and sensory perception (Barbut and Foegeding, 1993; Renard et al., 2006; Hermansson, 2008) of gel based foods such as yoghurts, cheese, processed meat and some desserts. Gels are composed of mostly water, and have a solid character due to the formation of a continuous network by biopolymers (proteins, polysaccharides), particles (casein micelles) or mixtures of the two (Mezzange et al., 2005). Forming a gel network requires a critical concentration of biopolymer and specific conditions that convert a sol into a gel. Factors affecting gel properties are type of biopolymer, gel formation conditions (heat-set, cold-set, enzymes), solution conditions (pH, salt), and interaction with other ingredients (Clark and Ross-Murphy, 1987; Ziegler and Foegeding, 1990; Mezzange et al., 2005).

3.1. Gelation of Biopolymers

A gel can be defined as "a soft, solid, or solid-like material composed of two or more components, one of which is liquid, presents in substantial quantity" (Almdal et al., 1993). Polymer gels and networks were classified in three groups by Ross-Murphy (1994, 1995): 1) covalently cross linked systems such as vulcanized rubber and polyacrylamide gels; 2) entanglement networks formed by interaction of chains when the product of concentration and molecular mass is greater than critical entanglement molecular mass (polymer melts and solutions) and 3) physical gels which are cross linked non-covalently (e.g., hydrogen bonding and hydrophobic interactions) and the cross-links act as junction zones. Many food biopolymers, such as agar and, gelatin, belong to the physical gel group. In contrast, globular proteins containing sulfhydryl can be a combination of types 1 and 3.

One of the challenges in comparing across gelation mechanisms of polymers is that they range from synthetic to biopolymers. Classical polymer systems may be a polymer melt that is fluid due to minimal interactions among molecules, and converted into a gel by chemically cross-linking among molecules by forming inter-molecular covalent bonds. In contrast, most biopolymers start as sols or concentrated suspensions and are formed into gels by various means that include covalent and non-covalent interactions. For simplicity sake, the interactions between polymer chains will be referred to as "cross-links" to signify interactions that are producing a continuous three-dimensional structure.

Food biopolymers are typically converted to gels by a sol to gel transition. First, aqueous polymer sols are made such that full hydration of the protein or polysaccharide is achieved. The sol (fluid) is converted to a gel (soft solid) by assembling the polymer molecules into a gel network. This transition is related to connectivity of the chemical or physical interactions linking into a network. Gels are characterized by their flat mechanical spectrum measured by oscillatory shear tests. Storage modulus (G′) shows a plateau extending to times of the order of seconds and loss modulus (G″) is significantly smaller than storage modulus in this plateau region (Ross-Murphy, 1994). Gel point can be identified by small amplitude oscillatory rheology technique where modulus is measured during the gelation process. Often, for practical purposes, the point where G′ and G″ crossover is used to indicate the gel point; however, it is dependent on oscillation frequency (ω). An approach to determine a frequency independent gel point is by the Winter-Chambon (1986) criteria. Gel point is the time when both G′ and G″ have same power low exponent (n), in other words both scales with ω^n. Frequency spectrum of G′ and G″ are measured at different time

intervals and gel point is determined as the time where G ′ is parallel to G″ (tanδ=G″/G′= tan (nπ/2)). Based on this experiment, another way to find that time is plotting log tanδ versus time curves for different frequencies and the intersection point of the curves gives gel point. Ideally, in suspensions prior to gelation the viscous properties dominates in the system (G″>G′). As the network is formed, a gel point is reached (G″>G′) and at the final stages the elastic behavior dominates over viscous behavior (G′>G″). A cured gel must show a relatively flat mechanical spectrum of G′ and G″ over a range of frequencies, and G′>>G″ (Clark and Ross-Murphy, 1987) (Fig.1).

Polysaccharides and proteins are the two biopolymers responsible for gel formation in food products. Their gelation mechanisms and gel properties can be different. Generally, polysaccharides form reversible cold setting gels. By cooling, transition from disordered to order states occurs and this allows for interaction among polymer strands and formation of a gel network. Crosslinks between chains can be formed by different means. Heat-induced gelation is a common mechanism for forming protein gels. Most proteins unfold upon heating and gel by progressive aggregation into a gel network. Globular proteins such as β-lactoglobulin, ovalbumin, and plant storage proteins, form irreversible heat set gels by this process. Concentrations to form a gel are five to ten folds higher for protein gels compared to polysaccharide gels (Renard et al., 2006). Heat set protein gels can involve four different types of molecular interactions; covalent disulfide bonding, electrostatic interactions, hydrogen bonding and hydrophobic interactions. Proteins can yield different gel microstructures (fine stranded and particulate) depending on ionic strength and pH of the system.

3.2. Agar Gels and Carrageenan Gels

Carrageenan and agar are polysaccharides extracted from marine algae. They have been used in several industrial applications due their gel forming ability. They form thermoreversible gels by transition from disordered (coil) to a helical conformation (Goodall, and Norton 1983; Hermansson, 1989) (Fig. 2, Fig. 3). This transition takes place very fast and is similar to a first order phase transition (Ross-Murphy, 1994).

Agar is a polysaccharide food additive that falls under the category of Generally Recognized as Safe (GRAS). It is noted for the ability to form strong, brittle gels. Polymers in agar are composed of D-galactose and 3, 6 anhydro-L-galactose and have low content of sulfate esters (Fig.2). Agar is a mixture of two polysaccharides, agarose and agoropectin (Armisen and Galatas, 2009), in different proportions depending on source and extraction process. Agarose has a high molecular weight (above 100 kDa) with very low sulfate content (below 0.15%) and is the main gelling component. Agaropectin has low molecular weight (below 20 kDa) and has 5-8% sulfate esters. Agar forms reversible physical gels through hydrogen bonding and a gel network can form even at concentrations as low as 0.1% w/w (Armisen and Galatas, 2009). Agar gels form a network with very high exclusion limits. Exclusion limit is the size of the biggest globular protein which cannot pass through the pores in the gel network and the exclusion limit for a 2% agarose gel is 30,000 kDa. The formation and melting of agar gels shows a high degree of hysteresis; it gels around 38 ^{o}C and melts around 85 ^{o}C. The large pores that allow for passage of large molecules (i.e., high exclusion limit) also contribute to low water holding ability. Most of the water from the gel network can be released under pressure. However, it has so-called “gel memory” as it can

recover all water back into structure if submerged in water after compression (Armisen and Galatas, 2009).

Carrageenan is an anionic polysaccharide extracted from seaweeds which has been used extensively in various food products due to its gelation and thickening properties. Similar to agar, it has a galactose backbone. Carrageenan is a high molecular weight (400-560 kDa) linear polymer composed of repeating galactose and 3, 6 anhydrogalactose units which are joined by alternating α 1-3 and β1-4 glycosidic linkages (Clark and Ross Murphy, 1987; Chen et al., 2001; Rey and Labuza, 1981) (Fig. 3). Depending on source, carrageenan varies in the amount of sulfate groups and their positioning along the chain. Three types of carrageenan, kappa (κ), lambda (λ), iota (ι), differing degree of sulfate substitution, have different gelling properties. Gel formation is generally induced by heating to form random coil structures then lowering the temperature and a structural transition from random coil to double helix. Helices form junction zones that lead to a three-dimensional network (Chen et al., 2002). By small angle X-ray scattering profiles, it was found that κ-carrageenan forms two or three associated helices upon gelation (Yuguchi et al., 2002) (Fig. 3). Gel properties are affected by the type and the quantity of counter-ion present in the system (Hermansson et al., 1991). Kappa carrageenan has approximately 25% sulfate esters and forms strong and brittle gels in the presence of potassium salts. It is synergistic with locust bean gum and the interaction between them changes the gel texture to be less brittle, more elastic and flexible with better water holding ability. Locust bean (LB) gum is a galactomannan consisting of linear chains of 1-4 linked β-D-mannopyranosly groups and 1-6 linked α-D-galactopyranosly side chains. Galactose content of LB is about 20% (Fernandes et al., 1993; Stading and

Hermansson, 1993). The gelling mechanism of mixed system of LB and κ-carrageenan is not well understood. The rheology and gelling properties of κ-carrageenan have been investigated alone (Yuguchi et al, 2002; Chen et al., 2002; Watase and Nishinari, 1982) and in the presence of ι-carrageenan (Ridout et al., 1996), other gums (Fernandes et al., 1993; Stading and Hermansson, 1993; Chen et al., 2001) and milk proteins (Langerdorff et al., 2000).

3.3. Multicomponent Gels (Composite Food Gels)

Most food products contain more than one component (e.g., biopolymer or dispersed particle) and various types of molecular interactions that build up the structure. The interaction between biopolymers is very important for textural properties of foods. Upon mixing of two biopolymers in a solution, there can be three main outcomes depending on molecular properties of polymers (molecular weight, charge, solubility) and solvent quality (pH, ionic strength): 1) co-solubility; polymers can form a single phase when they are co-soluble which can happen in very dilute systems, 2) segregation (thermodynamic incompatibility); polymers repel each other forms phases rich in one type polymer and, 3) association (complexation); polymers attract each other and form complexes in the same phase (Fig. 4) (de Kruif and Tuinier, 2001; Hermansson, 2008; Tolstoguzov, 2008). When phase separation occurs during gel formation, different structures are formed due to entrapment of a dispersed phase by gel formation. The properties of gel system are dependent on the properties of different phases, their distributions and also interfacial interactions between phases (Hermansson, 2008). The relative kinetics of gel formation and

phase separation is the key element determines the gel morphology. Changing the relative rates of phase separation and gelation is one way to form different structures.

Multicomponent gels can be classified in three groups: mixed gels, complex gels and filled gels (Zasypkin et al., 1997). Mixed gels are formed when two or more biopolymers form independent networks and there are no interactions between polymers. The structures of these gels would show two inter-penetrating continuous networks. Complex gels are formed from strands composed of two or more biopolymers. In filled gels, one or several biopolymers forming a network (continuous phase) that is filled with dispersed particles (i.e., a discontinuous phase).

Filler particles, such as fat globules, are dispersed within the polymer network and affect the overall macroscopic properties of the gel. Filler particle can be "inactive", and have no association with the gel network, or form an "active" association with the network. Inactive fillers decrease small strain rigidity as phase fraction of filler (φ_{filler}) increases. These fillers essentially form holes in the gel network. In some cases, inactive filler can form inter-particle interactions within the dispersed phase. Active fillers increase or decrease small strain rigidity as phase fraction of filler (φ_{filler}) increases depending on the ratio of filler and gel network storage modulus.

Multicomponent gel technology has led to the development of novel food products. Creating new textures or altering the existing ones by manipulation of structures requires understanding the gelation of biopolymers in a mixed system, interaction of macromolecules and filler particles effect on food gel networks (Tolstoguzov and Braudo, 1983; Tolstoguzov,

2008). By controlling the ingredients and processing parameters, different gel structures can be formed thorough modifications of the interactions between components in mixed systems.

3.4. Food Structure

Food structure can be conceptualized as the structures observed in foods at the nano, micro and macroscopic levels. In other words, it is how molecules assemble into a food product. Food structure is a key element responsible for sensory properties such as texture perception (Hutchings and Lillford, 1988) and also can be related to health and nutrition. Moreover, with the advances in gastronomy, structuring foods for pleasure and luxury is another way to look at the structures. Establishing structure-property relationships has been a major focus of researchers in working with non-food materials in fields of material science and engineering. Investigations taking the approach of "food material science" started to formalize into a focused area of food science starting in 1980s with studies on meat, plant foods and baked products (Blanchard and Lillford, 1988; Peleg and Bagley, 1983).

Different gel structures exist in foods that are responsible for food quality. Depending on solution conditions, proteins can form fine stranded and particulate gel structures. Fine-stranded gel networks can be obtained by gelation of proteins under conditions of high electrostatic charge, which would be solution conditions outside of the isoelectric region or at low salt concentrations. Particulate gels are formed by proteins in the isolectric region or at high salt concentrations, where low net charge cause micro-phase separation (Ako et al., 2009). Factors affect the kinetics of aggregation and network formation such as protein concentration, charge, and heating rate, are important for final gel structure and results in changing pore size, size of protein aggregates, and degree of micro-

phase separation (Ako et al., 2009; Stading et al., 1993; Leksrisompong, 2011). In contrast to proteins, polysaccharides are less affected by the solution conditions and tend to form fine stranded gel structures. Morphology of the network can vary with concentration and gelation process conditions (Stading et al., 1993).

Different structures in single polymer systems are obtained by altering the polymer concentration, solution conditions (i.e., pH, salt), and process conditions (time, temperature, shear). Another way to alter structure is adding another gelling or non gelling component to the system. Mixing two polymers and forming a gel can result in different type of gel networks, mostly based on phase separation (Zasypkin et al., 1997). Protein-protein and protein-polysaccharide interactions are important for the formation of mixed systems with different structures. Various combinations of mixed protein-polysaccharide gels have been extensively studied to form gels with different structures, physical and sensory properties (Brownsey and Morris, 1988; Zasypkin et al., 1997; de Jong and van de Velde, 2007; van der Berg et al., 2008; Cakir et al., 2011; Leksrisompong, 2011; Turgeon and Beaulieu, 2011). Microstructures formed through mixed protein-polysaccharide gels have been characterized by van der Berg et al. (2007). These are protein continuous, bicontinuous, coarse stranded and polysaccharide continuous. It has been showed that gel microstructure affects the breakdown properties, serum release and fracture properties of mixed gels (van der Berg et al., 2007; de Jong and van Velde, 2007; Cakir et al., 2011). The structure of mixed system is determined by distribution of phases, properties of phases and also interactions between phases (Hermansson, 2008). Gel structure is an important factor determining sensory texture, rheological behavior and functional properties such as water, fat holding (Stanley,

1994). Gel structure can be examined by microscopy techniques such as atomic force microscopy, light microscopy, confocal laser scanning microscopy, and electron microscopy. Quantification of the microstructure is achieved by image processing and analysis softwares, which can be quite complicated depending on the structure (Aguilera and Lillford, 2008). Details of microstructure quantification can be found elsewhere (Russ, 2004). As well as interest in the development of new food materials, how these structures are broken down under oral conditions is also considered. This breakdown process will determine the acceptability of foods by consumers. Understanding of food structure and breakdown is important to link the texture to the sensory perception.

4. Oral Processing and Food Breakdown

Oral processing involves the breakdown of the food, mixing particles by continuously secreted saliva and formation of a bolus to swallow. Different foods require different oral strategies for processing of various textures (Chen, 2009). Based on oral processing consideration and material properties (rheological/fracture/tribology), foods can be classified as fluids, semi-solids, soft and hard solids (Foegeding et al., 2010). Fluids do not require chewing, oral processing time is very short, and they are characterized by rheological and tribological properties (Chen and Stokes, 2012). Semi-solids are differentiated from fluids in having a substantial yield stress and their oral processing involves palateing; which is compressing the food between the tongue and hard palate. Solids are chewed to reduce the particle size and prepare for swallowing. Hard solids have crispy, crunchy attributes that are associated with sound while soft solids do not have an auditory component to their texture.

Oral processing is the preparation of food for swallowing and digestion. During oral processing, food is exposed to structural transformations with force applied by teeth (mechanical breakdown) and lubrication effect of saliva (thermal, enzymatic breakdown) (Brown et al., 1998; van der Bilt, 2002). Mastication is a rhythmic motor activity of the jaw which is controlled by central pattern generators in the brainstem (Lund, 1976) and regulated by sensory feedback via oral and circumoral receptors in the periodontal ligament and jaw closing muscles (Lavigne et al., 1987; van der Bilt, 1995; Peyron et al., 1996; Lucas et al., 2004). Sensory information about the forces and displacements is used by the central nervous system to change the form and timing of chewing cycles (van der Bilt et al., 1995). Mastication is variable within and between individuals and affected by food texture, anatomical characteristics of masticatory apparatus, and physiological factors such as bite force, occlusal area, number of teeth, muscle volume, activity and coordination of muscles, saliva production, swallowing threshold and also by personality characteristics (Bourdiol and Mioche, 2000; van der Bilt, 2002; Rey et al., 2007; Vinyard et al., 2008).

Considering solid foods, the first phase of transformation in the mouth involves particle size reduction of food, followed by moistening and softening with the saliva and finally formation of a cohesive bolus for swallowing (Brown et al, 1998; van der Bilt, 2002; Engelen and van der Bilt, 2008). Breakdown of food involves two processes, selection and breakage (Lucas et al., 2002). The possibility of a particle being contacted by the teeth is the selection process. Once the particle is selected and breaks, breakage process indicates the degree of size reduction, size and number of fragments. Selection of particles is determined by the particle size and the tendency of particles to clump together to form a bolus (Lucas et

al., 2002). Selection is also related to subjects's manipulation ability of food. Breakage is associated with the mechanical properties of food and mechanical action applied. Tooth shape, food characteristics, and coordination of jaw-muscle activity affect the breakage process (Lukas and Luke, 1983; van der Bilt, 2002). When food particles are bitten, the saliva is released and tongue presses the particles against palate and packs them together with saliva (Lucas et al., 2002). Tongue movements, as well as lips and cheeks, play important roles for food manipulation, swallowing and also in evaluation of food (Okada et al., 2007; Boyar, 1986). Saliva dissolves the food and releases compounds giving taste and odor. It also softens the fragments of food, thus the friction is decreased. Saliva has an important role in adhering food particles together to form a cohesive bolus (Lucas et al., 2002). Saliva originated from three sources: 1) sublingual glands (beneath the tongue) that secrete mucous-rich film over the oral cavity to reduce friction; 2) the parotid gland (near the ear), lying on the same side of the mouth as that on which food is chewed, sprays a thin serous wetting secretion over particles just after they are fragmented during jaw closing; 3) the submandibular glands (beneath the jaw) produce thicker saliva that forms a pool in the anterior part of the floor of the mouth.

Food is processed in the mouth until structure breakdown and lubrication reach a point to initiate swallowing (Hutchings and Lillford, 1988) (Fig. 5). Lucas et al. (2002, 2004) proposed a model to explain bolus formation and explained the factors important to converting particles into a bolus and swallowing. Food particles adhere both to themselves and to oral lining. Factors that control if the particles aggregate and stick together or stick to oral surfaces are surface tension and viscosity of salivary fluid, adhesion work in food-food

and food-oral lining interfaces and friction needs to be overcome by tongue to move the particles from mucosa. Fragments should have a critical particle size (0.82-3.04 mm for different foods), depending on mechanical characteristics of the food (Jalabert-Malbos et al., 2007). Particle size distributions are similar among subjects for a given food but different among foods. Particle size distribution provides information on how easily foods are processed (Prinz and Lucas, 1995; Jalabert-Malbos et al., 2007). Lubrication can come from saliva, water or fat release from the food. Swallowing is triggered when the physical properties of a food bolus reaches a certain state that can be transported through the soft tissues of pharynx and esophagus safely (Hutchings and Lillford, 1988; Lucas et al., 2002; Peyron et al., 2011). However, optimum physical properties of a bolus for swallowing are not fully known. Swallowing initiation is possibly a process that takes several bolus properties into account (Peyron et al., 2011). It may also include information from muscles or receptors and sensory experiences. In a chewing sequence, multiple swallows can occur (Hiiemae, 2004). Interposed swallows occur within chewing cycles and terminal swallow ends the mastication sequence (Okada et al., 2007). Generally, mastication sequence ends with some irregular jaw movements and terminal swallow. This process at the end of chewing sequence before the terminal swallow is called as clearance (Hiiemae et al., 1996) (Fig. 6).

5. Oral Processing Analysis of Texture

The relationship between food properties and mastication has historically been investigated to answer questions related to three areas (Peyron et al., 2002): 1) clinical and

dental studies; 2) studies on the masticatory process, receptors, reflexes and sensory feedback; 3) food science, relation between sensory experiences, mechanical properties of food and mastication parameters. Many different techniques have been used to address research questions in first and second group and they are beginning to be more highly utilized in food science.

Masticatory function has been one of the main interests in dental studies because of its relevance to dental health. It is a measure of an individual's ability to break down food during chewing (van der Bilt, 2002). Masticatory function has been determined by measuring color change in chewing gum, sugar loss in gum, optical scanning of chewed particles, and sieving to determine particle size. Sieving has been widely used as a way of measuring particle size distribution by determining weight percentage of masticated food that would pass through a series of sieves with different pore sizes. As one would expect, mean particle size decreases as a function of chewing strokes (van der Bilt, 2002). Some other techniques used to record masticatory functions are: recording electrical activities of masticatory muscles (electromyography, EMG), recording jaw movements (electrognathography, EGN), recording of force during chewing or biting, and observation of tongue and soft tissues by videofluorography and ultrasonic echo-sonography (Woda et al., 2006; Boyar and Kilcast, 1986). Among these methods, EMG and jaw tracking have been used to study food texture.

Studying oral processing via electromyography (EMG) and 3-dimensional jaw tracking (JT-3D) in addition to mechanical and sensory techniques is a powerful combination to characterize the complex nature of food texture (Chen, 2009). Electromyography is the

science of recording electrical activity of muscle fibers. When muscles are activated, electrical action potentials are propagated along stimulated muscle fibers; these changes are recorded by electrodes. These bioelectrical activities have been closely related to the forces developed during mastication (Hylander and Johnson, 1993, Woda et al., 2006). Electromyographic activities of the main masticatory muscles which are accessible to surface electrodes - masseter, anterior temporalis and anterior digastric muscles - can be measured by surface electrodes attached on the skin. The muscles are located by direct palpation and anatomical landmarks (Hylander and Johnson, 1993; Mioche et al., 1999). In order to understand mastication completely, along with the muscle activities, jaw movement patterns should be recorded. The three dimensional tracking of the mandibular movements provide information on mandibular velocity, direction and quantity of the movements. Several EMG and JT parameters have been analyzed to understand the changes in chewing behavior with different textural properties. Examples of parameters are: number of chews, chewing time, frequency, total or mean muscle activity, peak muscle activity, vertical, lateral and anterior-posterior movement amplitudes, opening and closing velocities, opening, closing and occlusal durations, and average duration of cycles. These parameters can be examined over the complete sequence, or different parts of the chewing sequence such as initial cycles, middle cycles or last cycles (Brown et al., 1998; Lassauzay et al., 2000; Peyron et al., 2002; Foster et al., 2006). Several researchers report good reproducibility between and within sessions of EMG recordings (Howell et al., 1993, Brown et al., 1994; Ferrario and Sforza, 1996; Peyron et al., 2002). These parameters provide information about the texture of

product and how food is processed in the mouth up to swallowing and serve as one physiological assessment of texture.

Muscle activity has anticipating and sensory input components. If the food resistance is expected, then the anticipating muscle activity is generated. Sensory-induced muscle activity begins as soon as food contact occurs (van der Bilt, 2002). Anticipating muscle activity occur immediately after jaw closing movement starts, peripherally induced activity starts 23 ms after the onset of the load, 85% of activity needed to overcome load is due to peripheral, sensory origin (van der Bilt, 2002). If chewing rate is doubled, then only 40% of activity is due to sensory origin. When jaw speed increases, control of muscle activity shifts from sensory induced (closed-loop) to feed forward (open-loop) control (van der Bilt, 2002). With the changes in physical properties, food resistance varies from cycle to cycle. Thus, immediate muscle response is required to maintain a constant chewing rhythm. A major part of muscle activity is used to overcome food resistance while a low amount is required for basic rhythmic jaw movements. It is shown that induced modifications occur 20 ms after stimulus and adaptation is complete within two cycles (Peyron et al., 2002). Various mechanoreceptors and nerve endings located in different parts of mouth, teeth and muscles sense the forces and this information is transferred to the brain and texture of food is perceived (Chen and Stokes, 2012; Guinard and Mazzuchelli, 1996; Trulsson and Essick, 1997). Research on physiological parameters (muscle activities and jaw movements) involved in oral processing provides a link between food physics, oral processing and sensory perception (Chen, 2009).

6. Sensory Analysis of Texture

Sensory science studies the human responses to external stimuli as they are perceived by human senses. It is a multidisciplinary area and involves research in psychology, physiology, psychophysics and statistics (Drake, 2007). A wide range of sensory techniques are available to measure human responses to food and characterize food texture. Two basic categories of sensory tests are analytical and affective (consumer) tests. Analytical tests (difference, threshold, descriptive tests) are objective and use trained judges, while consumer tests (preference, hedonic, conjoint, just about right, interview, focus group and focus panel) are subjective and use consumers (Lawless and Heymann, 2010; Meillgard et al., 2007).

6.1. Descriptive Analysis

Descriptive tests, as the most comprehensive and useful analytical sensory technique, have been used to establish relationships between sensory and instrumental measures. Descriptive tests are conducted by a trained group of judges (6-12) to identify and quantify sensory attributes of food products. The extent of training varies based on the number and complexity of the attributes evaluated. Training may require 60-120 h in some cases (Chambers et al., 2004) or a few hours may be enough for describing a few, distinct attributes (Drake, 2009). The results obtained from a descriptive panel are similar to instrumental data as panelists are treated as sensors of instruments.

Panelist selection and creating the lexicon (sensory language) are very critical parts of descriptive tests (Drake and Civille, 2003). Panels are trained and calibrated with a well defined and reproducible lexicon. Panelists should have the ability to describe sensations and discriminate among them. A good lexicon should be discriminating and descriptive and

composed of attributes which are representative, discriminatory, orthogonal (non-redundant), unambiguous and ideally having references. Language development requires using representative sample sets. In establishing a lexicon, a large number of products should be screened to account for comprehensiveness of attributes and variability among products. Non-redundancy is another key property of a good lexicon; different terms should not be used to describe the same attribute. All terms should have definitions and these definitions should be clear and have the same meaning to every panelist. References are also important factors in developing a robust sensory language. Using multiple references (either food or chemical) is recommended since different individuals can identify an attribute better in some references over others. Having a language that can be related to consumer concepts and instrumental measurements is another important part of developing a lexion. However, the ability to have these relations is not always possible. Details of establishing a lexicon and several established descriptive analysis techniques with different approaches are reviewed elsewhere (Murray et al., 2001, Lawless and Heymann, 2010, Drake and Civille, 2003).

Descriptive analysis methods used in texture evaluation include Texture Profile Analysis (Brandt et al., 1963), Quantitative Descriptive Analysis® (Stone et al., 1974; Stone and Sidel, 2004), the Spectrum Method® (Meilgaard et al., 2007), Free-choice Profiling (Willams and Langron, 1984) and generic descriptive analysis. Quantitative Descriptive Analysis (QDA) and the Spectrum Method have been commonly used in texture research. QDA and Spectrum have similar size of panel members (8-12 individuals), but differences exist in the methods and training the panel. In QDA, the panel leader facilities the process, but the leader is not part of panel and not involved in discussion. On the other hand, in

Spectrum, the leader leads the panel by participating in panel training (scale usage, language development and application). Data is recorded using line scales and 15-point category scales for QDA and Spectrum, respectively. A product specific scaling is used in QDA, whereas a universal scaling is the choice for the Spectrum method (Drake and Civille, 2003). The terms in a lexicon can be non-technical in QDA. In this technique, it is assumed that judges use different parts of line scales, thus relative differences among products are obtained, not absolute values, which can make it more difficult to compare results from different panels. Intensity scales in Spectrum are absolute and universal. They have the same intensity across scales for different attributes. However, product specific scaling can also be available in Spectrum technique. Also terms are technical. This characteristic of the Spectrum method brings an important amount of time and financial investment to method development and training the panel (Drake and Civille, 2003; Lawless and Heyman, 2010).

6.2. Descriptive Analysis Combination with Time-Intensity Methods

Sensory perception of flavor and texture is a dynamic process with perception and intensity of attributes changes throughout oral processing steps of first chew, mastication, and swallowing. This phenomenon has been addressed at a first approximation in the texture profile method separating terms according to, first bite, mastication, and residual. In general, descriptive methods judge the perceived intensity of an attribute (e.g., level of sweetness) and, thus require integration of the sensory perception over time. Changes occur during this time frame can not be obtained from static judgments (Lee and Pangborn, 1986; Cliff and Heymann, 1993; Dijksterhus and Piggott, 2000). Time-intensity (TI) methods allow panelists to scale their sensations over time and it provides rate-related, duration and intensity

information. Research on TI was started on taste sensation; with the first published study on the perception of salty taste (Holway and Hurvich, 1937). This was followed by TI of bitterness (Sjostrom, 1954) and sweetness (Lawless and Skinner, 1979; Birch and Munton, 1981). Methodology improved over the years from using clocks, papers, and food pedal controlled chart recorders to computerized systems (Cliff and Heymann, 1993; Lawless and Heymann, 2010). This resulted in many investigations using TI in the 1980s and 1990s. Some parameters extracted from TI methods are peak intensity, total duration, area under the curve, areas under the rising and descending phases, rising and declining slopes and time to peak. Time dependent sensory data can be collected in different ways. Discontinues sampling is the earliest approach where panelist rate the attribute at different phases of eating as done in texture evaluation in first chew, mastication and residual. Data can also be collected by continuous tracking of attributes, mostly done on perception of taste and aroma. Another method of TI which is developing is temporal dominance sensations (TDS) (Pineau et al., 2009). In this technique, dominant sensations (the most striking perception at a given time) are selected by panelists from a predetermined attributes and evaluated over time individually. The main advantage of TDS over other TI methods is the possibility of gathering temporal information on up to 10 attributes at one evaluation session. Other techniques give time intensity measurement of a single attribute.

Descriptive methods can be combined with time-intensity methods for specific purposes and products (Lawless and Heymann, 2010). Seo et al., (2009) conducted a time-scanning descriptive test for evaluation of hot beverages by putting a time limit for the evaluation of each attribute. The purpose was to avoid the possibility that each panelist

would evaluate the product at different amounts of time, thus causing evaluation of a hot beverage at different temperatures. Application of TI methodology on texture studies is more limited compared to studies on taste and odor. Ice cream coldness, iciness and sensory viscosity (Mooere and Shoemaker, 1981), in addition to melting behavior of spreads (Tuorila and Vainio, 1993), were studied with TI. Melting property of ice cream and fats gives time-intensity curves that start with a maximum intensity and declines (unidirectional). Gelatin hardness (Larson-Powers and Pangborn, 1978), meat tenderness (Butler et al., 1996; Duizer et al., 1996; Zimoch and Gullett, 1997), viscosity of chocolate puddings (Pangborn and Koyasako, 1981), juiciness of meat (Peyvieux and Dijksterhius, 2001; Zimoch and Gullett, 1997), adhesiveness and cohesiveness of peanut butter (Rine, 1987) are some other textural attributes evaluated by continuous TI. Maximum firmness is perceived at 0 time and decreases as time progresses; unlike taste and flavor perception that have maximum intensity after 10-15 sec (Larson-Powers and Pangborn, 1978). Duizer et al. (1996) investigated the relationship between time-intensity, physiological and instrumental measures and suggested reexamination of early and late mastication effects for the evaluation of meat tenderness. They demonstrated that maximum intensity perception occurs over the first to fourth bite. Lenfant et al. (2009) applies Temporal Dominance of Sensation for the evaluation of dynamics of texture perception during consumption of breakfast cereals. There are differences in the sensory trajectory among the different cereals; however, some common observations are made on which sensations occurs at different phases of oral processing. Perception of hardness, crackliness and crunchiness occurs at the initial phase of mastication,

while brittleness and lightness are perceived in the middle phase. Stickiness is observed in last phase of mastication.

Conducting TI tests is not easy and individual variations in the TI curves are observed (Peyvieux and Dijksterhuis, 2001). A profiling study before the experiment has been recommended for choosing the appropriate attributes and consistent judgments of panelists. Analyzing TI profiles of texture can be more difficult than TI measurements of flavor, thus extra training may be required. An approach to panel training for TI studies is discussed by Peyvieux and Dijksterhuis (2001). Peyvieux and Dijksterhuis (2001) stated that using TI in the evaluation of some textural attributes can be problematic. After the food is completely comminuted, the data for textural attributes (e.g. tenderness) may not be valid. "A mashed food bolus is neither tender nor tough; it can be fibrous, grainy, soft, but tenderness seems not to apply anymore" (Dijksterhuis and Piggott, 2000). The dynamic nature of texture perception results in appearance and disappearance of different sensations over time. Studies of TI evaluations of sensations can lead to innovative advances in sensory science, however the cost and time required in collecting data can be high. Some issues regarding the method and how to make the decision on using these techniques are reviewed by Lawless and Heymann (2010). Characterization of product properties associated with their breakdown behavior and psychological information on how to relate perceived texture and changing stimuli are essential (Dijksterhuis and Piggott, 2000). Investigations with TI methods can contribute to understanding of these essential elements.

7. Rheological Analysis of Texture (Material Properties)

Many instrumental techniques have been developed to determine the rheological characteristics of food materials. Rheology is the science of the deformation and flow of matter, concerned with forces, deformations and time (Blair, 1958). Rheological characteristics of foods include material properties evaluated prior to fracture (linear and nonlinear regions), at the fracture point and also after fracture (breakdown pattern) (Fig. 7). Before fracture, in the linear viscoelastic region (LVR), stress is directly proportional to strain. Very small deformations are applied in this region with the goal of causing no structural changes during testing. The slope of the stress-strain curve in LVR under normal forces is termed the Young's (Elastic) Modulus and gives information about the rigidity of the material. The range of this region varies depending on material property (composition, gel network structure and crosslink density). Non-Hookean solids will have a non-linear region between the linear region and the point of fracture. Based on the shape of the curve in this region, materials can be classified as strain hardening (solid line) or strain weaking (dotted line) (Fig. 7). In a strain hardening material, stress increases with strain greater than an ideal elastic response (Hookean), whereas in a strain weakening material, stress increases with strain less than ideal elastic response. Structural damage may occur to some degree in this region due to larger deformations. Thus, the stress-strain curve is generally not fully reversible (Walstra, 2003). The slope of the curve in the non-linear region is thus an apparent modulus and changes with the magnitude of deformation. If strain reaches a magnitude causing macroscopic structural damage, fracture occurs and a sudden decrease in stress is observed. At this point, fracture stress and fracture strain are two important

parameters related to material properties. Fracture stress reflects the strength of the material while fracture strain is related to deformability of network. Another parameter derived from the curve is area up to fracture which is called as specific work of fracture (J/m^3) or toughness (Walstra, 2003).

7.1. Experimental Techniques

Instrumental techniques to study textural properties of foods have historically been classified into fundamental, empirical and imitative tests (Blair, 1958). *Fundamental rheological tests* measure the material properties of foods by determining direction and magnitudes of stresses and strains. The tests require the material to be homogeneous and isotropic on a scale in proportion to the sample size and testing cell to provide measurements that are independent of sample size, dimension and test. Some examples are small and large strain tests for solids which gives well defined physical properties of the system such as small strain tests providing information on viscoelastic nature of food with storage modulus (G′) and loss modulus (G″) parameters.

Empirical tests are not designed to calculate fundamental materials properties and therefore have no restrictions on testing conditions. Empirical test are used for several reasons. In some cases, the complexity of the food material is such that a test may probe two or more phases simultaneously. For example, think of compressing a chocolate covered cherry! In other cases, the geometry of the material and or testing method is so complex that precise stresses and strains cannot be calculated. Empirical tests will not provide basic material properties; however, they have been useful in different parts of industry for quality control purposes (Rosenthal, 1999). Penetrometers are one the empirical test used widely in

testing quality of gel type materials. An example of penetrometers is the bloom gelometer, developed for testing of gelatin gels (Bloom, 1925). In this test, the force is measured when a certain weight of cylindrical plunger (12.7 mm diameter) penetrates 4 mm into the surface of the gel. Gelatins are characterized based on their gel strength defined by Bloom units (100 Bloom-very weak gel, 250 Bloom-firm gel). Some other empirical methods are compressors (Brinell hardness tester, Baker compressimeter), shearing devices (Kramer shear press, Warner-Bratzler, pea tendometer, consistometers (Bostwick consistometer for ketchup), tenderometers (Breen, 1975; Friedman et al., 1963, Szczesniak et al., 1963), and extensiograph, farinograph, amylograph.

Imitative tests try to mimic the mouth conditions which food is subjected to. Based on the characterization of texture terms by the scientist in General Foods in 1960s and the denture tenderometer developed at the MIT (Protector et al., 1955), instrumental TPA was developed by Friedman et al., (1963). The texturometer applies a two-cycle compression of a bite size sample to 25% of its original height (75% compression) for simulation of jaw movement in first chews. Analysis of force-deformation (time) curve provides different textural measures (Fig. 8):

1) Hardness: height of the first compression peak

2) Cohesiveness: ratio of A_2 (area under the second compression peak) and A_1 (area under the first compression peak)

3) Elasticity (springiness): C-B, where B is the distance from the initial sample contact to the second contact during second cycle. C is the same measurement for an inelastic standard

4) Adhesiveness: area under the negative peak for the first bite which represents work required to pull the plunger away from the sample

5) Brittleness (fracturability): height of the first significant peak in the case of multiple peak shape curves.

6) Chewiness: product of hardness, cohesiveness, elasticity

7) Gumminess: product of hardness and cohesiveness

After instrumental and sensory TPA were developed, the relation between those was investigated and instrumental TPA gave good correlations with sensory texture profiling (Szczesniak et al., 1963). Instrumental TPA was adapted to the Instron universal Testing Machine by Bourne (1968) only by changing the definition of cohesiveness. He considered the areas under only the compression portion and removed the decompression part from the calculations. This definition was further modified by Drake (1966) and Peleg (1976) by subtracting the decompression area from compression area to obtain net work (Bourne, 1978). TPA was also critically judged and some modifications were proposed by Sherman (1969). TPA has been used to evaluate the texture of different types of foods with different testing conditions (sample size, shape, size of compression unit, percent deformation, test speed) and review of these studies and discussions, modifications on the TPA terminology can be found elsewhere (Breene, 1975).

7.1.1. Fundamental Rheological Methods

Fundamental rheological tests measure the physical properties of foods. The usefulness of fundamental tests is that material properties can be linked to molecular mechanisms to explain structure-function relationships. Rheological properties of solids are

explained by the relationship of two parameters, stress and strain. Stress (σ) is the applied force to per unit area, strain (ε) is the deformation per unit length (Steffe, 1996). The direction of applied force with respect to surface determines the type of stress being normal (perpendicular) or shear (parallel). Normal stresses are applied in compression and extension tests, while shear stresses take place in rotational rheometry and torsion tests.

Two extremes of rheological behavior are elastic and viscous properties. Ideal elastic materials (solids) obey Hooke's law where the relationship between stress and strain is linear. The proportionality constant between stress and strain is the elastic modulus (E) under normal stress conditions and shear modulus (G) under shear stress conditions. Stress-strain relationships for elastic materials is time/rate independent. Ideal viscous materials (fluids) obey Newton's law where the relationship between stress and strain rate (degree of deformation with respect to time) is linear. Foods are viscoelastic and exhibit both solid-like and fluid-like behavior. Viscoelastic characteristics of materials depend on the rate at which force is applied, thus time scale is an important factor. Deborah number (De) takes the time into account and defines the solid or fluid nature of the materials.

De= t/T where t is the response time of material and T is the time frame of the experiment. For solid-like behavior, De is expected to be large (De>>1).

Different regions of a stress-strain curve (linear, nonlinear, fracture, post-fracture) are observed with increase magnitude of deformation and these were previously described. Understanding rheological properties at different level of deformations can give a full spectrum of material behavior and offers the possibility of relating to sensory and oral processing.

Small Deformations (Linear Viscoelastic Region)

The linear viscoelastic region is probed by small strain rheological test, small amplitude oscillatory shear (SAOS) and transient experiments (creep compliance, stress relaxation). In SAOS tests, sinusoidal stress or strain is applied to material and material's response to this dynamic shear is measured. These tests are widely used to study gel network formation and time dependent viscoeleastic properties. Storage modulus (G′), loss modulus (G″) and phase angle (δ) are the main parameters obtained from the test. Storage modulus represents the energy stored elastically in the material over the time frame of the test, while loss modulus is a measure of the energy dissipated. Phase degree ($\tan\delta = G''/G'$) indicated the relative degree of viscoleasticity at a given frequency. For an ideal solid, applied stress and response strain are in-phase and the phase angle is 0°. For an ideal liquid, applied stress and response strain are 90 degree out of phase, and phase angle is 90° (Steffe, 1996; Daubert and Foegeding, 1998).

A typical approach to SAOS testing is as follows. First the linear viscoleastic region (LVR) is established by progressively increasing stress (stress sweep) or strain (strain sweep) and determining the magnitude where linearity between stress and strain is lost. This is often a gradual rather than a sharp transition and operational definitions, such as a 10% decrease in linearity, are used. This should also be established over a range of frequencies. Subsequent tests are conducted within the LVR. Frequency sweeps (G′ and G″ are measured as a function of frequency (ω) at constant strain or stress and temperature) are used to establish mechanical spectra of a material. It is desirable to conduct these tests over at least three orders of magnitude in frequency. Temperature sweeps (G′ and G″ are measured as a

function of temperature at constant stress or strain and frequency) and time sweeps (at constant frequency and temperature) allow for determining how materials adjust to the environment (Rao, 1999).

Large Deformations (Nonlinear Region and Fracture)

It is easier to establish theoretical models based on data from the LVR because it is assumed that non-destructive forces and deformations are used to study time or temperature dependent changes in the material. Although, this regime provides a mechanical fingerprint of food materials, studying rheological properties under large deformations is more related to end use of foods; food breakdown and texture (Bot et al., 1996). Large deformation behavior involves the non-linear region and fracture. Large strain tests (shear, compression, torsion) and large amplitude oscillatory tests can be used to study these regions and obtain material properties.

Non -linear Region

The non-linear region defines the region starting from where the stress-strain relation deviates from linearity and ends at the fracture point. The shape of the curve is specific to a material and can be classified as ideal elastic (Hooekan solid behavior up to fracture; in this case it would be linear with no non-linear region), strain hardening (stress increases with strain faster than for ideal solid) and strain weaking/softening (stress increases slower with strain than for ideal solid). Models have been developed to describe and quantify non linearity of materials (Blatz et al., 1974; Peleg, 1984). For biopolymer gels, the equation proposed by Blatz et al. (1974) (BST equation) has been used to model stress-strain curve by fitting two parameters, modulus (E or G) and an elasticity parameter (n).

$$\sigma = \frac{3E}{2n}\left(\lambda^{n-1} - \lambda^{-(n+2)/2}\right)$$

Elasticity parameter is 2 for ideal elastic material and it is a measure of deviation from nonlinearity. λ is the stretch ratio. The BST model was applied to gelatin gels (Bot et al., 1996; Groot et al., 1996) to study their large deformation behavior at varying experimental conditions and n was reported between 2.5 and 5.5. McEvoy et al. (1985) used the BST model in agarose and gelatin gels. Agarose deviates from ideal elastic behavior more than gelatin which is explained by more extended junction zones with shorter flexible chain segments between zones. Although the BST model gives good fit to data, a link between fitting parameters and the molecular structure needs to be established. Molecular interpretation of strain hardening models proposed by Flory and by Thelor, along with applications of other models by Monte Carlo stimulations, is discussed by Groot et al., (1996). They state factors attributable to strain hardening behavior of gelatin gels as finite polymer length, fractal structure of the strands and presence of stiff rods and flexible coils in the structure. Also, it is concluded that theories explaining gelatin gel behavior can be applied to other polymers with strain hardening behavior. Studies of nonlinear behavior via large amplitude oscillatory shear (LAOS) can also provide new measures to probe nonlinear material properties of soft solids. Some applications and information on methodology can be found elsewhere (Edwolt et al., 2008).

Fracture Properties

Fracture properties of food are more relevant to deformations in the mouth and sensory perception. Materials under large deformation fracture at a critical strain. Fracture

properties of viscoelastic materials involve several parameters as a function of strain rate, which include fracture stress, fracture strain, work of fracture and fracture modulus (van Vliet and Walstra, 1995). The changes that define fracture are (van Vliet and Walstra, 1995):

1) All bonds that structural elements are connected through in macroscopic plane are broken.
2) Changes in structure over length scales larger than size of structural units.
3) Specimen falls apart into small pieces.

All three must occur, for fracture to happen, while for flow only first one is needed and for yielding (spreading) just the first two. Fracture in viscoelastic materials can also be described by an energy balance (Luyten et al., 1991; van Vliet, 2002) which can be written as:

$$W = W' + Wm'' + Wc'' + Wf$$

where W= total energy input, W′= stored energy, Wm″= dissipated energy caused by network flow, Wc″= dissipated energy by the friction components in the network, Wf= energy for fracture. The latter can involve flow of liquid through gel network due to deformation and friction between fillers and continuous phase (Luyten et al., 1991).

In purely viscous materials, all deformation energy is dissipated (W= Wm″), no fracture occurs. On the other hand, in purely elastic, all deformation energy is stored, until part of it released for fracture. Viscoelastic properties of foods affect the fracture since they determine which part of energy is stored and used for fracture. The proportion of the stored energy will be affected by deformation rate, thus the fracture will depend on rate as well.

Estimation of stored energy can be done in two ways; hysteresis experiments (recoverable energy) and dynamic experiments.

Recoverable energy (degree of elasticity) is determined by compression-decompression test using area under force-deformation curve during compression (W_1) and decompression (W_2) were calculated and %RE were expressed as

$$\%RE = \frac{W_2}{W_1}\ x\ 100$$

which represents the ratio of recoverable work to total work (Kaletunc et al., 1991).

Recoverable energy decreases with increasing strain and decreasing strain rate. The amount of recoverable energy is hard to determine exactly; because some delayed elastic recovery can occur after unloading. A second way to estimate stored energy is measuring loss tangent in small strain dynamic testing (Luyten et al., 1991). Phase angle varying between 0-90^o gives information about the elastic and viscous character of materials. For example, if the loss tangent, ratio of G″ to G′, is 0.31-40, then recoverable energy is about 71-76% assuming G″ represents energy lost and G′ energy stored. Deviations between RE obtained from small and large strain tests can be due to some fracture inside the sample before macroscopic fracture occurs. Moreover, magnitudes of applied stress and strains are different, thus energy dissipation can be different under these conditions.

Different large deformation methods can give different types of information on large deformation behavior. Appropriate test can be chosen depending on material type and the property of interest or information relevant to end use of food. Materials can be deformed to fracture by compressive, tensile or shear forces. When forces in compression and tension are only in one direction, they are said to be uniaxial (Hamann et al., 2006; Luyten et al., 1992).

Uniaxial compression, uniaxial tension, torsion, and bending are methods used to determine fracture properties. Food materials can fracture in shear, tension and compression or a combination. The mode of fracture can be determined by looking at the fracture plane angle relative to the longitudinal axis.

Not all tests can be applied to all type of materials. Compression tests have been widely used because they are easy to perform and the specimen is not attached to the testing machine. Friction between sample and testing surfaces and loss of moisture during deformation can cause problems associated with compression testing. Based on the analysis of stresses in compression (Hamann et al., 2006), if a sample fractures in the longitudinal direction, it indicates failure in compression or tension, while fracture plane at angle of 45^{o} with the longitudinal axis indicates failure in shear (Fig. 9). Mode of fracture in compression can depend on length to diameter (L/D) ratio. If this ratio is less than 0.7, then it has an effect on the results (Peleg, 1977; Diehl et al., 1979). Compression test has limitation at higher strains (>2-2.5), because of non-predictable changes in sample dimensions (Truong and Daubert, 2000). Tensile tests are difficult with food materials because they require strong attachment of samples to the testing equipment and fracture should occur away from where the sample is attached. The advantage of tensile tests is that you have in theory infinite strain and fracture is easy to observe.

Torsion tests offer the advantage of being in pure shear. Although shape change occurs under pure shear, volume does not change. As with tensile testing, the torsion test requires strong attachment of the sample. The pure shear conditions of torsion testing means that tensile, compressive and shear stresses have equal magnitudes but different direction.

Capstan shape sample ensures the fracture in the center during twisting action. The test was developed by Diehl et al. (1979) to test fracture properties of fruits and vegetables. Torsion test may not be applicable to soft and sticky materials (Troung and Daubert, 2000). In the torsion test, if a sample fractures plane perpendicular to longitudinal direction, it indicates failure in shear, while fracture plane at angle of 45^{o} with the longitudinal axis indicates failure in tensile (typical for brittle materials) (Fig. 9). Bending test combines compression, tension, and some shear. In tension and bending tests, it is possible to make artificial notches and notch sensitivity can be determined (Luyten et al., 1992). Although rate of deformation changes differently for each method, fracture stress and strain obtained by from different tests are in good agreement. Relative rate of deformation depends on height of sample. Rate of deformation increases in compression and it decreases in tension. In bending, change in the rate is different in different parts of the piece.

Fracture stress, strain and modulus are common mechanical parameters reported in the texture studies of food materials. In addition, changes after the point of fracture (van der Berg et al., 2008) with compression are studied to understand breakdown pattern of foods. Moreover, fracture energy of foods have been evaluated by cutting (Atkins and Vincent, 1984), bending, tension and wedge-fracture test (Vincent et al., 1991; Alverez et al., 2000; Charalambides et al., 1995; Gamonpilas et al., 2008).

Post-fracture Behavior (Breakdown Properties)

Breakdown properties of materials are related to their viscoelastic behavior which results from the energy balance between stored and dissipated energy (van der Berg et al., 2008). The shape of the stress-strain or force-deformation curve after the fracture point can

give information about the breakdown properties of materials related to sensory perception. In whey protein/ polysaccharide mixed gels, van der Berg et al. (2008) reported shape of the normalized force versus normalized true strain curve varied among gels and related to crumbliness perception. A sharp decrease followed by leveling off is associated with a crumbly sensory texture, while gradual decrease after fracture indicates a low crumbly sensation (Fig. 10). Moreover, the slope of the curve shows the speed of fracture propagation. If the slope is large, a free-running crack occurs and fracture happens readily. Post fracture evaluation of the force-deformation curve is done qualitatively. In order to quantify the critical speed of fracture, a wedge test is performed at different speeds. Critical speed of fracture is determined as the speed at which 50% of the samples fractured (van der Berg et al., 2008). If a material has a low critical speed of fracture, such as crumbly gels, it has a large elastic component allowing for a free running crack. A negative correlation is obtained between crumbly score and the critical speed of fracture. Post fracture behavior of other mixed protein and polysaccharide gels have been studied (Cakir et al., 2011, Leksrisompong et al., 2011). With the addition of polysaccharides to protein gels, significant changes occur in the microstructure and slope of the breakdown curve. Protein gels (egg white or whey protein isolate) show steep or semi-steep decrease, while the addition of polysaccharides causes very slow fracture to occur.

Fracture Mechanics

Experiments and observations done by Griffith (1921) showed the contradictory fact of measured fracture stress of brittle materials is lower than prediction based on atomic bond energies. Griffith explained this fact by the presence of microscopic cracks or flaws in the

brittle materials and quantified the relation between strength and crack size (Anderson, 1995; Callister, 2010) leading the foundation of fracture mechanics. Irwin (1957) established the linear elastic fracture mechanics (LEFM) and also considered ductile materials where additional energy is required for crack propagation in ductile materials due to plastic deformation. Rice (1968) introduced the J integral for use in modeling elastic plastic fracture mechanics.

In fracture mechanics, the basic assumption is that all materials are inhomogeneous at some scale and have small defects which can grow and initiate the fracture. Magnitude and distribution of defects govern the strength of the material (Alverez et al., 2000). Once the material is deformed, the stress is the highest at these weak points. The requirements for a crack growth to cause fracture are (Atkins and May, 1985): 1) stress at the crack tip should be higher than cohesive and adhesive stresses between structural elements (if this happens then crack starts to grow causing fracture initiation); and 2) stored energy release during crack growth should be larger than amount of energy required to form new surfaces. If the two requirements are met, then crack propagates spontaneously (fracture propagation) (Luyten et al., 1991; van Vliet, 2002).

First criterion is related to a stress intensity factor (K_I). Stress intensity factor relates local stress to the crack tip in terms of the applied stress and the geometry, based on linear elastic fracture model:

$$K_I = Y\ \sigma\sqrt{\pi a}$$

Where K_I is stress intensity factor (fracture toughness), σ is the applied stress at the onset of crack growth (fracture stress) and Y is the dimensionless geometric factor (function

of the crack length and sample width, geometry, manner of load application) and "a" is the initial crack length (Kinloch and Young 1983; Williams, 1977; Callister, 2010). Mathematical expressions for Y for different crack-specimen geometries have been established and these are relatively complex. Stress intensity depends on crack size, shape, notch sensitivity of material and inhomogeneity (Luyten et al., 1991; Alverez, 2000).

The key concepts for fracture mechanics are illustrated using fracture in a linear elastic, brittle material. Stress intensity factor (K_I) is used to measure the fracture toughness. Fracture toughness indicates the stress needed to propagate a crack. The subscript I indicates the mode of fracture (opening, sliding, shearing). Units for K_I are $Pa\sqrt{m}$.

The second criterion is related to critical strain energy release rate (fracture surface energy; G), which is the energy to extend a crack over a unit area (Lillford, 2001).

$$G= \pi\sigma^2 a/ E$$

Stress intensity factor and fracture surface energy is related to each other by $G= K^2/ E(1-v^2)$ (plane strain conditions) or $G= K^2/E$ (plane stress conditions) where E is Young's modulus and v is Poisson ratio. Both stress intensity factor and fracture energy can be a measure of resistance to crack propagation and toughness of a material.

Fracture mechanisms can be understood by studying two aspects; fracture stress notch sensitivity and fracture surface energy. Notch sensitivity is measured by fracture stress as a function of notch length. A notch is introduced to the sample as an initiating point for fracture which imitates naturally occurring cracks or defects in the material (Griffith 1921; Anderson 1995). This measure provides information on the size of the largest structural element causing fracture and how sensitive fracture is to the flaws. Therefore, notch

sensitivity is related to crack initiation. Fracture surface energy is the work required to fracture one unit area of material which governs the crack propagation.

There are three ways of applying a force to enable a crack to propagate: Mode I crack –opening mode (a tensile stress normal to the plane of the crack), Mode II crack- sliding mode (a shear stress acting parallel to the plane of the crack and perpendicular to the crack front), Mode III crack – tearing mode (a shear stress acting parallel to the plane of the crack and parallel to the crack front) (Anderson, 1995). There are different tests and sample configurations required to address these ways of applying stress. In each test type, the specimen with a preexisting crack is tested at a specified rate and load and crack displacement are recorded. Common methods are Single Edge Notched Tension (SENT), Single Edge Notched Bend (SENB), Center Crack Tension (CCT), Double Edge Notched Tension (DENT) and Compact Specimen. These tests were originally developed for testing of metals and engineering materials and later applied on polymers and gels. With tensile and bending tests, the start and propagation of fracture can be distinguished. Bending tests are not appropriate if the sample is very soft or deforms strongly before fractures. Tensile testing is a useful way to determine fracture parameters. It can be applied to materials with large fracture strains. Mathematical expression of stress intensity factor and fracture surface energy depends on the testing method used and they are calculated based on crack size, geometry, and fracture stress.

Fracture mechanics was developed on stiff, linear and brittle solids which exhibit *linear-elastic (brittle) fracture*. In brittle fracture, a crack propagates rapidly and very little plastic deformation occurs. The crack is unstable and propagates spontaneously without

increase in stress. However, most biological materials are non linear and exhibit plastic flow before fracture. During *elastic-plastic fracture (ductile)* fracture, plastic flow occurs and pieces after fracture do not fit to each other precisely (Fig. 11). Crack moves slowly and deformation at fractures surfaces can be observed. The region at the tip of crack can be considered in two parts; end region where fracture occurs and outer zone where plastic deformation happens (Broberg, 1968) (Fig. 11). The crack does not propagate immediately due to plastic deformation; it is stable and resists the extension. In these materials, strain energy is not absorbed by all fracture processes, but will be separated into dissipative parts such as plastic flow and yielding. Work of fracture also increases due to energy dissipation with yielding (Walstra, 2003). Total work is divided into work for fracture process (essential) and work for plastic deformation or flow (nonessential) (Hashemi, 1997). This means that more energy is required for ductile fracture (Callister, 2010). In some studies, total area to produce a complete fracture is divided by propagated crack area and called as "work to fracture" (Walstra, 2003). In others, approaches are developed to separate the total work into different components either by loading-unloading cycles or extrapolation to zero thickness (Plucknett and Normand, 2000; Hashemi, 1997; Dobraszczyk et al., 1987). Another approach is to use the J integral to explain elastic plastic fracture mechanics. The energy is the sum of elastic and plastic parts of deformation and of the crack propagation. Several models were proposed for J integral differing in geometry of sample, ratio of elastic/plastic deformation and modes of fracture (Chodak et al., 1994).

Notched sample fracture can start in a more controlled way. It enables obtaining energy in fracturing, notch sensitivity, and size of natural defects. This information provides

a better understanding of large deformation and fracture of material than do the fracture stress and strain alone (Lillford, 2001). Complexity of food is larger than engineering materials on which fracture mechanics techniques have been developed. These elements bring some difficulties to food scientist since very little data is available on similar materials for comparative purposes (Rojo and Vincent, 2008). There are studies on fracture mechanics of gels (Zhang et al., 2006; Alaoui et al., 2000; Stading and Hermansson, 1995; Plucknett and Normand, 2000; Tanaka et al., 2000; Gamonpilas et al., 2008; Cakir et al., 2011), cheese (Luyten et al. 1991; Charalambides et al., 1995), meat (Dobraszczyk et al., 1987; Puslow, 1985) and brittle foods such as fruits, vegetables and chips (Vincent 2004; Vincent et al., 2002; Alverez et al., 2000; Rojo and Vincent, 2008).

8. Relationship among Rheology, Sensory, Oral Processing

A full knowledge of the material properties of foods is essential to be able to understand their behavior during processing, handling, and eating. During eating of a food, dynamic and integrated perception of texture originates in part from material properties and how the food materials interact with the mouth. If we can relate physical and chemical properties of food associated with structure to texture perception, then we can better explain structure-function relationships. Numerous attempts have been made to investigate the relationship between sensory perception and fundamental rheological and fracture properties. The most common approach in the past has been to measure mechanical properties of a food then look for correlations with specific textural terms. We are proposing that information on how oral processing is adjusted to different food textures will aid in explaining how food structures are

translated into sensory texture. Therefore, physiological studies can give valuable insight in understanding of food texture. In the following section, sensory texture is reviewed based on rheology and oral processing.

8.1. Sensory and Rheology

Establishing the relationship between sensory and rheological parameters is critical in the texture evaluation. Generally, large deformation rheological properties are the best to relate to sensory perception of texture (Montejano et al., 1985). Each phase of sensory evaluation in relation to mechanical parameters is explained below focusing on mainly large deformation properties and soft solids. Discussion will be based on sensory attributes and definitions that were developed and used to evaluate texture of whey protein gels (Gwartney et al., 2002), agar gels (Barrangou et al., 2006), and cheese (Drake et al., 1999, Gwartney et al., 2002; Brown et al., 2003; Delahunty and Drake, 2004) (Table 2). In discussing investigations where attribute definitions do not coincide with those in Table 2, the new definition will be mentioned.

Tongue-palate Compression

Panelists are told to compress the sample between their tongue and hard palate and evaluate attributes of *springiness* and *compressibility*. Springiness is the degree to which sample returns to the original shape after partial compression, in other words it is a measure of degree of elasticity. Compressibility is the measure of degree of deformation before fracture. It should be noted that a broader array of texture properties are evaluated by this approach with semi-solids as it is the main oral processing activity (van der Berg et al.,

2008). For example, *crumbliness*, which is defined as "sample falls apart in pieces upon compression between tongue and hard palate" (van der Berg et al., 2008).

Compressibility: Compressibility for fine stranded WPI gels is two times higher than that of a particulate WPI gels (Gwartney et al., 2004; Cakir et al., 2012). This logically coincides with fracture strain. Fine stranded gels have fracture strain of 2.9 while particulate gels have 1.0. Fracture strain and compressibility are degree of deformation before the fracture, thus similar changes in this sensory attribute and mechanical parameter can be expected since the evaluations are similar. Addition of oil to fine stranded and particulate network reduces the compressibility (Gwartney et al., 2004). Change in compressibility in fine stranded gels corresponds to change in fracture strain, although this is not the case for particulate gels, suggesting that other properties are influencing texture evaluation.

Springiness: Similar to compressibility, fine stranded gels are springier than particulate gels (Gwartney et al., 2004). A particulate gel can release energy upon deformation mainly due to viscous flow, thus it can be expected that it does not return to its original shape as much as fine stranded gels once the load is removed. Springiness of fine stranded and particulate WPI gel networks have been also been judged as similar (Cakir et al., 2012). Differences in springiness perception of particulate gels can be explained by differences in the mechanical properties of gels in the studies. Oil addition decreases the springiness of fine stranded but not particulate WPI gels (Gwartney et al., 2004). Similarly, springiness of full-fat cheeses evaluated either in mouth or by hand, is lower than low-fat cheeses (Gwartney et al., 2002; Bryant et al., 1995; Brown et al., 2003, Rogers et al., 2009). Brown et al. (2003) also evaluated rate of recovery after partial compression and found springiness and sensory rate of

recovery are highly correlated. Hand springiness is negatively correlated to fracture modulus (Rogers et al., 2009; Brown et al., 2003). In WPI gels, springiness has the highest correlation with fracture strain, while it is more related to fracture stress of cheese. Springiness is also related to critical strain in small strain oscillatory measurement (Rogers et al., 2009). Springiness and compressibility of mixed WPI/κ-carrageenan gels does not change with altered microstructure within fine stranded and particulate networks. The major shift in these pre-fracture attributes occurs when the gel network changes from WPI continuous to κ-carrageenan continuous (Cakir et al., 2012), which may indicate the importance of network of continuous phase.

Crumbliness: Crumbliness of mixed WPI and polysaccharide gels has been investigated by van der Berg et al. (2008). These mixed gels represent a variety of microstructures being homogenous and phase separated (coarse stranded, protein continuous, bicontinuous). Crumbliness is not related to fracture properties such as fracture stress, strain, and energy (area under the force-displacement curve in compression test). However, it relates the breakdown pattern after fracture and also critical speed of fracture. Crumbly gels show a sharp decrease in normalized force-true strain curve after fracture whereas a gradual decrease occurs for low crumbly gels. Crumbly gels have low critical speed of fracture. They can use their high elastic energy for a fast fracture by free running crack. Another mechanical term that crumbliness is related to is recoverable energy. The presence of the correlation depends on the deformation speed of the test, with a good correlation at a compression speed of 20 mm/s but no correlation is found at 1mm/s. This was attributed to the need for mechanical tests to coincide with deformation rates used during oral processing. Recoverable energies

are 70-85% for crumbly gels, while they are 30-40% for non-crumbly gels. Crumbly gels also exhibit low serum release (water flowing out during compression), which is related to porosity of the gel network. The crumbliness definition is similar to first chew attribute fracturability which is explained in the following section.

First Chew

Hardness, *fracturability*, *deformability*, first chew *moisture release* and first chew *stickiness* are attributes evaluated in first chew by biting through a sample completely with the molars. Hardness/firmness is one of the most common sensory attribute that is defined in texture studies and it is a measure of force required to fracture a sample during the first chew of a sample placed between the molars. First bite, defined as the force required to fracture a piece of food using incisors, is a related textural property evaluated in some investigations. Definition of deformability is the same as compressibility evaluated in tongue-palate compression, only difference is that it is evaluated with molars. Fracturability/ crumbliness is the degree to which samples fractures into pieces.

Hardness: At similar protein concentrations, fine stranded gels are perceived as harder (Gwartney et al., 2004) or the same level of hardness (Cakir et al., 2012) compared to particulate gels. These differences could be due to a variety of reasons, including overall protein concentration differences between investigations, and the way that particulate gels were formed ($CaCl_2$-induced in Gwartney et al., 2004 and NaCl-induced in Cakir et al., 2012). While the reasons for different results are not clear, it shows that simply differentiating between gels as fine stranded or particulate does not reflect all the complexities of textural analysis. Increase in oil content of filled WPI gels results in harder

gels for both type of networks. This can be a combined effect of reinforcement of active filler and increased protein concentration in the aqueous phase (Gwartney et al., 2004). Cheese hardness increases with decrease in fat content (Bryant et al., 1995; Rogers et al., 2009; Brown et al., 2003), which can be explained by the changes in gel microstructure. Harder texture of low fat cheese is caused by 1) increased in protein network density in the gel phase and less number of fat globules dispersed in the network (Bryant et al., 1995). Moreover, fat globule size and shape is different for low and full fat cheeses (Rogers et al., 2009; Guinee et al., 2000). Significant correlations between hardness of cheese and fracture stress are reported (Gwartney et al., 2002; Wium et al., 1997). Cheese hardness was also correlated with maximum compliance in creep test (Brown et al., 2003; Rogers et al., 2009). Cheese hardness is also related to Young's modulus and work to fracture (area under the curve in compression test) (Wium et al., 1997). In relating fracture stress to sensory hardness, deformation rate of the test can be important. It has been showed that at deformation rates above 50 mm/min, the relation between fracture stress and hardness is constant (Wium et al., 1997). Strong relation between hardness and fracture stress also holds for fruits and vegetables (apple, melon, potatoes) (Diehl and Hamann, 1980). Hardness is also correlated with fracture modulus (Gwatney et al., 2004, Barrangou et al., 2006, Cakir et al., 2012) and energy for fracture (van der Berg et al., 2007). Phase separated WPI/κ-carrageenan gels have harder texture compared to WPI gels which can be due to increased local concentration of protein in the continuous phase. The main difference in hardness of these phase separated gels is obtained when the continuous matrix is changed from protein to carrageenan (Cakir et al., 2012).

The somewhat confusing relationships between mechanical properties and sensory hardness can be summarized by a few considerations. First, the sensory definition is related to the mechanical work (force over a distance) required to fracture a sample during the first chew. Increasing Young's modulus (i.e., force per deformation) and fracture force-related properties (fracture stress, stress intensity factor, and fracture surface energy) will logically be scaled with sensory hardness as they are essentially measuring the same thing in Hookean solids (i.e., no rate effects). However, foods are viscoelastic materials so the rate of testing can be important in assuring the conditions of mechanical testing are sufficiently similar to those during oral processing. Second, increasing the density of strands in a network, rigidity of individual strands or strength of strand connections, can all contribute to Young's modulus and/or fracture terms. Therefore, mechanical terms will be highly convoluted.

Fracturability/Crumbliness: Gwartney et al. (2004) reported particulate gels having much higher fracturability than fine stranded gels. It has been also found that they have same level of fracturability (Cakir et al., 2012). In both investigatons, fracturability of particulate gels have intensities of 11, discrepancy between two studies is seen only for fine stranded gels. Concentrations of proteins in both studies are similar while salt concentration varies (25 mM NaCl vs. 50 mM NaCl). Effect of oil addition (Gwartney et al., 2004) slightly increases or decreases the fracturability of fine stranded and particulate gels, respectively. Phase separation via κ-carrageenean does not cause a significant change in this attribute. Therefore, the main factor determining the degree of breakdown in first chew is the network forming the continuous phase. Fracturability has been found to positively correlated to fracture strain and negatively correlated to held water (Gwartney et al., 2004, Cakir et al.,

2012), and positively related to recoverable energy (Cakir et al., 2012) in model foods. All these relations are in agreement with the study of van der Berg et al. (2008) on crumbliness of mixed gels. Reduced fat cheeses have higher fracturability than high fat counterpart (Gwartney et al., 2002) and fracturability of cheese is related to fracture stress, strain, modulus and also maximum compliance.

Deformability: This attribute is called "cohesiveness" in TPA sensory terms. Generally, texture lexicons have used either compressibility or deformability since they are the same measures but one is evaluated with tongue other with molars. Deformability of agar gels varying in concentration of agar and glycerol and is correlated with fracture strain (Barrangou et al., 2006). When this attribute is evaluated by hand, a higher correlation with fracture strain ($r = 0.98$) is obtained. Oral evaluation of deformability is an attribute that has proven difficult in training a panel to produce consistent results. Since deformability is essentially an oral evaluation of strain required for fracture it is not surprising that fracture strain and deformability show good correlation in texture evaluation of protein gels (Montejano et al., 1985) and surimi gels (Hamann and Lanier, 1986).

Moisture release: Release of moisture with first chew is related to water holding properties of the gel networks (Gwartney et al., 2004; Cakir et al., 2012). Fine stranded network has very strong water holding ability, thus release is very low upon facture. On the other hand, particulate networks are associated with their high moisture release. Addition of oil does not have any influence on water release of fine stranded gels while causing reduced release in particulate gels (Gwartney et al., 2004). Phase separated networks (bicontinuous, coarse stranded) have more moisture release (Cakir et al., 2012) due to change in microstructure.

Mastication

Attributes in this phase are evaluated after 5-8 or 8-10 chews. *Particle size, particle size distribution, cohesiveness, adhesiveness, smoothness of pieces, chalkiness, moisture release, degree of breakdown, dryness, oily mouthfeel,* and *number of chews* are the sensory terms that can be judged.

Particle size, particle size distribution, smoothness of pieces and rate of breakdown: Fine stranded WPI gels have slow breakdown that produces large, smooth particles with a narrow size distribution, while particulate gels are characterized by the opposite (Gwartney et al., 2004). The differences in the intensities of attributes are very different for fine stranded and particulate networks, being two extremes on the scale. Similar results were shown for WPI/κ-carrageenan gels (Cakir et al., 2012), although differences are smaller, and particle size distribution is reported to be more homogenous for the particulate network. Particle size and rate of breakdown are most related to fracture strain, but in opposite ways; respective correlation coefficients of $r = 0.94$, and $r = -0.92$ (Gwartney et al., 2004). Gels with high fracture strain are broken down into larger pieces at a slower rate. This is also true for mixed gels. Fracture stress is also associated with these terms (Cakir et al., 2012).

Cohesiveness and adhesiveness: Cohesiveness is the measure of degree to which sample mass stays together as chewing progress. In other words, how well particles stick to each other. On the other hand, adhesiveness describes how sample mass or pieces stick to oral surfaces. Fine stranded WPI gels have very low intensities of cohesive or adhesive properties. In contrast, particulate gels are characterized by their high cohesiveness and adhesiveness. These attributes are not changed with addition of oil (Gwartney et al., 2004).

Changing the microstructure via phase separation does not result in alteration of adhesive and cohesive properties of mixed WPI/κ-carrageenan gels (Cakir et al., 2012). In this study, differences in adhesiveness and cohesiveness of fine-stranded vs. particulate gels are also small. The significant change in these attributes, especially cohesiveness, occurs when there is a phase inversion and κ-carrageenan becomes the continuous phase. Cohesiveness and adhesiveness are negatively correlated to fracture strain and held water (Gwartney et al., 2004, Cakir et al., 2012) and also RE (Cakir et al., 2012). Despite the fact that no change observed in adhesiveness and cohesiveness of WPI gels with oil addition, or phase separation in model foods, in cheese, decrease in fat content result in decrease in adhesiveness and cohesiveness is observed (Bryant et al., 1995; Rogers et al., 2009). Adhesiveness of cheese is also correlated to fracture strain (Gwartney et al., 2004). Pressure sensitive, surface adhesion of food can be measured instrumentally (Steiner et al., 2003; Rogers et al., 2009) and area under the adhesion curve can be determined. When this test was applied on cheese and caramels, a negative correlation was obtained between sensory adhesiveness and instrumental adhesiveness. Possible reason for this observation can be the effect of saliva. Another rheological parameter that has been related to adhesiveness is tanδ based on a study evaluating the sensory properties of 100 fish gels varying in sensory texture (Hamann and Webb, 1979).

Chewiness (number of chews): Number of chews required to prepare the sample is strongly related to fracture stress of model foods (Gwartney et al., 2004; Cakir et al., 2012), apples (Diehl and Hamann, 1979) and cheese (Gwartney et al., 2002). Chewiness in TPA is obtained by multiplying hardness, cohesiveness and springiness. This parameter shows poor

correlation with sensory chewiness of twenty-one different type of foods such as nuts, cheese, caramel, meat, gels, hard candy, marshmallow, bread, carrot (Meullenet et al., 1998) which covers the texture spectrum in various foods. It is true that chewiness is a result of combination of many different physical parameters, however defining it by this mathematical formula without any fundamental explanation can be an oversimplification.

Residual

Particle and moisture mouthcoating: These sensory attributes are amount of particle or moisture evaluated after samples are expectorated after mastication. Moisture mouthcoating has been reported higher for fine stranded gels by Gwartney et al. (2004), yet it was higher for particulate gels in the investigation of Cakir et al. (2012).

Overall, tongue-palate compression and first chew attributes are successfully explained and related to mechanical properties. Chewdown attributes, with the exception of chewiness (number of chews), have been difficult to predict by current rheological measures. More research in this area is needed to understand the perception of mastication attributes, especially adhesiveness and cohesiveness, and how these are related to food material properties.

8.2. Sensory and Oral Processing

In the previous section, the sensory attributes and how they are related to mechanical parameters are explained. In addition, understanding sensory based on oral processing and relating these three disciplines is very important to answer the question of how we do perceive texture of foods. In this field of research, there have been very limited investigations. Hardness is the one the most studied sensory attributes in oral processing.

Increased hardness of model food results in increases in chewing time, muscle activity, and jaw movements (Peyron et al., 2002; Foster et al., 2006). Hardness of biscuits is related to muscle activity in the first 5 chewing cycles, on the other hand crunchiness is more related to the subsequent 5 chews (Brown et al., 1998). Tenderness of meat is another sensory attribute studied by oral processing and first chew and subsequent chews also contribute the perception of tenderness (Mioche and Martin, 1998). Most investigations, only try and relate oral processing to one or two sensory parameters and there are only a few investigations on the comprehensive approach on sensory attributes. Some examples of those are studies conducted on texture of caramel and cheese (Cakir et al., 2011) and mixed WPI/κ-carrageenan gels (Cakir et al., 2012). Changes in cheese texture by fat reduction are increased hardness, springiness and decreased cohesiveness and adhesiveness as described in the previous section. Oral processing adapted to these changes in cheese texture by increasing jaw closing muscle activity, decreasing cycle duration and increasing the duration of occlusion. Frequency of chewing is also increased with fat reduction which can be associated with the less adhesive property of low fat cheese. Caramels with similar hardness with different intensities of adhesiveness show significant differences in oral processing. Increased jaw opening and closing muscle activity, opening duration and jaw movements is associated with the more adhesive texture (Cakir et al., 2011). Oral processing of mixed WPI/κ-carrageenan gels with various microstructure and sensory properties shows that fracture modulus and sensory hardness are strongly associated with muscle activities and number of cycles. When the gels are more adhesive, the chewing frequency is lower which

can be attributed to increased cycle duration due to stickiness of sample to oral surfaces. Chewing frequency is related to elasticity of gels more than fracture properties.

9. Conclusion

Creating foods with desirable sensory textures requires a fundamental understanding of factors perceived as texture and the physiology of texture perception. Continuous changes in physical properties of foods during chewing make the evaluation of texture a dynamic and complex process which requires a multidimensional approach including assessment of rheological/fracture characteristics, sensory perception and oral processing.

References

Aguilera, J. M., & Lillford, P. J. (2008). Structure-property relationships in foods. In: *Food materials science: principles and practice*. J. M. Aguilera & P. J. Lillford (Eds.), New York: Springer Science.

Ako, K., Nicolai, T., Durand, D., & Brotons, G. (2009). Micro-phase separation explains the abrupt structural change of denatured globular protein gels on varying the ionic strength or the pH. *Soft Matter,* 5 (20), 4033-4041.

Alaoui, H., Woignier, T., Pernot, F., Phalippou, J., & Hihi, A. (2000) Stress intensity factor in silica alcogels and aerogels. *Journal of Non Crystalline Solids*, 265(1–2), 29-35.

Almdal, K., Dyre, J., Hvidt, S., & Kramer, O. (1993). Towards a phenomenological definition of the term 'gel'. *Polymer Gels and Networks,* 1(1), 5-17.

Alvarez, M. D., Saunders, D. E. J., Vincent, J. F. V., & Jeronimidis, G. (2000). An engineering method to evaluate the crisp texture of fruit and vegetables. *Journal of Texture Studies,* 31(4), 457-473.

Anderson, T. L. (2005). *Fracture mechanics: fundamentals and applications.* Boca Raton, FL: Taylor & Francis.

Armisen, R., & Galatas, F. (2009). Agar. In: *Handbook of hydrocolloids.* G.O. Philips and P.A. Williams (Eds.)*,* Boca Raton, FL; Cambridge: CRC Press; Woodhead Pub.

Atkins, A. G., & Vincent, J. F. V. (1984). An instrumented microtome for improved histological sections and the measurement of fracture toughness. *Journal of Materials Science Letters,* 3(4), 310-312.

Atkins, A. G., & Mai, Y. W. (1985). *Elastic & Plastic fracture: Metals, polymers, ceramics, composites, biological materials,* Ellis Horwood, Chichester.

Barbut, S., & Foegeding, E. A. (1993). Ca^{2+} induced gelation of pre-heated whey protein Isolate. *Journal of Food Science,* 58(4), 867-871.

Barrangou, L. M., Drake, M. A., Daubert, C. R., & Foegeding, E. A. (2006). Sensory texture related to large-strain rheological properties of agar/glycerol gels as a model food. *Journal of Texture Studies,* 37(3), 241-262.

Birch, G.G., & Munton, S.L. (1981). Use of the "SMURF" in taste analysis. *Chemical Senses,* 6 (1): 45-52

Blair, G.W. (1958). Rheology in Food Research. *Advances in Food Research.* 8, 1-61.

Blanchard, J. M. V., & Lillford, P. J. (1988). *Food Structure and Behaviour*. Academic Press, London.

Blatz, P. J., Sharda, S. C., & Tschoegl, N. W. (1974). Strain energy function for rubberlike materials based on a generalized measure of strain. *Transactions of the society of rheology*, 18(1), 145-161.

Bloom, Oscar T. 1925. Machine for testing jelly strength of glues, gelatins and the like. U. S. Patent 1,540,979. June 9, 1925

Bot, A., van Amerongen, I. A., Groot, R. D., Hoekstra, N. L., & Agterof, W. G. M. (1996). Large deformation rheology of gelatin gels. *Polymer Gels and Networks,* 4(3), 189-227.

Bourdiol, P., & Mioche, L. (2000). Correlations between functional and occlusal tooth-surface areas and food texture during natural chewing sequences in humans. *Archives of Oral Biology,* 45(8), 691.

Boyar, M. M. (1986). Electromyography as a novel method for examining food texture. *Journal of Food Science,* 51(3), 859.

Boyar, M. M., & Kilcast, D. (1986). Food texture and dental science. *Journal of Texture Studies,* 17, 221.

Bourne, M. C. (1968). Texture profile of ripening pears. *Journal of Food Science,* 33(2), 223-226.

Bourne, M.C. 1978. Texture profile analysis. *Food Technology*, 32(7), 62-66,72.

Brandt, M. A., Skinner, E. Z., & Coleman, J. A. (1963). Texture profile method. *Journal of Food Science,* 28(4), 404-409.

Breene, W. M. (1975). Application of texture profile analysis to instrumental food texture evaluation. *Journal of Texture Studies*, 6 (1) 53-82.

Broberg, K.B. (1968). Critical review of some theories in fracture mechanics. *International Journal of Fracture*, 4(1), 11-19.

Bryant, A., Ustunol, Z., & Steffe. J. (1995). Texture of cheddar cheese as influenced by fat reduction. *Journal of Food Science,* 60(6), 1216-1219.

Brown, J. A., Foegeding, E. A., Daubert, C. R., Drake, M. A., & Gumpertz, M. (2003). Relationships among rheological and sensorial properties of young cheeses. *Journal of Dairy Science,* 86(10), 3054-3067.

Brown, W. E. (1994). Methods to investigate differences in chewing behavior in humans: I. Use of electromyography in measuring chewing. *Journal of Texture Studies,* 25(1), 1-16.

Brown, W. E., Eves, D., Ellison, M., & Braxton, D. (1998). Use of combined electromyography and kinesthesiology during mastication to chart the oral breakdown of foodstuffs: Relevance to measurement of food texture. *Journal of Texture Studies,* 29(2), 145-167.

Browsey, G. J., & Morris, V. J. (1988). Mixed and filled gels-models for foods. In Blanshard, J. M.V. and Mitchell, J. R. (Eds.), *Food Structure-Its Creation and Evaluation.* Butterworths, London, 7-23.

Butler, G., Poste, L.M., Mackie, D. A., & Jones, A. (1996). Time-intensity as a tool for the measurement of meat tenderness. *Food Quality and Preference,* 7(3–4), 193-204.

Callister, W. D. (2010). *Materials science and engineering: an introduction.* Hoboken, NJ: John Wiley & Sons.

Chambers, D. H., Allison, A. A., & Chambers, E. (2004). Training effects on performance of descriptive panelists. *Journal of Sensory Studies,* 19(6), 486-499.

Charalambides, M. N., Williams, J. G., & Chakrabarti, S. (1995). A study of the influence of ageing on the mechanical properties of Cheddar cheese. *Journal of Materials Science,* 30(16), 3959-3967.

Chen, Y., Liao, M., Boger, D. V., & Dunstan, D. E. (2001). Rheological characterization of κ-carrageenan/locust bean gum mixtures. *Carbohydrate Polymers,* 46(2), 117-124.

Chen, Y., Liao, M., & Dunstan, D. E. (2002). The rheology of K+-κ-carrageenan as a weak gel. *Carbohydrate Polymers,* 50(2), 109-116.

Chen, J. (2009). Food oral processing—A review. *Food Hydrocolloids,* 23(1), 1-25.

Chen, J., & J. R. Stokes. (2012). Rheology and tribology: Two distinctive regimes of food texture sensation. *Trends in Food Science & Technology*.

Childs, J. L., & Drake M. A. (2009). Consumer perception of fat reduction in cheese. *Journal of Sensory Studies,* 24(6), 902-921.

Clark, A. H., & Ross-Murphy, S. B. (1987). Structural and mechanical properties of biopolymer gels. *Biopolymers Advances in Polymer Science*, 83, 57-192.

Çakır, E., & Foegeding, E. A. (2011). Combining protein micro-phase separation and protein–polysaccharide segregative phase separation to produce gel structures. *Food Hydrocolloids,* 25(6), 1538-1546.

Çakır, E., Daubert, C. R., Drake, M. A., Vinyard, C. J., Essick, G., & Foegeding, E. A. (2012). The effect of microstructure on the sensory perception and textural characteristics of whey protein/κ-carrageenan mixed gels. *Food Hydrocolloids,* 26(1), 33-43.

Chodák, I., Chorvath,I., Seidler, S., Janigova, I., & Radusch, H. J. (1994). The Effect of Crosslinking on Toughness of Composite Ldpe/Silica. *Journal of Macromolecular Science, Part A: Pure and Applied Chemistry*, 31(10), 1455-1467

Cliff, M., & Heymann, H. (1993). Development and use of time-intensity methodology for sensory evaluation: A review. *Food Research International,* 26(5), 375-385.

Daubert, C.R., & Foegeding, E.A. (1998). Rheological principles of food analysis. In: *Food Analysis,* 2nd ed.*,* Nielsen, S.S. (Ed.), Aspen Publishers: Gaithersburg, Maryland, 551–569**.**

de Jong, S., & van de Velde, F. (2007). Charge density of polysaccharide controls microstructure and large deformation properties of mixed gels. *Food Hydrocolloids,* 21(7), 1172-1187.

de Kruif, C.G., & Tuinier, R. (2001). Polysaccharide protein interactions. *Food Hydrocolloids,* 2001, 15, 4–6, 555-563.

Delahunty, C. M., & Drake, M. A. (2004). Sensory character of cheese and its evaluation. In: *Cheese: Chemistry, Physics and Microbiology*, 1, 455-487, Academic Press.

Diehl, K. C., Hamann, D. D., & Whitfield, J. K. (1979). Structural failure in selected raw fruits and vegetables. *Journal of Texture Studies*, *10*, 371-400.

Diehl, K. C., & Hamann, D. D. (1980). Relationships between sensory profile parameters and fundamental mechanical parameters for raw potatoes, melons and apples. *Journal of Texture Studies*, 1980, 10 (4), 401-420.

Dijksterhuis, G. B., & Piggott, J. R. (2000). Dynamic methods of sensory analysis. *Trends in Food Science & Technology,* 11(8), 284-290.

Drake, M. A., Gerard, P. D., Truong, V. D., & Daubert, C. R. (1999). Relationship between instrumental and sensory measurements of cheese texture. *Journal of Texture Studies,* 30(4), 451-476.

Drake, M. A., & Civille, G. V. (2003). Flavor Lexicons. *Comprehensive Reviews in Food Science and Food Safety,* 2(1), 33-40.

Drake, B. (1966). Advances in the determination of texture and consistency of foodstuffs. *Proc. 2nd Int. Congress Food Science and Technology, Warsaw, Poland.*

Drake, M. A. (2007). Invited review: Sensory analysis of dairy foods. *Journal of Dairy Science*, 90 (11), 4925-4937.

Drake, M. A. (2009). Modern sensory practices. In: *The sensory evaluation of dairy products*. S. Clark, M. Costello, M.A. Drake, F. Bodyfelt (Eds.), Springer

Dobraszczy, B. J., Atkins, A. G., Jeronimidis, G., & Purslow, P. P. (1987). Fracture toughness of frozen meat. *Meat Science,* 21(1), 25-49.

Duizer, L. M., Gullett, E. A., & Findlay, C. J. (1996). The relationship between sensory time-intensity, physiological electromyography and instrumental texture profile analysis measurements of beef tenderness. *Meat Science,* 42(2), 215-224.

Edwoldt, R.H., Hosoi, A.E., & McKinley, G.H. (2008). New measures for characterizing nonlinear viscoelasticity in large amplitude oscillatory shear. *Journal of Rheology,* 52 (6), 1427

Engelen, L., & van der Bilt, A. (2008). Oral physiology and texture perception of semisolids. *Journal of Texture Studies,* 39(1), 83.

Fernandes, P. B., Gonçalves, M. P., & Doublier, J. L. (1993). Influence of locust bean gum on the rheological properties of kappa-carrageenan systems in the vicinity of the gel point. *Carbohydrate Polymers,* 22(2), 99-106.

Ferrario, V. F., & Sforza, C. (1996). Coordinated electromyographic activity of the human masseter and temporalis anterior muscles during mastication. *European Journal of Oral Sciences,* 104(5-6), 511.

Foegeding, E.A. (2006). Food biophysics of protein gels: a challenge of nano and macroscopic proportions. *Food Biophysics*, 1(1), 41-50.

Foegeding, E.A.,Çakır, E., & Koç, H. (2010). Using dairy ingredients to alter texture of foods: Implications based on oral processing considerations. *International Dairy Journal*, 20 (9), 562-570.

Foegeding, E. A., Daubert, C. R., Drake, M. A., Essick, G., Trulsson, M., Vinyard, C. J., & van de Velde, F. (2011). A comprehensive approach to understanding textural properties of semi- and soft-solid foods. *Journal of Texture Studies,* 42(2), 103-129.

Foster, K.D., Woda, A., & Peyron, M.A. (2006). Effect of texture of plastic and elastic model foods on the parameters of mastication. *Journal of Neurophysiology*, 95, 3469-3479.

Friedman, H. H., Whitney, J. E., & Szczesniak, A. S. (1963). The Texturometer: A new instrument for objective texture measurement. *Journal of Food Science,* 28(4), 390-396.

Gamonpilas, C., Charalambides, M., & Williams, J. (2008). Determination of large deformation and fracture behaviour of starch gels from conventional and wire cutting experiments. *Journal of Materials Science,* 44(18), 4976-4986.

Goodall, D.M., & Norton, I.T. (1987). Polysaccharide conformations and kinetics. *Accounts of Chemical Research*, 20 (2), 59–65.

Griffith, A. A. (1921). The phenomena of rupture and flow in solids. *Philosophical Transactions of the Royal Society of London*. Series A, Containing Papers of a Mathematical or Physical Character*,* 221, 163-198.

Groot, R.D., Arjen Bot, A., & Agterof, W. G. M. (1996). Molecular theory of strain hardening of a polymer gel: Application to gelatin. *Chemical Phyiscs,* 104 (22), 9202-9219.

Guinard, J., & Mazzucchelli, R. (1996). The sensory perception of texture and mouthfeel. *Trends in Food Science & Technology,* 7(7), 213-219.

Guinee, T. P., Auty, M. A. E., & Fenelon, M. A. (2000). The effect of fat content on the rheology, microstructure and heat-induced functional characteristics of Cheddar cheese *International Dairy Journal*, 10 (4), 277-288.

Gwartney, E. A., Foegeding, E. A., & Larick, D. K. (2002). The texture of commercial full-fat and reduced-fat cheese. *Journal of Food Science,* 67(2), 812-816.

Gwartney, E. A., Larick, D. K., & Foegeding, E. A. (2004). Sensory texture and mechanical properties of stranded and particulate whey protein emulsion gels. *Journal of Food Science,* 69(9), 333-339.

Hamann, D. D., Zhang, J., Daubert, C. R., Foegeding, E. A., & Diehl, K. C. (2006). Analysis of compression, tension and torsion for testing food gel fracture properties. *Journal of Texture Studies,* 37(6), 620-639.

Hamann, D. D., & Webb, N. B. (1979). Sensory and instrumental evaluation of material properties of fish gels. *Journal of Texture Studies,* 10(2), 117-130.

Hashemi, S. (1997). Work of fracture of PBT/PC blend: Effect of specimen size, geometry, and rate of testing. *Polymer Engineering & Science,* 37(5), 912-921.

Hermansson, A-M. (1989). Rheological and microstructural evidence for transient states during gelation of kappa-carrageenan in the presence of potassium*. Carbohydrate Polymers.*, 10(3), 163-181

Hermansson, A., Eriksson, E., & Jordansson, E. (1991). Effects of potassium, sodium and calcium on the microstructure and rheological behaviour of kappa-carrageenan gels. *Carbohydrate Polymers,*16(3), 297-320.

Hermansson, A-M. (2008). Structuring water by gelation. In: *Food materials science: principles and practice*. J. M. Aguilera & P. J. Lillford (Eds.), New York: Springer Science.

Hiiemae, K., Heath, M.R., Heath, G., Kazazoglu, E., Murray, J., Sapper, D., & Hamblett, K. (1996). Natural bites, food consistency and feeding behaviour in man**.** *Archives of Oral Biology,* 41, 175-189.

Holway, A. H., & Hurvich, L. M. (1937). Differential gustatory sensitivity to salt. *The American Journal of Psychology,* 49(1), 37-48.

Howell, P.G., Ellis, S., Johnson, C.W., Watson, I.B., & Klineberg, I. (1993).The recording and analysis of EMG and jaw tracking. II. reproducibility of jaw tracking. *Journal of Oral Rehabilitation,* 20(1), 33.

Hylander, W. L., & Johnson, K. R. (1993). Modelling relative masseter force from surface electromyograms during mastication in non-human primates. *Archieves of Oral Biology,* 38(3), 233-240.

Hutchings, J. B., & Lillford, P. J. (1988). The perception of food texture - the philosophy of the breakdown path. *Journal of Texture Studies,* 19(2), 103-115

ISO. (1992). *Sensory analysis: vocabulary (ISO 5492)*, Geneva, Switzerland.

Irwin, G. (1957). Analysis of stresses and strains near the end of a crack traversing a plate, *Journal of Applied Mechanics,* 24, 361–364.

Jalabert-Malbos, M. L, Mishellany-Dutour, A., Woda, A., & Peyron, M. A. (2007). Particle size distribution in the food bolus after mastication of natural foods. *Food Quality and Preference,* 18(5), 803-812.

Kaletunc, G., Normand, M. D., Johnson, E. A., & Peleg. M. (1991). Degree of elasticity determination in solid foods. *Journal of Food Science,* 56(4), 950-953.

Kinloch, A. J., & Young, R. J. (1983). *Fracture behaviour of polymers.* London ; New York; New York, NY, USA: Applied Science Publishers; Sole distributor in the USA and Canada, Elsevier Science Pub.

Langendorff, V., Cuvelier, G., Michon, C., Launay, B., Parker, A., & de kruif, C. G. (2000). Effects of carrageenan type on the behaviour of carrageenan/milk mixtures. *Food Hydrocolloids,* 14(4), 273-280.

Lassauzay, C., Peyron, M.A., Albuisson, E., Dransfield, E., & Woda, A. (2000). Variability of the masticatory process during chewing of elastic model foods. *European Journal of Oral Sciences,* 108(6), 484.

Larson-Powers, N., & Pangborn, R. M. (1978). Descriptive analysis of the sensory properties of beverages and gelatins containing sucrose or synthetic sweeteners. *Journal of Food Science,* 43(1), 47-51.

Lavigne, G., Kim, J. S., Valiquette, C., & Lund, J. P. (1987). Evidence that periodontal pressoreceptors provide positive feedback to jaw closing muscles during mastication. *Journal of Neuorophysioogy*, 58(2), 342-358.

Lawless, H.T., & Skinner, E.Z. (1979). The duration and perceived intensity of sucrose taste. *Attention, Perception, & Psychophysics*, 25 (3), 180-184.

Lawless, H. T., & Heymann, H. (2010). *Sensory evaluation of food: principles and practices.* New York: Springer.

Lee, W.E. III, & Pangborn, M. (1986). Time-intensity: the temporal aspects of sensory perception. *Food Technology,* 40(11), 71-78, 82.

Leksrisompong, P. (2011). How micro-phase separation explains gelation properties of globular protein gel. Doctoral dissertation, North Carolina State University.

Lenfant, F., Loret, C. Pineau, N. Hartmann, C., & Martin, N. (2009). Perception of oral food breakdown. The concept of sensory trajectory. *Appetite,* 52(3), 659-667.

Lillford, P. J. (2001). Mechanisms of fracture in foods. *Journal of Texture Studies,* 32(5-6), 397-417.

Lucas, P. W., Prinz, J. F., Agrawal, K.R., & Bruce, I. C. (2004). Food texture and its effect on ingestion, mastication and swallowing. *Journal of Texture Studies,* 35(2), 159-170.

Lucas, P. W., Prinz, J. F., Agrawal, K.R., & Bruce, I. C. (2002). Food physics and oral physiology. *Food Quality and Preference,* 13(4), 203-213.

Lucas, P.W., & Luke, D.A. (1983). Methods for analyzing the breakdown of food during human mastication. *Archives of Oral Biology*, 28(9):813-819.

Luyten, H., van Vliet, T., & Walstra, P. (1991). Characterization of the consistency of Gouda cheese: fracture properties. *Netherlands, Milk and Dairy Journal,* 45(1), 55-80.

Luyten, H., van Vliet, T., & Walstra, P. (1992). Comparison of various methods to evaluate fracture phenomena in food materials. *Journal of Texture Studies,* 23(3), 245-266.

Lund, J.P. (1976). Evidence for a central neural pattern generator regulating the chewing cycle In: *Mastication*. D. J. Anderson, B. Matthews (Eds.), Bristol: Wright, 204-212.

McEvoy, H., Ross-Murphy, S. B., & Clark, A. H. (1985). Large deformation and ultimate properties of biopolymer gels: 1. Single biopolymer component systems. *Polymer,* 26, 1483-1492.

Meilgaard, M. (2007). *Sensory evaluation techniques.* Boca Raton: Taylor & Francis.

Meullenet, J-F, Lyon, B. G., Carpenter, J. A., & Lyon, C. E. (1998). Relationship between sensory and instrumental texture profile attributes. *Journal of Sensory Studies*, 13(1), 77-93.

Mezzenga, R., Schurtenberger, P., Burbidge, A., & Michel, M. (2005). Understanding foods as soft materials. *Nature materials,* 4, 729 – 740.

Mioche, L., Bourdiol, P., Martin, J. F., & Nol, Y. (1999). Variations in human masseter and temporalis muscle activity related to food texture during free and side-imposed mastication. *Archives of Oral Biology,* 44(12), 1005.

Montejano, J. G., Hamann, D. D., & Lanier, T. C. (1985). Comparison of two instrumental methods with sensory texture of protein gels. *Journal of Texture Studies,* 16(4), 403-424.

Moore, L. J., & Shoemaker, C. F. (1981). Sensory Textural Properties of Stabilized Ice Cream. *Journal of Food Science,* 46(2), 399-402.

Morris, E. R., Rees, D. A., & Robinson, C. J. (1980). Cation-specific aggregation of carrageenan helices: domain model of polymer gel structure. *Journal of Molecular Biology,* 138, 349-362.

Murray, J. M., Delahunty, C. M., & Baxter, I. A. (2001). Descriptive sensory analysis: past, present and future. *Food Research International,* 34(6), 461-471.

Okada, A., Honma, M., Nomura, S., & Yamada, Y. (2007). Oral behavior from food intake until terminal swallow. *Physiology Behavior,* 90(1), 172.

Pangborn, R. M., & Koyasako, A. (1981). Time-course of viscosity, sweetness and flavor in chocolate desserts. *Journal of Texture Studies,* 12(2), 141-150.

Peleg, M. (1976). Texture profile analysis parameters obtained by an instron universal testing machine. *Journal of Food Science,* 41(3), 721-722.

Peleg, M., & Bagley, E.B. (1983). *Physical Properties of Foods.* AVI Publishing, Westport, CT.

Peleg, M. (1984). Application of nonlinear phenomenological rheological models to solid food materials. *Journal of Texture Studies*, 15, 1-22.

Peleg, M. (1977). Operational conditions and the stress-strain relationship of solid foods theoretical evaluation. *Journal of Texture Studies,* 8(3), 283-295.

Peyron, M.A., Mioche, L, Renon, P., & Abouelkaram, S. (1996). Masticatory jaw movement recordings: a new method to investigate food texture. *Food Quality and Preference,* 7(3-4), 229.

Peyron, M. A., Lassauzay, C., & Woda, A. (2002). Effects of increased hardness on jaw movement and muscle activity during chewing of visco-elastic model foods. *Experimental Brain Research,* 142(1), 41.

Peyron, M.A., Gierczynski, I., Hartmann, C., Loret, C., Dardevet, D., Martin, N., & Woda, A. (2011). Role of physical bolus properties as sensory inputs in the trigger of swallowing source. *PLoS ONE, Public Library of Science,* 6(6), 1-8.

Peyvieux, C., & Dijksterhuis, G. (2001). Training a sensory panel for TI: a case study. *Food Quality and Preference,*12(1), 19-28.

Plucknett, K. P., & Normand, V. (2000). Plane stress essential work of fracture of 'pseudo-ductile' gelatin/maltodextrin biopolymer gel composites. *Polymer,* 41(18), 6833-6841.

Pineau, N., Schlich, P., Cordelle, S., Mathonnière, C., Issanchou, S., Imbert, A., Rogeaux, M,. Etiévant, P., & Köster, E. (2009). Temporal dominance of sensations: Construction of the TDS curves and comparison with time–intensity. *Food Quality and Preference,* 20(6), 450-455.

Prinz, J. F., & Lucas, P. W. (1995). Swallow thresholds in human mastication. *Archives of Oral Biology,* 40(5), 401.

Proctor, B. E., Davison, S., Malecki, G. J., & Welch, M. (1955). A recording strain gage denture tenderometer for foods. I. Instrument evaluation and initial tests. *Food Technology.* 9,471.

Purslow, P. P. (1985). The physical basis of meat texture: Observations on the fracture behaviour of cooked bovine M. Semitendinosus. *Meat Science.* 12 (1), 39-60.

Rao, M. A. (1999). *Rheology of fluid and semisolid foods: principles and applications.* Gaithersburg, Md.: Aspen Publishers.

Renard, D., van de Velde, F., & Visschers, R. W. (2006). The gap between food gel structure, texture and perception. *Food Hydrocolloids,* 20(4), 423-431.

Rey, D. K., & Labuza, T. P. (1981). Characterization of the effect of solutes on the water-binding and gel strength properties of carrageenan. *Journal of Food Science,* 46(3), 786-789.

Rey, A., González, R., Martínez-de-Juan, J. L., Benedito, J., & Mulet, A. (2007). EMG assessment of chewing behaviour for food evaluation: Influence of personality characteristics. *Food Quality and Preference,*18(3), 585-595.

Rice, J. R. (1968). A path independent integral and the approximate analysis of strain concentration by notches and cracks. *Journal of Applied Mechanics,* 35, 379–386.

Ridout, M. J., Garza, S., Brownsey, G. J., & Morris, V. J. (1996). Mixed iota-kappa carrageenan gels. *International Journal of Biological Macromolecules,* 18(1–2), 5-8.

Rine, S. (1987). Computerized analysis of the sensory properties of peanut butter. MS thesis, University of California, Davis.

Rogers, N. R., Drake, M. A., Daubert, C. R., McMahon, D. J., Bletsch, T. K., & Foegeding, E. A. (2009). The effect of aging on low-fat, reduced-fat, and full-fat Cheddar cheese texture. *Journal of Dairy Science,* 92(10), 4756-4772.

Rojo, F. J., & Vincent, J. F. V. (2008). Fracture properties of potato crisps. *International Journal of Food Science & Technology,* 43(4), 752-760.

Rosenthal, A. J. (1999). *Food texture: measurement and perception.* Gaithersburg, Md.: Aspen Publishers.

Ross-Murphy, S. B. (1994). Rheological characterisation of polymer gels and networks. *Polymer Gels and Networks,* 2(3-4), 229-237.

Ross-Murphy, S. B. (1995). Rheological characterization of gels. *Journal of Texture Studies,* 26(4), 391-400.

Russ, J.C. (2004). *Image Analysis of Food Microstructure*. CRC Press, Boca Raton, FL.

Seo, H., Lee, M., Jung, Y., & Hwang, I. (2009). A novel method of descriptive analysis on hot brewed coffee: time scanning descriptive analysis. *European Food Research and Technology,* 228(6), 931-938.

Sherman, P. (1969). A Texture profile of foodstuffs based upon well-defined rheological properties. *Journal of Food Science,* 34(5), 458-462.

Sjöström, L. B. (1954). The descriptive analysis of flavor. In: *Food Acceptance Testing Methodology,* D. Peryam, F. Pilgrim, and M. Peterson (Eds.), Quartermaster Food and Container Institute, Chicago, 25–61.

Stading, M., & Hermansson, A. (1993). Rheological behavior of mixed gels of κ-carrageenan-locust bean gum. *Carbohydrate Polymers,* 22(1), 49-56.

Stading, M., Langton, M., & Hermansson, A. (1993). Microstructure and rheological behaviour of particulate β-lactoglobulin gels. *Food Hydrocolloids,* 7(3), 195-212.

Stading, M., Langton, M., & Hermansson, A. (1995) Small and large deformation studies of protein gels. *Journal of Rheology*, 39(6), 1445-1450.

Stanley, D.W. (1994). Understanding the materials used in foods — Food materials science. *Food Research International,* 27(2), 135-144.

Steffe, J. F. (1996). *Rheological methods in food process engineering.* East Lansing, MI: Freeman Press.

Steiner, A. E., Foegeding, E.A., & Drake, M.A. (2003). Descriptive analysis of caramel texture. *Journal of Sensory Studies*, 18, 4, 277-289.

Stone, H., Sidel, J. L., & Bloomquist. J. (2004). Quantitative descriptive analysis. In: *Descriptive Sensory Analysis in Practice.* Food & Nutrition Press, Inc., 53-69.

Szczesniak, A. S. (1963). Classification of textural characteristics. *Journal of Food Science,* 28(4), 385-389.

Szczesniak, A. S., Brandt, M. A., & Friedman, H. (1963). Development of standard rating scales for mechanical parameters of texture and correlation between the objective and the sensory methods of texture evaluation. *Journal of Food Science, 2*8(4), 397-403.

Tanaka, Y., Fukao, K., & Miyamoto, Y. (2000). Fracture energy of gels. *The European Physical Journal: Soft Matter and Biological Physics,* 3(4), 395-401.

Tolstoguzov, V. (2008). Food Polymers. In: *Food materials science: principles and practice*. J. M. Aguilera and P. J. Lillford (Eds.), New York: Springer Science.

Tolstoguzov, V. B., & Braudo, E. E. (1983). Fabricated foodstuffs as multicomponent gels. *Journal of Texture Studies,* 14(3), 183-212.

Truong, V. D., & Daubert, C. R. (2000). Comparative study of large strain methods for assessing failure characteristics of selected food gels. *Journal of Texture Studies,* 31(3), 335-353.

Trulsson, M., & Essick, G. K. (1997). Low-threshold mechanoreceptive afferents in the human lingual nerve. *Journal of Neurophysiology,* 77(2), 737-748.

Tuorila, H., & Vainio, L. (1993). Perceived saltiness of table spreads of varying fat compositions. *Journal of Sensory Studies,* 8(2), 115-120.

Turgeon, S. L., & Beaulieu, M. (2001). Improvement and modification of whey protein gel texture using polysaccharides. *Food Hydrocolloids,* 15(4–6), 583-591.

van den Berg, L., van Vliet, T., van der Linden, E., van Boekel, M. A. J. S., & van de Velde, F. (2007). Breakdown properties and sensory perception of whey proteins/polysaccharide mixed gels as a function of microstructure. *Food Hydrocolloids,* 21(5–6), 961-976.

van den Berg, L., van Vliet, T., van der Linden, E., van Boekel, M. A. J. S., & van de Velde, F. (2007). Serum release: The hidden quality in fracturing composites. *Food Hydrocolloids,* 21(3), 420-432.

van den Berg, L., Carolas, A. L., van Vliet, T., van der Linden, E., an Boekel, M. A. J. S., & van de Velde, F. (2008). Energy storage controls crumbly perception in whey proteins/polysaccharide mixed gels. *Food Hydrocolloids,* 22(7), 1404-1417.

van der Bilt, A., Weijnen, F.G., Ottenhoff, F.A., van der Glass, H.W., & Bosman, F. (1995). The role of sensory information in the control of rhythmic open-close movements in humans. *Journal of Dental Research,* 74, 1658-1664.

van der Bilt, A. (2002). Human oral function: a review. *Brazilian Journal of Oral Sciences,* 1(1), 7-18.

van Vliet, T., van Aken, G. A., de Jongh, H. H. J., & Hamer. R. J. (2009). Colloidal aspects of texture perception. *Advances in Colloid and Interface Science,* 150(1), 27-40.

van Vliet, T., & Walstra, P. (1995). Large deformation and fracture behaviour of gels. *Faraday Discussion*, 101, 359-370.

van Vliet, T. (2002). On the relation between texture perception and fundamental mechanical parameters for liquids and time dependent solids. *Food Quality and Preference,*13(4), 227-236.

Vincent, J. F. V., Jeronimidis, G., Khan, A. A., & Luyten, H. (1991). The wedge fracture test a new method for measurement of food texture. *Journal of Texture Studies,* 22(1), 45-57.

Vincent, F.V.J. (2004). Application of fracture mechanics to the texture of food. *Engineering Failure Analysis*. 11(5), 695-704.

Vinyard, C. V., Wall, C. E., Williams, S. H., & Hylander, W. L. (2008). Patterns of variation across primates in jaw-muscle electromyography during mastication. *Integrative and Comparative Biology*, 48, 294–311.

Walstra, P. (2003). *Physical chemistry of foods.* New York: Marcel Dekker.

Watase, M., & Nishinari, K. (1982). The rheological study of the interaction between alkali metal ions and kappa-carrageenan gels. *Colloid & Polymer Science,* 260(10), 971-975.

Wilkinson, C., Dijksterhuis, G. B., & Minekus, M. (2000). From food structure to texture. *Trends in Food Science & Technology,* 11(12), 442-450.

Williams, A. A., & Langron, S. P. (1984). The use of free-choice profiling for the evaluation of commercial ports. *Journal of the Science of Food and Agriculture,* 35(5), 558-568.

Williams, J. G. (1977). Fracture mechanics of polymers. *Polymer Engineering & Science,* 17(3), 144-149.

Wium, H., Qvist, K.B., & Gross, M. (1997). Uniaxial compression of UF-feta cheese related to sensory texture analysis. *Journal of Texture Studies,* 28 (4), 455-476.

Winter, H.H. & Chambon, F. (1986). Analysis of linear viscoelasticity of a crosslinking polymer at the gel point. *Journal of Rheology,* 30 (2), 367-382.

Woda, A. (2006). The regulation of masticatory function and food bolus formation. *Journal of Oral Rehabilitation,* 33(11), 840.

Yuguchi, Y., Thu Thuy, T. T., Urakawa, H., & Kajiwara., K. (2002). Structural characteristics of carrageenan gels: temperature and concentration dependence. *Food Hydrocolloids,* 16(6), 515-522.

Zasypkin, D. V., Braudo, E. E., & Tolstoguzov, V. B. (1997). Multicomponent biopolymer gels. *Food Hydrocolloids,* 11(2), 159-170.

Zhang, J., Daubert, C. R., & Foegeding, E. A. (2006). Polyacrylamide gels as elastic models for food gels: fracture properties affected by dextran and glycerol. *Journal of Texture Studies,* 37(2), 200-220.

Ziegler, G.R., & Foegeding, E.A. (1990). The gelation of proteins. *Advances in Food and Nutrition Research*, 34, 203-298, 1990

Zimoch, J., & Gullett, E. A. (1997). Temporal aspects of perception of juiciness and tenderness of beef. *Food Quality and Preference,* 8(3), 203-211.

Table 1. Early classification of textural parameters (adopted from Szczesniak (1963)[a], Civelle and Szczesniak (1973)[b]

Mechanical Characteristics		
Primary parameters	Definition	Common terms
Hardness	Force necessary to attain a given deformation	Soft---Firm--Hard
Cohesiveness	Strength of internal bonds making up the body of the product[a] / Extent to which a material can be deformed before it fractures[b]	
Viscosity	Rate of flow per unit force	Thin--Viscous
Elasticity/Springiness	Rate at which a deformed material goes back to its undeformed condition after force is removed	Plastic--Elastic
Adhesiveness	Work necessary to overcome the attractive forces between the surface of food and oral surfaces(tongue, tooth, palate) where food comes in contact	Sticky--Tacky--Gooey
Secondary parameters		
Brittleness/Fracturabilty	Force with which material fractures(hardness and cohesiveness)	Crumbly--Crunchy--Brittle
Chewiness	Energy required to masticate a solid food product to a state ready for swallowing (hardness, cohesiveness, elasticity)	Tender--Chewy--Tough
Gumminess	Energy required to disintegrate a semi-solid food product to a state ready for swallowing (hardness, cohesiveness)	Short--Mealy--Pasty--Gummy
Geometrical Characteristics		
Particle size and shape	Perception of discrete particles	Gritty, Grainy, Coarse
Particle shape and orientation	Highly organized structures of different geometrical arrangements	Fibrous, Cellular, Crystalline
Other Characteristics		
Moisture content		Dry--Moist--Wet--Watery
Fat content		
Oiliness	Oily feeling in the mouth	Oily
Greasiness	Solidity and difficulty of removal of fatty film from oral cavity	Greasy

Table 2. Gel texture attributes, evaluation techniques and definitions

Initial	**Technique:** Move gel in mouth without chewing
Smoothness[a]	Degree to which sample perceived as smooth when evaluated with tongue
First Compression	**Technique:** Compress the sample between the tongue and hard palate
Springiness[a]	Degree to which the sample returns to the original shape after partial compression between the tongue and hard palate
Compressibility[a]	Degree to which the sample deforms or compresses before fracture using the tongue and hard palate
First Chew	**Technique:** Bite completely through with the molars
Hardness[a,c]	Force required to fracture the sample with the molars
Fracturability/Crumbliness[ac]	Degree to which the sample fractures into pieces on the first bite with the molars
Moisture release[a]	Extent to which moisture is released from the sample during the 1st bite with the molars
Deformability[b]	The degree to which the sample deforms or compresses before fracture
First chew sticky[d]	Sticky sensation experienced during the first chew
Mastication	**Technique:** Chew 5-8 times and evaluate [a,c]
Particle size[a]	Size of breakdown particles (small to large)
Particle size distribution[a]	Degree of homogeneity in the particle distribution size distribution
Cohesiveness [a,c]	Degree to which the sample mass stays together as chewing progresses
Adhesiveness [a,c]	Degree to which the mass or pieces stick to any mouth surfaces
Smoothness of pieces [a,c]	Degree to which the mass or particles feel smooth
Chalkiness[a]	Degree to which fine chalk-like particles are perceived
Moisture release [a]	Degree to which moisture is released during mastication
Rate of breakdown [a]	Rate at which the sample breaks into breakdown smaller and smaller particles (slow to fast)
Degree of breakdown[c]	Amount of breakdown as a result of mastication (amount of meltability)
Dry[d]	The degree of dryness or moistness sensed in the mouth
Oily[d]	Oily, fatty, greasy mouthfeel of any kind
# chews(chewiness) [a]	Number of chews required to prepare the sample for swallowing when chewing at a rate of 1 chew per second
Residual	**Technique:** Expectorate the sample and evaluate
Particle mouthcoating	Amount of particles remaining in the mouth after expectoration
Moisture mouthcoating	Amount of moisture remaining in the mouth after expectoration
Other	
Deformability (hand)	The deformation % of sample at fracture by pressing the sample between thumb and first two fingers until sample fractures

[a]Gwartney et al. (2004), [b]Barrangou et al. (2006), [c]Brown et al. (2003), [d]Delehunty and Drake (2004)

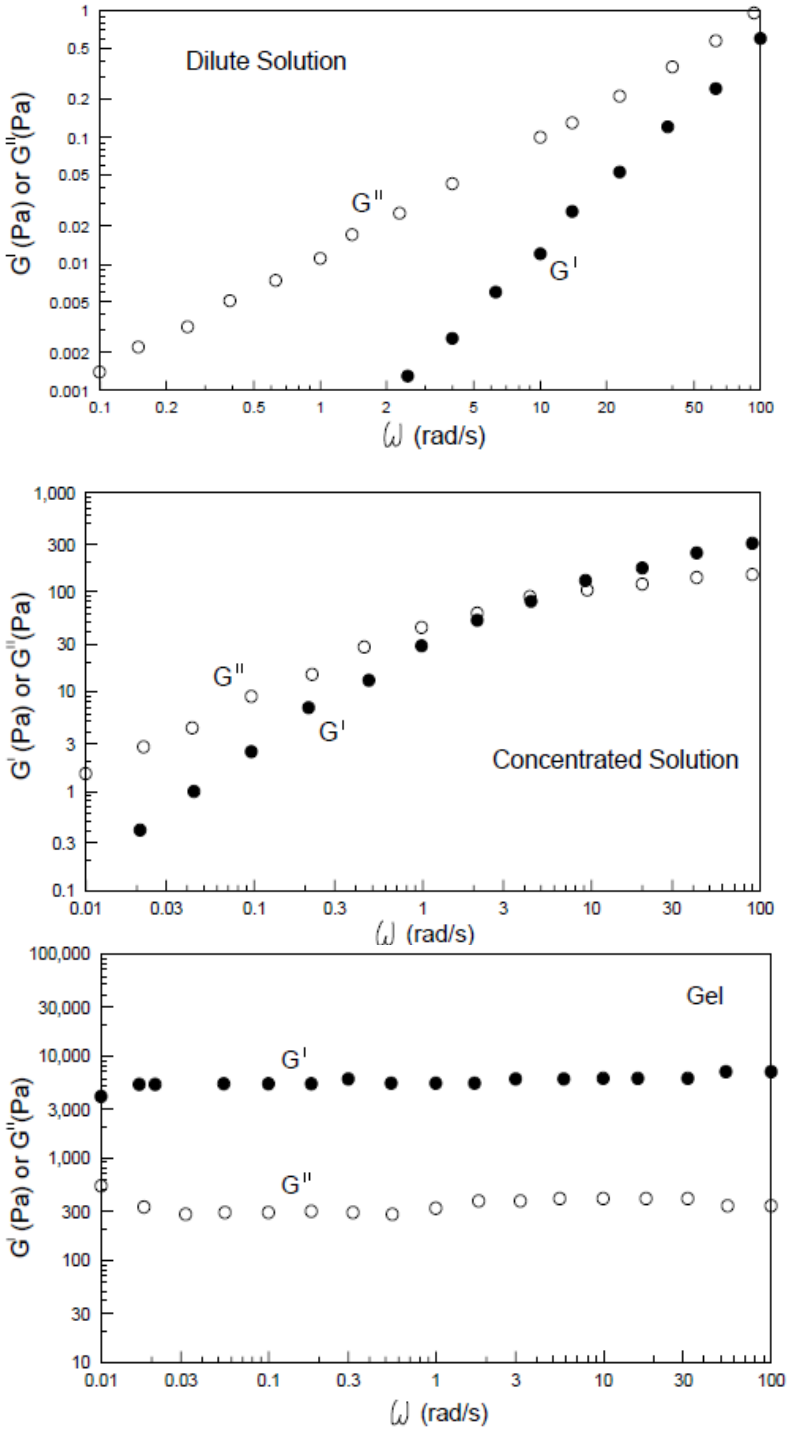


Figure 1. Mechanical spectra for dilute solution (5% dextrin), concentrated solution (5% λ-carrageenan) and gel (1% agar) (reprinted from Steffe (1996) - drawn based on data from Ross-Murphy (1988)-Small deformation measurements, In: Food Structure-Its creation and evaluation)

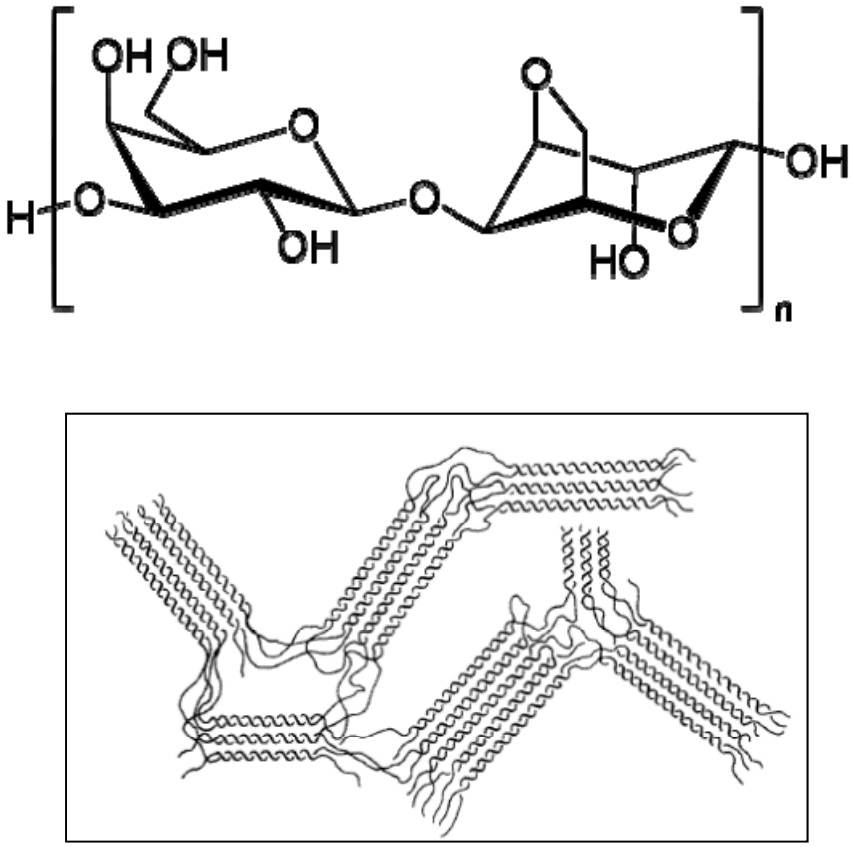


Figure 2. Structure of agarose polymer (top) (reprinted from Wikipedia) and model for agarose gelation (bottom) (showing double helices and assocation of double helices into junction zones (reprinted from Clark and Ross Murphy (1987)).

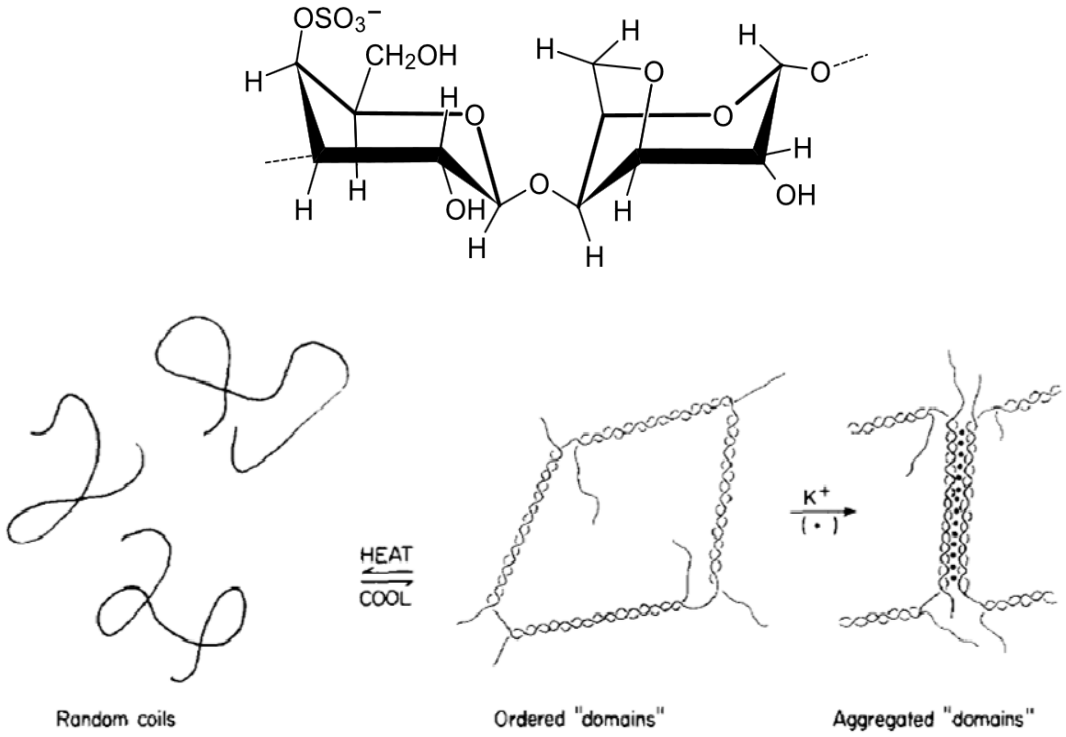


Figure 3. Structure of κ-carrageenan (top) (reprinted from Wikipedia) and model for its gelation (reprinted from Morris et al. (1980)).

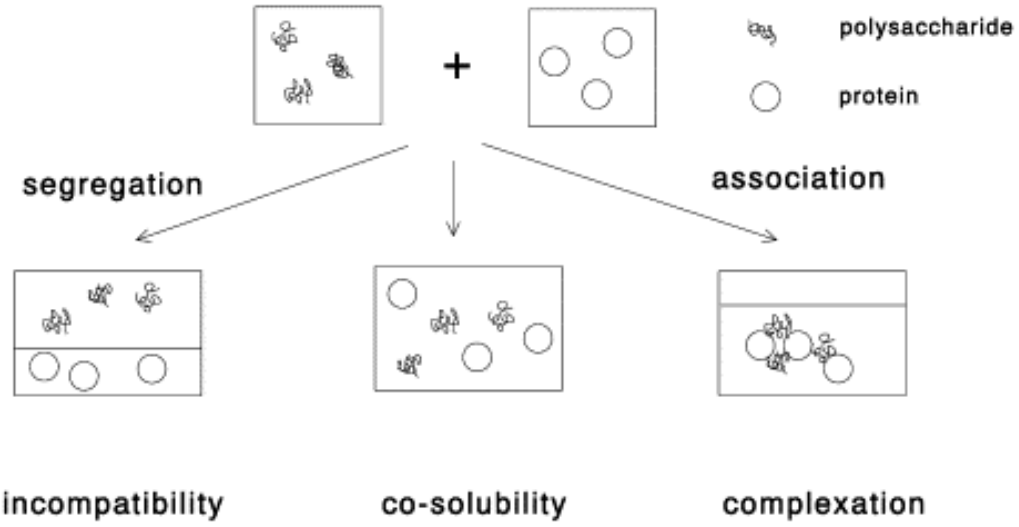


Figure 4. Behaviors of proteins and polysaccharides when they are mixed (reprinted from de Kruif and Tuinier (2001)).

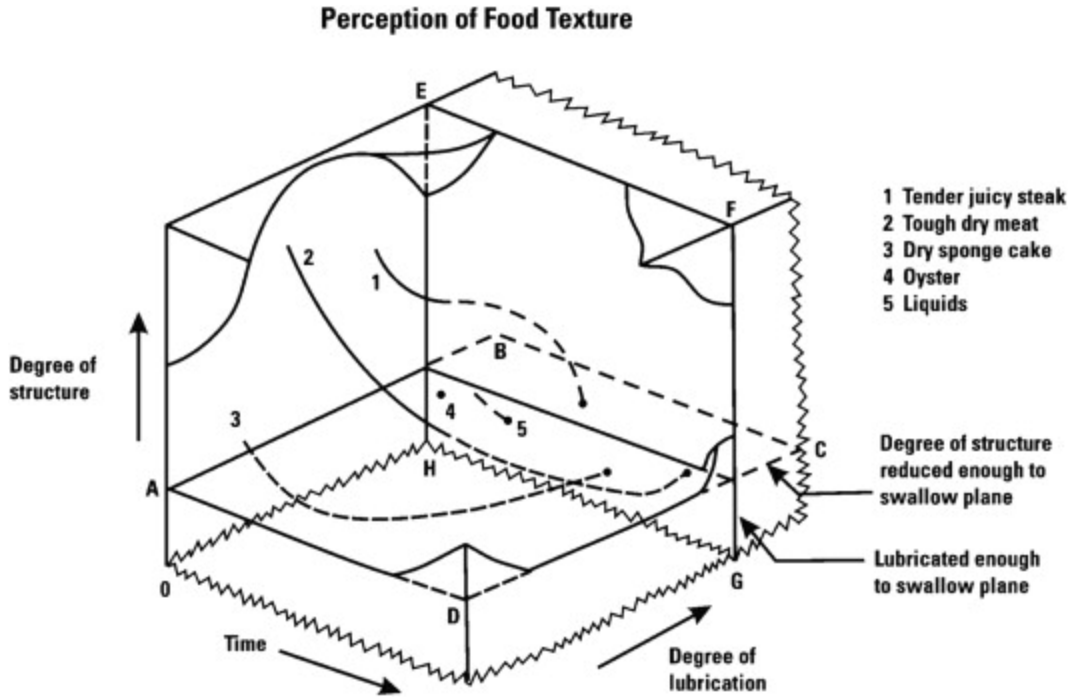


Figure 5. Model for in mouth processing of food (reprinted from Hutchings and Lillford, (1988)).

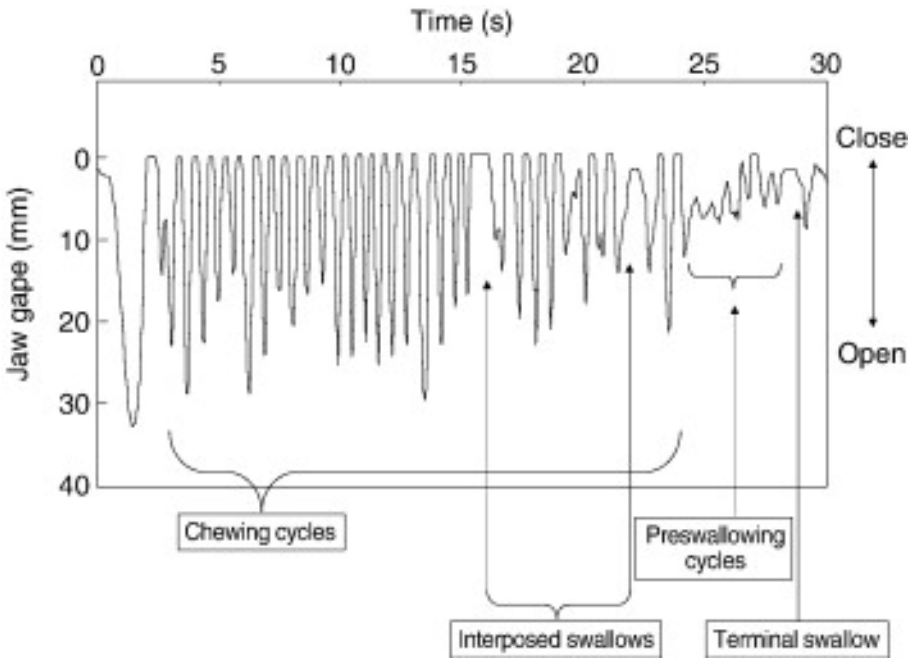


Figure 6. Mandibular movement during a complete feeding sequence (reprinted from Okada et al. (2007)).

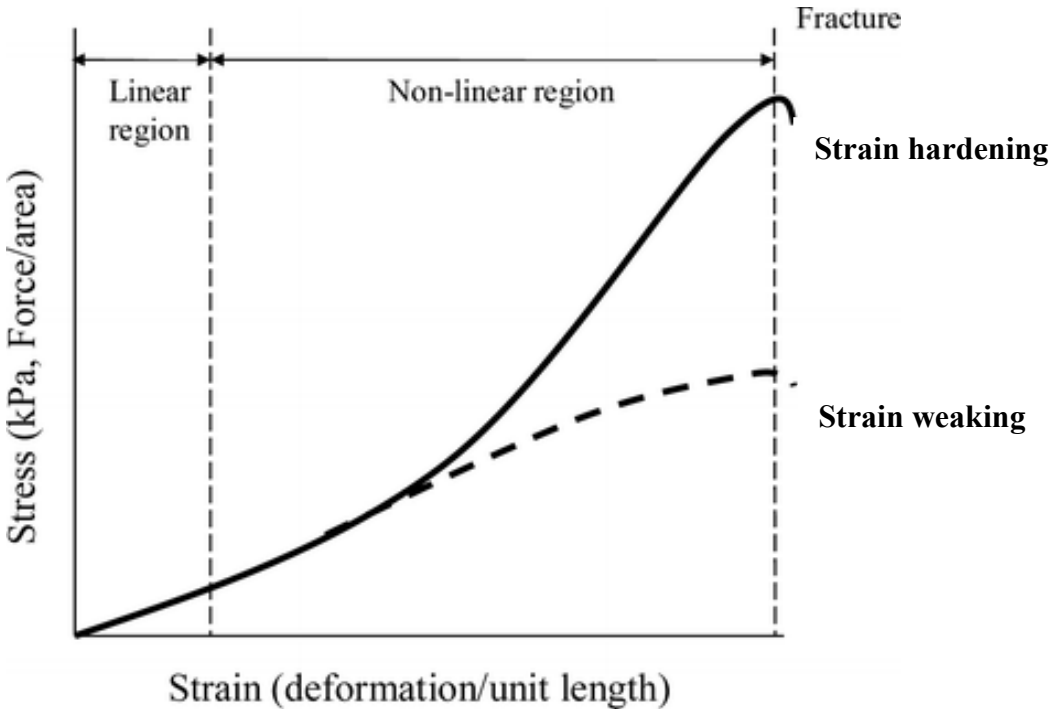


Figure 7. An example of stress-strain plot showing three regions of deformation: Linear, nonlinear and fracture. Solid line represents strain-hardening behavior; dotted line represents strain-weaking behavior (reprinted from Foegeding (2006)).

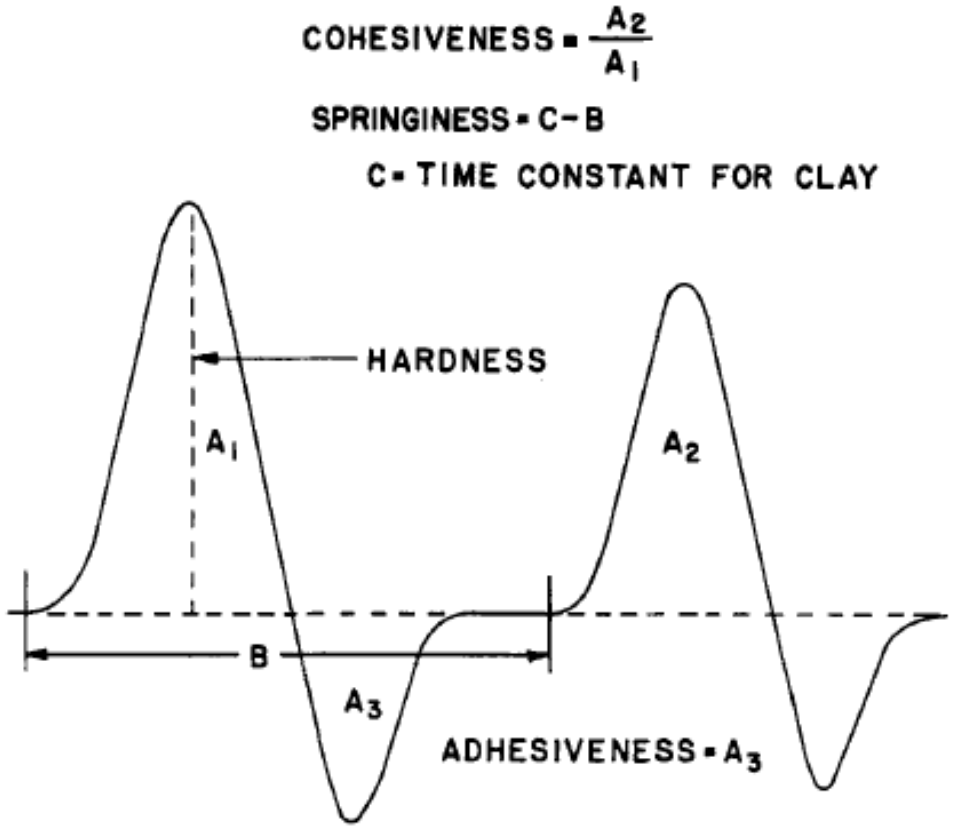


Figure 8. General Foods texturometer curve (reprinted from Friedman et al. (1963)) showing force versus time curve for double compression. A_1- first compression A_2- second compression.

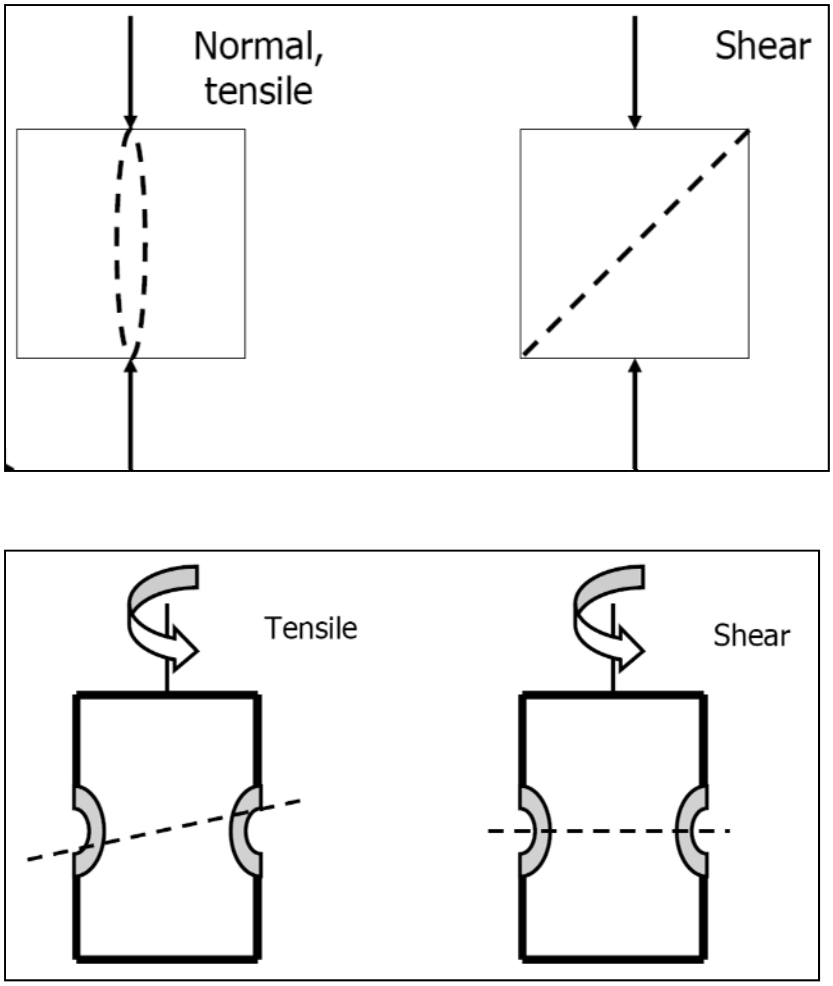


Figure 9. Different fracture modes in compression (top) and in torsion (bottom) testing (reprinted from Daubert, C.-Food Rheology class notes)

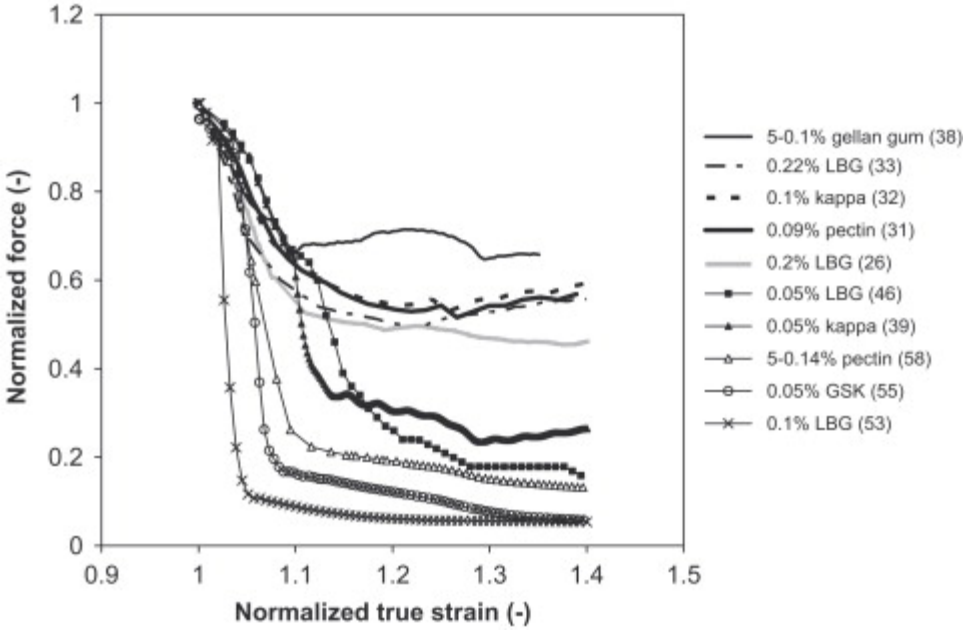
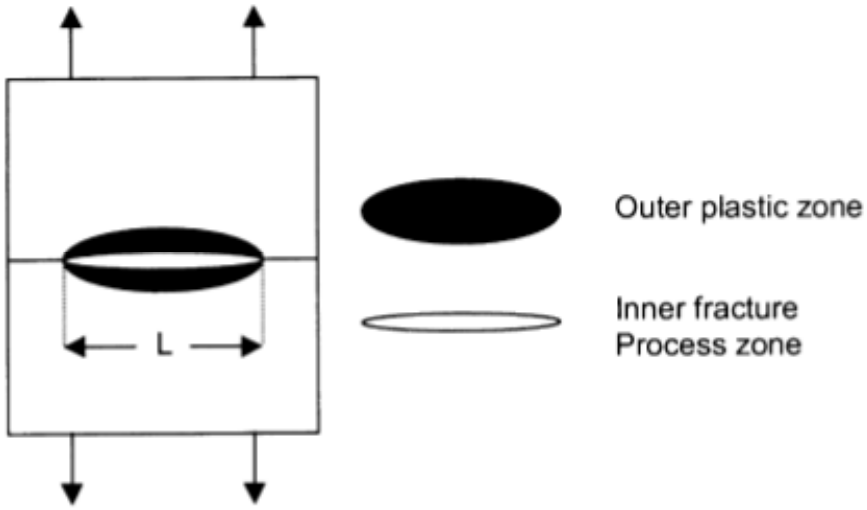


Figure 10. Normalized force versus normalized true strain curves after fracture point of WPI mixed gels. Low crumbly gels are represented with bold curves without marker symbols. Crumbliness scores are presented in the brackets next to sample name (reprinted from van der Berg et al. (2008)).

a.



b.

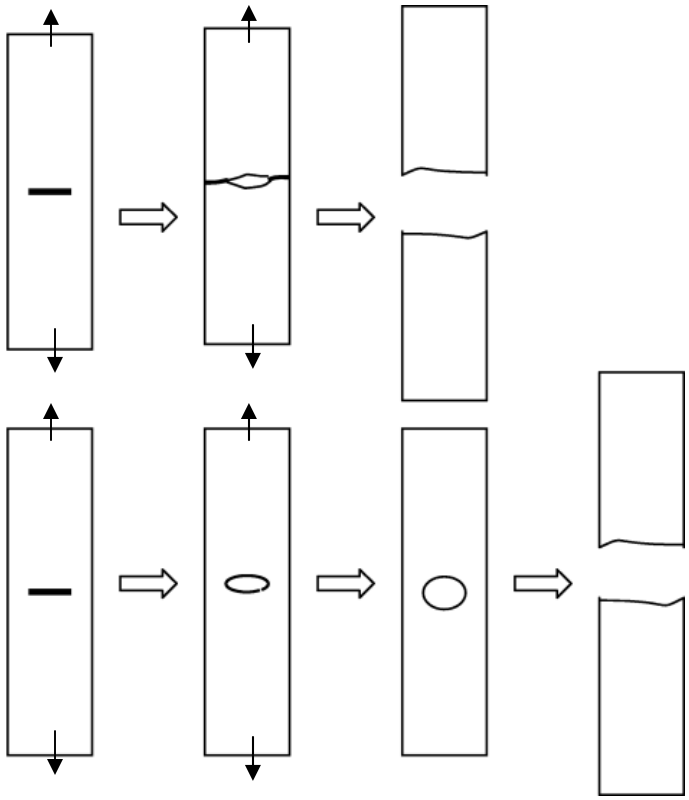


Figure 11. a. Schematic showing fracture process zone and plastic deformation zone in a notched tension test (reprinted from Hashemi (1997)) **b.** Schematic showing brittle fracture (top) and elasto-plastic (bottom) fractures (reprinted from Zhang et al. (2006)).

CHAPTER 2

Alteration of Oral Processing with Increased Fracture Stress and Fracture Strain of Model Foods

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Abstract

Model foods were developed with increased fracture stress (agar gels) or increased fracture strain (κ-carrageenan-locust bean gum gels) and their textures were evaluated by measuring muscle activity during chewing using electromyography (EMG) and by recording mandibular movements with three dimensional jaw tracking (JT). When the food became stronger and more deformable, more chewing cycles and greater muscle activity were required to prepare samples for swallowing. Adaptation of the jaw movements to increased gel strength or deformability was observed as larger or smaller movements, respectively. Chewing frequency and chewing cycle duration remained the same, indicating a consistent rhythmic jaw movement pattern. Among other mechanical parameters, stress intensity factor was found to be correlated with fracture stress and both explained changes in muscle activities. Fracture surface energy was associated with fracture strain and both were strongly related to occlusal duration of mastication. Moreover, fracture modulus (fracture stress/fracture strain) was closely associated with jaw vertical movements. Model foods designed with increased fracture stress and strain required different oral processing strategies for mastication.

Practical Applications

A fundamental understanding of the breakdown of food structure during mastication is needed to understand how to design specific textural properties. Continuous changes in physical properties of foods during chewing make the evaluation of texture a dynamic and complex process. Oral processing, which considers first bite, mastication and swallowing, is the main physiological element of texture evaluation. In this study, model foods were designed to vary in fracture stress (hardness) or fracture strain (deformability) and the texture was characterized by mechanical properties and oral processing (muscle activities and jaw movements during mastication). Change in hardness and deformability resulted in significant modification of oral processing. Muscle activities during chewing increased as model food became harder. Occlusal durations were influenced by changes in fracture strain. Understanding the effect of mechanical properties of foods on oral processing will aid in designing foods with specific breakdown patterns.

Keywords

Fracture stress, fracture strain, gel texture, oral processing, EMG, jaw tracking

1. Introduction

Physical and chemical properties of foods provide the textural properties which are associated with their acceptability by consumers. It is an ever present challenge to design desirable textures and at the same time fulfill the changing consumer demands, such as low calorie, low fat, high protein and convenient products (Sloan, 2011). Formulating specific textures requires a fundamental understanding of food structure components perceived as texture and the physiology of texture perception. Texture perception results from the combined action of motor and sensory components of mastication when food is prepared for swallowing. This involves structural transformations with force applied by teeth and the lubrication effect of saliva (Brown et al., 1998; van der Bilt, 2002) in order to form a cohesive bolus which triggers swallowing (Hutchings and Lillford, 1988).

Mastication is a rhythmic motor activity of the body which is controlled by the central pattern generators in the brainstem (Lund, 1976) and regulated by sensory feedback via oral and circumoral receptors in the periodontal ligament and jaw closing muscles (Lavigne et al., 1987; van der Bilt et al., 1995; Peyron et al., 1996; Lucas et al., 2004; Essick and Trulsson, 2008). Sensory information about the forces and displacements is used by the central nervous system to change the form and timing of chewing cycles (van der Bilt et al., 1995). The continuous changes in physical properties of foods during mastication make the evaluation of texture a dynamic and complex process (Foegeding, 2008). Studying oral processing via electromyography (EMG) and three dimensional jaw tracking (JT) (electrognathography, EGN), in addition to characterizing the mechanical and sensory properties of foods, can provide new insight into the complex nature of food texture (Chen,

2009). Electromyography is the science of recording electrical activity of muscle fibers. When muscles are activated, electrical action potential is propagated along active muscle fiber and these changes can be recorded by electrodes. These bioelectrical activities have been closely related to the forces developed during mastication (Woda et al., 2006). The three dimensional tracking of the mandibular movements provides the mandibular velocity, direction and quantity of the movements. Muscle activities and jaw movements provide an understanding of the relations between the physical properties of foods and oral processing, and help explain sensory perception of texture (Chen, 2009).

Textural properties of a wide range of natural foods such as cheese (Agrawal et al., 1998; Mioche et al., 1999; Meullenet et al., 2002; Gonzalez et al., 2002; Cakir et al., 2012), carrot, apple , biscuit, toast (Brown et al., 1994a), cooked rice (Kohyama et al., 1998), meat (Brown et al., 1994a; Sakamoto, 1989; Mioche and Martin, 1998), peanuts, almonds and artificial materials such as silicone elastomers Optosil and Optacal (Edlung and Lamn, 1980; Olthoff et al., 1984; van der Bilt et al., 1991; Slagter et al., 1992; Buschang et al., 1997; Fontijn-Tekamp et al., 2004) have been studied with EMG and/or JT. Jaw movements differ during chewing of foods with various food structures, such as cheese, meat, coconut and chocolate (Peyron et al., 1996). Higher vertical and lateral jaw movements are observed for chewing harder mature cheese compared to young cheese (Peyron et al., 1996). However, hardness may not be the only difference between cheeses and modifications in jaw movements can be related to other sensory or physical parameters. Not only jaw movements, but also jaw closing muscle activities vary during chewing of various foods with different structures. The relationship between muscle activity/chew and stress at maximal

strain (fracture stress) of different food structures was explained by a power function and suggested that muscle activity required for each chew was used as sensory input to modify the motor component of mastication (Mioche et al., 1999).

Hardness is a general term that describes the maximum force or stress during a prescribed compression of a food (used in mechanical testing and sensory analysis). Material properties determined by rheological or fracture mechanics methods allow for a universal description of structure. Toughness (R, energy required to form unit surface area) and Young's modulus (E) have been shown to be associated with food breakdown (measured by single bite with postcanine teeth) (Agrawal et al., 1997), EMG activity (Agrawal et al., 1998), jaw closing angle and jaw movement (Agrawal et al., 2000). These studies, conducted on 15-28 different foods from soft cheese to hard nuts, demonstrated that $\sqrt{R/E}$ is an important criterion for oral processing. Chewing of hard, brittle foods (low $\sqrt{R/E}$) require wider movements than chewing softer, tougher foods (higher $\sqrt{R/E}$). Lateral movements were seen mostly in the closing phase while vertical movements were seen in the opening phase. Thus, it has been suggested that vertical amplitude of chewing cycles gives information about properties of food such as particle size, shape and volume, while mechanical properties of foods are more reflected by lateral movements.

Natural foods in these studies have complexity due to various sensory and mechanical properties which were not normalized, such as flavor. Moreover, it is not clear if the hardness or other studied properties are the only parameters causing changes in mastication. These difficulties in real food systems has been overcome by using model foods with low

level of complexity and precisely controlled mechanical properties. Increased hardness of gelatin-based model foods results in increased mastication time, muscle activity and vertical amplitudes (Peyron et al., 2002). Foster et al. (2006) studied caramels with different levels of hardness, as a plastic model, in addition to gelatin-based model foods as elastic models. At a similar hardness, plastic model foods have lower frequency but larger lateral and vertical amplitudes than elastic food. Hardness affected the muscle activities, while elastic-plastic (qualitatively defined) behavior affected the jaw movements.

The findings on natural and model foods demonstrate that mechanical properties of food are a major part of sensory feedback for modulation of the chewing cycle. Stress and strain at fracture are two fundamental physical parameters used to characterize food texture. These parameters are used to form texture maps which relate sensory terms (brittle, mushy, tough, rubbery) with fracture properties (Lanier, 1986). The objective of this study was to understand the effect of fracture stress (strength) and fracture strain (deformability) of soft solids on oral processing while differences in other textural properties are minimal. Two model foods agar gels and κ-carrageenan -locust bean gum gels, were developed with wide ranges of fractures stress and fracture strain, respectively. Agar gels have significant increase in gel strength and slight decrease in deformability when the concentration of agar is increased in the presence of glycerol (Barrangou et al., 2006). κ-Carregeenan gels have higher fracture strain when combined with locust bean gum (Chen et al., 2001). In addition, stress intensity factor, fracture surface energy, Young's modulus, and fracture modulus were determined to provide a more comprehensive description of mechanical properties. Neither gel networks melted at body temperature in the mouth during chewing so, unlike gelatin, oral

processing results in particle size reduction without the possibility of melting. To examine the modifications in oral response, muscle activities and jaw movement were recorded simultaneously by using EMG and 3D-JT during chewing of model foods.

2. Materials and Methods

2.1. Model Foods

Agar and κ-carrageenan-locust bean gum gels were developed with specific fracture properties. The fracture stress of agar gels was increased by increasing the agar concentration while fracture strain remained constant. In contrast, the fracture strain of κ-carrageenan-locust bean gum gels was increased while the fracture stress was held within a certain range.

Agar Gels

Food grade agar powder (TIC Gums, Belcamp, MD) was used in combination with glycerol (Protector Gamble Chemicals, New Milford, CT). Agar gels at three different concentrations (1, 3 and 5% w/w) containing 60% (w/w) glycerol were prepared according to the method of Barrangou et al. (2006) with slight modifications. Deionized water and glycerol were mixed at room temperature (22 ± 2C), and agar powder was slowly sprinkled into the water-glycerol mixture while stirring in order to avoid clumping. Artificial Dulce De Leche flavor (Mother's Murphy, Greensboro, NC) was added into the mixture at 0.2% (w/w) to provide a more pleasant sensation during chewing. The solution was mixed at 250 rpm for 30 min. After mixing, the solution was heated for 1 min in a microwave oven. Hot deionized water was then added to adjust to the original weight. The beaker was covered with aluminum foil

and held in a water bath at 85C for 30 min. The solution was poured into cylindrical glass tubes (i.d.=19 mm) with rubber stoppers at one end, covered with aluminum foil, held for 2 h at room temperature (22 ± 2C) and then stored at 4 ± 2C for 16-24 h for gelling. The gels were equilibrated at room temperature (22 ± 2C) for at least 1 h prior to mechanical tests and oral processing analysis. Samples were cut into 15 mm long cylinders for mastication and compression testing.

κ-Carrageenan-Locust Bean Gum Gels

κ-Carrageenan (C) and locust bean gum (LB) gels containing 10% (w/w) sucrose were prepared at varying ratios of 1:0, 3:1 and 1:1(C-LB (w/w)). CP Kelco provided κ-carrageenan (GenuGel® CHP-2, CP Kelco, Denmark) and locust bean gum (Genu®Gum RL-200Z, CP Kelco, Atlanta, GA). Crystalline potassium chloride (KCl) was obtained from Fisher Scientific (Fair Lawn, NJ). Weighed amounts of κ-carrageenan, locust bean gum powder and sucrose were premixed and added slowly into a 0.02M KCl solution while stirring at high shear (Corning stirrer, Lowell, MA, set speed 10). Natural & artificial strawberry flavor (Mother's Murphy, Greensboro, NC) was added to the mixture at 0.2% (w/w) to provide a more pleasant sensation during chewing. The C-LB gel solution was mixed for 15 min at room temperature and then held in a water bath at 90C for 15 min. Solutions were subsequently boiled using a heated stirrer plate (Corning PC351, Lowell, MA) for 3-5 min. After boiling, hot KCl solution was added to bring the sample to the original weight and then held in a water bath at 90C temperature for 30 min. The solution was poured into glass tubes (i.d.=19 mm) as described for agar gels. Samples were gelled at room temperature (22 ± 2C) for 16-24 h, and then stored at 4 ± 2C until testing. The gels

were equilibrated at room temperature (22 ± 2C) for at least 1 h prior to mechanical tests and oral processing analysis. Samples were cut into 15 mm long cylinders for mastication test.

2.2. Large Deformation Rheological Tests

Fracture stress and strain of agar gels were determined by uniaxial compression while κ-carrageenan-locust bean gum gels were tested with torsional fracture. Different deformation modes were used because failure of the gels having strain values higher than 2-2.5 could not be achieved by compression, and the agar gels required forces above the dynamic range of the rheometer used for torsion testing (Troung and Daubert, 2000). However, shear stress and strain values obtained by uniaxial compression are in close agreement with shear stress and strain values obtained by torsion (Hamann et al., 2006).

Compression

Fracture properties of cylindrical agar gels, 19 ± 1 mm diameter and 15 mm length, were determined by uniaxial compression. Samples were compressed between lubricated (mineral oil) parallel plates to the point of fracture using a universal testing machine (Instron Model 5565 Instron Engineering Corp., Canton, MA, U.S.A.) equipped with a 5 kN load cell. Compression of samples was controlled with Bluehill software (Instron, Canton, MA, U.S.A.). Gels (22 ± 2C) were compressed to 20% of the original height at a constant cross-head speed of 50 mm/min, and 8 samples were evaluated for each treatment. All samples fractured during compression so force and distance data were used to calculate shear stress and strain at fracture, as described below (Hamann et al., 2006; Troung and Daubert, 2000).

True compressive stress (σ_c, Pa) was calculated as $\sigma_c = \left(\frac{F}{A}\right)\lambda$

where F is force (N), A is cross sectional area (m^2) of samples before compression, λ is a shape correction factor defined as:

$$\lambda = \frac{L}{L_i}$$

where L is final height (m) of sample after deformation and L_i is initial height (m). Final height is calculated by the difference between initial height and deformation (ΔL, m). True compressive strain (ε_h) was calculated as:

$$\varepsilon_h = \ln\left(1 + \frac{\Delta L}{L_i}\right)$$

Shear stress (σ) and strain (γ) at fracture were calculated as:

$$\sigma = \frac{3}{4}\sigma_c \qquad \gamma = \frac{3}{2}\varepsilon_h$$

Torsion

The torsion method developed by Diehl et al. (1979) was used to measure fracture properties of κ-carrageenan-locust bean gum gels. Samples were equilibrated to room temperature (22 ± 2 °C) for 1 hour prior to testing and 9 samples of each treatment were deformed to fracture. Gels were removed from the cylindrical glass tubes and cut into 28.7 mm long cylinders. Notched plastic disks (Gel Consultants, Raleigh, NC) were fixed on the top and bottom of sample cylinders with cyanoacrylate glue (LocTite401, Loctile Corp., Rocky Hill, CT). The samples were ground into a capstan shape with a precision milling machine (Gels Constultants, Raleigh, NC) until center diameters of 10 mm were obtained. Capstan shaped gels were mounted vertically in a Haake VT550 Viscometer (Paramrus, NJ) and twisted to failure at a rotational speed of 4.5 rpm (corresponding to a shear rate of 0.47 s^{-1}). Time and

torque data were collected during deformation and used to calculate fracture stress and strain as described by Barrangou et al. (2006).

Shear stress (σ) at the minimum cross-section is calculated as $\sigma = MQc$

where M is torque (Nm); Q is a shape factor constant for the mid-section of the specimen, equal to 8.35 x 10^6 m^{-3}; and c is a constant defined as:

$$c = \frac{2K}{\pi r_{min}^3 Q}$$

where K is a shape factor constant for the boundary of the minimum cross-section of the specimen, equal to 1.08; and r_{min} is the radius of the smallest cross-section, equal to 5 mm.

Shear strain (γ) at the minimum cross-section is calculated as:

$$\gamma = ct\left(\frac{2\pi(rpm)}{60}\right)\left(\frac{Q}{Q+U}\right)$$

where t is time (s); rpm is the rotational speed; and U is a shape factor constant for the ends of the specimen, equal to 1.09 x 10^6 m^{-3}.

The corrected shear strain (γ_{corr}) is a necessary correction for strains > 0.8, and is calculated as:

$$\gamma_{corr} = \ln\left[1 + \frac{\gamma^2}{2} + \gamma\left(1 + \frac{\gamma^2}{4}\right)^{0.5}\right]$$

Center Crack Tension

Fracture surface energy and stress intensity factor of the gels were measured with the center crack tension method where a controlled crack of known dimensions is propagated via applied extensional stress (Anderson, 1995). Fracture surface energy (J/m^2) is the amount of energy required to fracture one unit area of material and dictates crack propagation. The gels

were prepared by pouring solutions into rectangular trays to 5 mm height. Samples were removed from the mold after gelation and cut into 5x18x120 mm shapes. A 9-mm-wide notch was cut into the middle of the sample with a sharp blade before testing. Samples were glued to a tension measurement fixture attached to an Instron 5540 universal testing machine (Instron Engineering Corporation, Canton, MA) equipped with a 50 N load cell. Tests were conducted at a constant speed of 10 mm/min and at room temperature (22 ± 2C). Fracture surface energy was calculated with the equation by assuming linearly elastic behavior.

$$2\mathrm{G_I} = \frac{K_I^2(1-\nu^2)}{E}$$

Where $\mathrm{G_I}$ is the fracture surface energy, K_I is the stress intensity factor, ν is the Poisson's ratio (0.5 for incompressible materials), and E is the Young's modulus. Young's modulus was calculated from the initial slope of the true stress and true strain curve by applying linear regression in the range of 0.02-0.1 true strain. The stress intensity factor K_I was calculated as:

$$K_I = \frac{P}{B\sqrt{W}}\sqrt{\frac{\pi a}{4W}\sec\frac{\pi a}{2W}}\left[1 - 0.025\left(\frac{a}{W}\right)^2 + 0.06\left(\frac{a}{W}\right)^4\right]$$

Where P is the force at the failure point; B is the specimen thickness; W is the specimen half width, and a is the half width of the notch.

2.3. Subject Selection

Subject selection and mastication data recording was conducted based on the method by Cakir et al. (2011). An initial group of 20 subjects attended a preliminary session where the oral processing analysis system and samples were introduced to them and the procedure

explained. Subjects chewed samples of agar or κ-carrageenan-locust bean gum gels while muscular activity and three dimensional jaw movements were recorded (as described in the following section). From this preliminary session, fourteen subjects (8 female, 6 male, 18-35 years old, mean 25) were selected on the basis of dental criteria and range of jaw movements. The dental criteria for inclusion were: normal class I occlusion, complete permanent teeth (except wisdom), no major dental treatment within 6 months (braces, surgery, extraction and restoration), no tooth decay or gum disease, no pain or sounds in the jaw joint (grinding, popping or clicking). Subjects included in the study had maximum jaw opening of at least 40 mm and lateral jaw movements of at least 7 mm. In addition to these criteria, subjects were required to have no sensory training in the last 6 months. Subjects were informed about the objectives of the study and gave their informed consent before participating. Experimental protocol was approved by North Carolina State University Institutional Review Board.

2.4. Masticatory Recordings

Muscular activity and three dimensional jaw movements were recorded simultaneously while subjects were chewing. Electromyographic activities of masseter (M), anterior temporalis (AT) and anterior digastric (AD) muscles were measured by surface electrodes (BioFLEX, BioRESEARCH Assoc., Inc., Milwaukee, WI) attached on muscles on the left and right side of the face. The subjects were asked to clench their teeth to allow for location of AT and M muscles and were asked to open their mouth to locate AD muscles. After cleaning the subject's skin with alcohol, electrodes, coated with a conductive gel, were attached on the skin on the located muscle sites. A ground electrode was placed on the subjects' neck to

minimize electrical background noise. Three dimensional movement of the mandible (anterior-posterior, vertical, lateral) was recorded by attaching a small magnet to the lower frontal incisors with a nontoxic adhesive (Stomahesive®, ConvaTec, Princeton, NJ) and recording movement within an electromagnetic field. The magnet was aligned with the center of *frenulum labii inferioris* and parallel to the horizontal plane. Subject's head was centered in a headgear that tracks the position of the magnet, with the upper crossbar of the headgear parallel to the eyes (interpupillary line). The alignment of the headgear with respect to the magnet was controlled with an alignment bar. During data collection, the position of the magnet was electronically transposed and the chewing pattern was obtained using BioPAK software (version 5.51, BioRESEARCH Assoc., Inc., Milwaukee, WI). For EMG data acquisition, a single channel differential input amplifier with adjustable gain was connected to electrodes. The amplifier gain was set to 5000 Hz during mastication data recording.

During data collection, the subject was seated comfortably and asked to avoid any head movements, facial expressions or talking during recordings. Subjects placed the sample on their tongue, and then brought their teeth together to create a reference point for the analysis. Upon a signal from the researcher, the subjects started chewing in a habitual manner. Data was recorded until complete swallowing of the food bolus. Between each data recordings, the subject could drink water or rest if they wished. Each subject participated in two sessions on consecutive weeks. Sessions were held on the same day of the week, at the same time for each subject. Each session lasted approximately 60 min. Subjects started each session by chewing gum for 1 min, to help them relax, before proceeding with a warm-up

sample. Three samples of each treatment were presented in random order at each session. Each sample was equilibrated to room temperature (22 ± 2C) prior to evaluation. Electromyography readings were monitored after each recording to assure low noise and proper attachment of the electrodes. If the noise exceeded 3μV, the subject's skin was cleaned and electrodes were replaced and the recording repeated. Subjects were unable to view the computer screen during the recordings.

2.5. Data Analysis

Raw EMG signals and jaw tracking recordings were first converted into a text file. Raw EMG data were then transformed into wave forms using the root mean square (RMS) function in the LabView Graphical Programming System (National Instruments Corporation, Austin, TX) as described by Hylander and Johnson (1993) and Vinyard et al. (2008). The raw data were filtered at 30 Hz through a digital low–pass filter and the magnitude of the muscle activity was calculated in 2 ms intervals. The EMG was quantified by calculating RMS values for a 42 ms time constant. EMG data in wave form and JT-3D data were superimposed using LabView and analyzed simultaneously. This allowed for coordination of EMG and JT-3D recordings in real time and examining EMG activity at certain spatial and directional phases of jaw movements. Different phases of a chewing cycle were determined based on vertical jaw movements. Each chewing cycle was analyzed in three sections: opening, closing and occlusion. Opening phase was from the end of occlusion to the maximum vertical amplitude; closing phase was between the maximum opening amplitude

and the beginning of the occlusion. Occlusion phase was between two successive cycles where teeth were kept together with little vertical movement.

Each chewing cycle in a mastication sequence was analyzed. Mastication parameters calculated from these data are shown in Table 1 with their explanations. Irregular jaw movements, which can be due to tongue pressure, side changes, bolus movement or interpose swallows, were identified and removed from the mastication sequence (explained in Results section). Sequence analysis and chewing cycle-by-cycle analysis were performed. Number of chews, total duration, and frequency parameters were reported for the whole chewing sequence. Parameters such as durations of different phases of the chewing cycle, amplitudes of three dimensional jaw movements, and jaw velocities were reported by averaging values obtained from every cycle made during a chewing sequence. Muscular activity/cycle was obtained by dividing total activity for the sequence by number of chewing cycles. In cycle-by-cycle analysis, the first three cycles, three cycles in the middle of the sequence and last three cycles were analyzed individually (when the number of cycles in a sequence was even, the last two cycles of the first half sequence and the first cycle of the second half was used to define middle three cycles). The data were represented for each subject after the values of three replicates were averaged for each treatment. Finally, the mean values obtained from 14 subjects were calculated and therefore results reported are an average of 3 replications x14 subjects for each chewing cycle.

2.6. Statistical Analysis

Analysis of variance was performed using a mixed model of Proc Mixed of SAS (version 9.2, SAS, Cary, NC) by treating treatment as a fixed effect and subjects and subject treatment interaction as random effects. When ANOVA test indicated a significant difference between treatments, Tukey tests were conducted for means separation at 0.05 significance levels. The relations between rheology and mastication parameters were examined by correlation coefficients (Proc CORR, SAS).

3. Results

3.1. Rheological Measurements of Gels

Fractures stresses of agar gels increased linearly as agar concentration increased (Fig. 1A). Gels were differentiated ($p<0.05$) with the fracture stresses of 40, 158 and 261 kPa for 1%, 2% and 3% (w/w) agar gels, respectively. While fracture stress increased, fracture strain remained similar between 0.92-0.96, with an average value of 0.95 (Fig. 1B). Glycerol was used to minimize changes in fracture strain, with results similar to those of Barrangou et al. (2006). Fracture modulus (fracture stress/fracture strain) and Young's modulus of agar gels scaled similar to fracture stress with the increased concentration (Fig. 1C, Fig. 1D). Increases in gel strength (fracture stress) and firmness (Young's modulus) with increased polymer concentration reflect an increase in the strand density of the gel network.

Fracture strain of κ-carrageenan-locust bean gum gels increased as the ratio of locust bean to κ-carrageenan increased (Fig. 1B). Chen et al. (2001) reported increased rupture strain of κ-carrageenan gels with the addition of locust bean gum. Fractures stresses of

κ-carrageenan-locust bean gels were in a range of 99-160 kPa (Fig. 1A). The fracture stress first increased with an addition of locust bean gum (25% (w/w)), then decreased when locust bean gum was increased to 50% (w/w) in the mixture. The same pattern was reported previously with a peak in fracture stress observed when 30- 40% locust bean was used (Chen et al., 2001). These two hydrocolloids formed a single phase with the absence of any macroscopic phase separation. κ-Carrageenan-locust bean gels were less stiff compared to agar gels and had similar fracture and Young's modulus values. Gels with high fracture strain had slightly lower moduli (Fig. 1C, Fig. 1D).

Stress intensity factor and fracture surface energy increased with increasing agar concentration or addition of locust bean gum to κ-carrageenan (Fig. 1E, Fig. 1F). Note that they did not follow fracture stress for κ-carrageenan-locust bean gum gels. Therefore, agar gels with varying fracture stress (i.e., gel strength) and κ-carrageenan-locust bean gum gels with varying fracture strain provided different mixtures of mechanical properties. Both gels did not melt during mastication and showed minimal adhesive properties (i.e., they did not stick to the surfaces of the mouth). Consequently, the main mastication process was for reduction in particle size rather than separation of adhesive particles from surfaces within the mouth.

The relations among mechanical parameters are showed with Pearson correlation coefficients in Table 2. Fracture modulus and Young's modulus were correlated with fracture stress, $r = 0.87$ and $r = 0.86$, respectively. Stress intensity factor was strongly associated with fracture stress ($r = 0.87$) whereas fracture surface energy was related to fracture strain ($r = 0.95$).

3.2. Mastication

Subject Performances

There was significant variation among subjects for all parameters, ($p<0.05$). This can be illustrated with minimum and maximum of the mean values of chewing parameters for 3% agar (Table 3). Chewing of the same sample could vary from 14 to 85 cycles, depending on subject. Individual differences in masticatory behavior have been well documented in the literature (Woda et al., 2006; Brown et al., 1994a; Rey et al., 2007). It can originate from psychological or physiological factors. Each subject has slightly different jaw morphology and there can be some anatomical differences in muscles and coordination of muscles. There are variations in the chewing rhythm, time for chewing, salivary flow rate, swallowing threshold and chewing efficiency (Brown et al., 1994a). Human psychology can also affect mastication. A questionnaire was conducted during the preliminary session in order to understand subjects' experience with the model foods. Questions involving liking and disliking of texture and flavor, subject's experience with model foods, and amount of saliva produced during chewing were asked to all subjects about both gels. Overall, there were no major difficulties for people to chew model foods. They commented that their experience with model foods was indifferent compared to a real food.

Changes in Parameters (Sequence Analysis)

An example sequence of jaw movement and muscle activity during mastication of a 3% (w/w) agar gel is given in Fig. 2. The magnitudes of initial cycles were greater due to moving the sample from tongue to molars and initial size reduction process. Vertical

movements of jaws were greater in magnitude than lateral and anterior-posterior movements. Lateral movements showed that the subject used both left and right sides for chewing, with preference to the right (75 % of cycles) in this example. Anterior and posterior movements were more apparent in initial and final stages of the sequence. Some irregular cycles were identified which could be due to tongue movements or side changing. Many people change bolus location from one side to another during normal chewing. Some of the sequences had interposed swallows which could be identified with long occlusion periods and high muscle activities, especially digastric muscles. Such irregular cycles and interposed swallows were not included in the mean calculation of the parameters. At the end of sequence, jaw movements and muscle activities were very irregular, which indicated the clearance and swallowing part of oral processing (Fig. 2). The length of this section could be different for different subjects. These sections of the sequence were not included in the sequence analysis.

The main effects of fracture properties on mastication parameters were the changes in number of cycles made and muscle activities. Increasing agar concentration increased fracture stress and the number of chewing cycles needed to form a bolus. This corresponded with more total muscle activity. Individual variations occurred in the muscle activities and jaw movements, as well as in modification of chewing behavior for foods. The mean values of mastication parameters were obtained by averaging all chews made by all subjects. The effect of increased fracture stress on oral processing parameters is given in Table 4. Mastication time (t-chews) was doubled when the fracture stress of agar gels increased four times from 40 kPa to 158 kPa (Table 4). Muscle activity/chew discriminated between

different levels of gel strength for temporalis and masseter muscles. A significant increase in digastrics muscle activity was also observed, but to a lower extent (Fig. 3). Another main finding was that the "chewing motor" runs at the same speed regardless of number of cycles. Mean cycle duration and frequency did not change significantly with fracture stress.

In addition to changes in muscle activation and number of cycles, there were some slight but significant changes in jaw movements. Three dimensional movements of the mandible were increased to manipulate gels with increased fracture stress, vertical amplitude being more significant (Table 4). As gel strength increased, chewing was observed to be faster with increased opening and closing velocities.

Increasing the deformability of κ-carrageenan-locust bean gum gels showed some similar effects on mastication parameters as the increased fracture stress (Table 5). Number of cycles and sequence duration were increased with increased level of fracture strain. The range of change was smaller compared to agar gels. Similar to agar gels, no effect was observed on frequency, cycle duration and closing duration. Opening duration was decreased while occlusal duration was increased. The occlusal duration discriminated differences in fracture strain. Increase in masseter and temporalis muscle activities per cycle and for complete sequence was observed. While there was no change in digastric activity per cycle (Fig. 4), when the activity for a whole sequence was considered, it increased as well (Table 5). Three dimensional movements decreased slightly with increased level of fracture strain (Table 5). In contrast to the response to different levels of fracture stress, the velocity of chewing was not affected by changes in gel deformability.

When the relationship between mechanical and mastication parameters were examined (Table 6), muscle activities and number of cycles were found to be more related to fracture stress and stress intensity factor while jaw movements were associated with fracture modulus. Number of cycles was significantly correlated with stress intensity factor ($r = 0.91$) and fracture stress ($r = 0.84$), and individual and total muscle activities also had significant correlations with stress intensity factor ($r = 0.81$-0.98). Occlusal duration had a significant correlation with fracture strain ($r = 0.83$) and with fracture surface energy ($r = 0.90$).

Changes throughout the Sequence (Cycle-by-Cycle Analysis)

The chewing process was separated into three sections to analyze the progressive changes during oral processing. A progressive reduction was observed for muscle activities (Fig. 5) and three dimensional movements of the jaw (Fig. 6) during chewing of both model foods. The greatest change in the muscle activities occurred in the initial phase. Changes in the middle and last phases were minimal. Gel strength and deformability also resulted in differences in muscle activities along the sequence. Similarly, decreases in vertical movements were the highest in the initial part of the sequence for all model foods (Fig. 6). Changes in vertical amplitude along the sequence were not dependent on gel deformability. Major changes in other mastication parameters were also in the initial phase of the chewing sequence (data is not shown). Magnitude of occlusal duration was the only parameter increased along the chewing sequence.

A decrease in parameters throughout the chewing sequence can result from adaptation of chewing behavior to the decrease in particle size and the volume of the bolus. The feedback from each chew by sensory nerve endings in oral mucosa and periodontal

membranes will affect the characteristics of the subsequent chews, including force level (Brown et al., 1994b). Food resistance varies from cycle to cycle and immediate muscle response is required to maintain a constant chewing rhythm (van der Bilt, 2002).

The large differences observed among the first cycles was observed was likely due to maximal size reduction taking place in the initial cycles (Lassauzay et al., 2000). In later stages, food fragments become softened by saliva and physical properties of the samples was modified. Differences in muscle activities for three levels of fracture stress of agar gels were greater at the initial stage of chewing, and in later stages the differences became smaller with less muscle activity required. Stronger gels required more chewing effort to achieve the initial size reduction. In these model foods, changes and differences in jaw movement along the sequence was not as prominent as muscle activities. This could be explained by model foods not exhibiting notable levels of adhesive and cohesive properties. Textural properties such as cohesiveness and adhesiveness would be sensitive to chewing and mixing with saliva and therefore recognized more in the later stages of mastication.

Relationships between mastication parameters and fracture properties were also investigated for the initial, middle and last phase of the chewing sequence (Table 7). In the initial phase, fracture stress was related to durations and jaw movements. Fracture modulus in the initial phase was only found to be associated with durations. As seen in the whole sequence, correlations between occlusal duration and fracture energy, and correlations between muscle activities and fracture stress and stress intensity factor were significant. In the middle section of the chewing sequence, mastication parameters were more associated with stress intensity factor. Jaw movements in the middle and last sections showed good

correlations with fracture modulus. The relation between occlusal duration and fracture strain and fracture energy improved in the middle and last phases. From this analysis, we can suggest different fracture properties may play roles at different stages of the chewing process. Changes in mastication parameters were more associated with fracture stress in first chews, whereas stress intensity factor seemed to be more related to the parameters in following cycles of the oral processing. The effect of fracture properties on jaw movements was less apparent in these model foods, although fracture modulus seemed to be the parameter affecting the jaw movements.

4. Discussion

Fisher ratios obtained from statistical analysis were higher for temporalis and masseter muscles than digastric muscle; indicating gel texture has a larger effect on the activity of temporalis and masseter. This is logical as the temporalis and masseter are involved in jaw closing, while the digastric causes jaw opening. In chewing, food particles are fractured in the closing phase of the cycle, and movements are slow in this phase (Agrawal et al., 1998); consequently, the activities of jaw elevators could be more indicative of food texture and mechanical breakdown. These model foods did not have adhesive properties and therefore adhesion between upper and lower teeth was not a part of the opening effort after chewing. Thus, changing gel strength and deformability did not affect the activity of digastric muscle to a large extent. The minor increase in digastric muscle activity with increased level of hardness could be related to higher amplitude of vertical movement to process stronger model foods. There was a slight decrease in digastrics activity in response to increased level

of deformability, which can also be related to a decrease in vertical amplitude for samples with increased deformability.

The velocity of opening and closing movements increased with increased hardness. During chewing of stronger gels, an increase in three dimensional movements was accompanied with increased opening and closing velocities, thus mean cycle duration did not change and was maintained between 637 and 650 ms. The jaw continued its rhythmic movement. Similarly, when gels with higher deformability were chewed, vertical and lateral excursions decreased along with velocities. The overall cycle duration was maintained between 591 and 604 ms without a significant change. Alteration of opening and closing movements to maintain cycle duration is also seen when bolus size is increased (Bhatka et al., 2004).

The effect of gel strength or food hardness (maximum stress or force at a given level of compression) on chewing was previously investigated by other researchers. An increase in masseter activity and muscle contraction duration was reported with increased hardness of artificial foods (Shiau et al., 1999). Hard gum requires greater masseter activity compared to soft gum; and three dimensional movements and velocities increase with hardness so that cycle duration does not change with hardness (Anderson et al., 2002; Plesh et al., 1986). Changes in muscle activity with increased hardness of agar gels in this investigation are in agreement with increased hardness in a gelatin-based model food (Peyron et al., 2002; Foster et al., 2006). Mioche and Peyron (1995) found good correlation between bite force and hardness of elastic, plastic and brittle materials (silicone elastomers, waxes, and pharmaceutical tablets). A perfect linear relation between yield stress and number of cycles

before swallowing has also been reported (Engelen et al., 2005). Engelen et al. (2005) showed that oral physiology parameters (saliva, masticatory performance) explained less than 10% of variation in swallowing threshold and concluded that the dominant factor was physical properties of food such as hardness, dryness.

In addition to food hardness (strength), $\sqrt{R/E}$ parameter, involving toughness/fracture energy and Young's modulus, can be important as the physical property used as sensory feedback for the modulation of the central pattern generator (Agrawal et al., 1998). Criterion of $\sqrt{R/E}$ for food fragmentation (change in the square root of the specific surface area of the food particles), has been applied for most of the foods. However, if the food particles are very thin, R will be the only factor. In the case of high fracture force requirements (hard foods), $\sqrt{RE}$ is the food property controls breakdown properties (Lucas et al., 2002). For model foods in our study, $\sqrt{R/E}$ did not show significant relationship with muscle activity. Fracture surface energy (R) and $\sqrt{RE}$ showed a significant relation with muscle activity for the model foods, indicating that model foods can be stress limiting (requires high fracture forces) based on the classification of Agrawal et al. (2000). Making a strong conclusion at this point may not be possible since the sample number was limited compared to their study.

5. Conclusions

Fracture properties of model foods caused significant modifications of muscle activities and jaw movements during mastication. The jaw continued its consistent rhythmic movement by

adjusting the mastication parameters, as well as modifying some parameters based on sensory feedback from each chew. Physiological adaptation to the decrease in particle size and food breakdown was observed. Increase in fracture stress resulted in higher muscle activities, jaw movements and velocities, while fracture strain (deformability) caused increase in muscle activities but a slight decrease in jaw movements. Adaptation to increased level of strain was less prominent compared to changes with increased fracture stress. Data sets of models foods were combined and relations between fracture properties and oral processing parameters were investigated. When considered as a whole, stress intensity factor, fracture strain and fracture modulus were the most descriptive parameters. However, when viewed by phases, different parameters were more important at different stages. Model foods used in this study provided a wide range of changes in mechanical properties that resulted in altered oral processing. Combining this information with sensory analysis of model foods is the subject of our subsequent paper.

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References

Agrawal, K. R., Lucas, P. W., Prinz, J. F., & Bruce, I. C. (1997). Mechanical properties of foods responsible for resisting food breakdown in the human mouth. *Archives of Oral Biology*, 42, 1–9.

Agrawal, K. R., Lucas, P. W., Bruce, J. C., & Prinz, J. F. (1998). Food properties that influence neuromuscular activity during human mastication. *Journal of Dental Research.* 77, 1931- 1938.

Agrawal, K. R., Lucas, P. W., & Bruce, J. C. (2000). The effects of food fragmentation index on mandibular closing angle in human mastication. *Archives of Oral Biology,* 45, 577-584.

Anderson, T. L. (1995). F*racture mechanics: fundamentals and applications*, 2nd edn. CRS, New York.

Anderson, K., Throckmorton, G.S., & Buschang, P. H. (2002). The effects of bolus hardness on masticatory kinematics. *Journal of Oral Rehabilitation,* 29, 689-696.

Barrangou, L. M., Daubert, C. R., & Foegeding, E. A. (2006). Textural properties of agarose gels. I. Rheological and fracture properties. *Food Hydrocolloids,* 20, 184-195.

Bhatka, R., Throckmorton, G. S., Wintergerst, A. M., Hutchins, B., & Buschang, P. H. (2004). Bolus size and unilateral chewing cycle kinematics. *Archives of Oral Biology,* 49, 559-566.

Brown, W. E., Langley, K. R., & Macfie, H. J. H. (1994a). Characterization of patterns of chewing behavior in human subjects and their influence on texture perception. *Journal of Texture Studies, 25,* 455–468.

Brown, W. E., Shearn, M., & Macfie, H. J. H. (1994b). Method to investigate differences in chewing behavior in humans: II. Use of electromyography during chewing to assess chewing behavior. *Journal of Texture Studies,* 25*,* 17-31.

Brown, W. E., Eves, D., Ellison, M., & Braxton, D. (1998). Use of combined electromyography and kinesthesiology during mastication to chart the oral breakdown of foodstuffs: relevance to measurement of food texture. *Journal of Texture Studies,* 29, 145–167.

Buschang, P.H., Throckmorton, G. S., &Travers, K. H. (1997). The effects of bolus size and chewing rate on masticatory performance with artificial test foods. *Journal of Oral Rehabilitation,* 24*,* 522-526.

Chen, Y. Liao, M. L., Boger, D.V., & Dunstan, D. E. (2001). Rheological characterisation of κ-carrageenan/locust bean gum mixtures. *Carbohydrate Polymers,* 46, 117-124.

Chen, J. (2009). Food oral processing – A review. Food Hydrocollids, 23*,* 1-25.

Diehl, K. C., & Hamann, D. D. (1979). Relationships between sensory profile parameters and fundamental mechanical parameters for raw potatoes, melons and apples. *Journal of Texture Studies*, 10, 401-420.

Edlund, J., & Lamm, C.J. (1980). Masticatory efficiency. *Journal of Oral Rehabilitation,* 7, 123–130.

Engelen, L., Fontijn-Tekamp, A., & van der Bilt, A. (2005). The influence of product and oral characteristics on swallowing. *Archives of Oral Biology*, 50, 739-746.

Essick, G., & Trulsson, M. (2008). Tactile sensation in oral region. In: *Encyclopedia of Neuroscience*, L.R.Squire (Ed.), 3999-4005, Springler-Verlag, Maryland Heights, MO.

Foegeding, E.A. (2007). Rheology and sensory texture of biopolymer gels. *Current Opinion in Colloid and Interface Science*. 12, 242–250.

Fontijn-Tekamp, F.A., van der Bilt , A., Abbink, J.H., & Bosman, F. (2004). Swallowing threshold and masticatory performance in dentate adults. *Physiology & Behavior,* 83, 431-436.

Foster, K.D., Woda, A., and Peyron, M.A. (2006). Effect of texture of plastic and elastic model foods on the parameters of mastication. *Journal of Neurophysiology,* 95*,* 3469-3479.

Gonzalez, R., Sifre, S., Benedito, J., & Nogues, V. (2002). Comparison of electromyographic pattern of sensory experts and untrained subjects during chewing of Mahon cheese. *Journal of Dairy Research,* 69, 151-161.

Hamann, D. D., Zhang, J., Daubert, C. R., Foegeding, E. A., & Diehl, K. C. (2006). Analysis of compression, tension and torsion for testing food gel fracture properties. *Journal of Texture Studies,* 37, 620–639.

Huttchings, J. B., & Lillford, P. J. (1988). The perception of food texture – The philosophy of the breakdown path. *Journal of Texture Studies,*19, 103-115.

Hylander, W. L., & Johnson, K. R. (1993). Modelling relative masseter force from surface electromyograms during mastication in non-human primates. *Archives of Oral Biology*, 38, 233-240.

Kohyama, K., Ohtsubo, K., & Toyoshima, H. (1998). Electromyographic study on cooked rice with different amylose contents. *Journal of Texture Studies,* 29*,* 101-113.

Lanier, T.C. (1986). Functional properties of surimi. *Food Technology,* 40,107-114,124.

Lassauzay, C., Peyron, M. A., Albuisson, E., Dransfield, E., & Woda, A. (2000). Variability of the masticatory process during chewing of elastic model foods*. European Journal of Oral Sciences,* 108, 484-492.

Lavigne, G., Kim, J. S., Valiquette, C., & Lund, J. P. (1987). Evidence That Periodontal Pressoreceptors Provide Positive Feedback to Jaw Closing Muscles During Mastication. *Journal of Neurophysiology,* 58, 342-358.

Lucas, P.W., Prinz, J. F., Agrawal, K. R., & Bruce, I. C. (2002). Food physics and oral physiology. *Food Quality and Preference,*13*,* 203-213.

Lund, J. P. (1976). Evidence for a central neural pattern generator regulating the chewing cycle. In: *Mastication*. Anderson D.J., Matthews B. (Eds.) Bristol Wright, 204-212.

Meullenet, J.-F.C., Finney, M. L., & Gaud, M. (2002). Measurement of biting velocities, and pre-determined and individual crosshead speed instrumental imitative tests for predicting cheese hardness. *Journal of Texture Studies,* 33, 45–58.

Mioche, L., Bourdiol, P., Martin, J. F., & Noel, Y. (1999). Variations in human masseter and temporalis muscle activity related to food texture during free and side imposed mastication. *Archives of Oral Biology*, 44, 1005-1012.

Mioche, L., & Martin, J-F. (1998). Training and sensory judgment effects on mastication as studied by electromyography. *Journal of Food Science* 63, 1-5.

Mioche, L., & Peyron, M. A. (1995). Bite force displayed during assessment of hardness in various texture contexts. *Archives of Oral Biology,* 40, 415-423.

Olthoff, L.W., van der Bilt, A., Bosman, F., & Kleizen, H.H. (1984). Distribution of particle sizes in food comminuted by human mastication. *Archives of Oral Biology,* 29, 899-903.

Peyron, M.A., Mioche, L, Renon, P., & Abouelkaram, S. (1996). Masticatory jaw movement recordings: A new method to investigate food texture. *Food Quality and Prefererence,* 7, 229-237.

Peyron, M.A., Lassauzay, C., & Woda, A. (2002). Effects of increased hardness on jaw movement and muscle activity during chewing of visco-elastic model foods. *Experimental Brain Research,* 142, 41-51.

Plesh, O., Bishop, B., & Mccall, W. (1986). Effect of gum hardness on chewing pattern. *Experimental Neurology,* 92*,* 502-512.

Rey, A., Gonzalez, R., Martínez-Da-Juan, J.L., Benedito, J., & Mulet, A. (2007). EMG assessment of chewing behaviour for food evaluation: Influence of personality characteristics. *Food Quality and Prefererence,*18, 585-595.

Sakamoto, H., Harada, T., & Matsukubo, T. (1989). Electromyographic Measurement of textural changes of foodstuffs during chewing. *Agricultural and Biological Chemistry,*53, 2421 -2433.

Shiau, Y.Y., Peng, C.C., & Hsu, C.W. (1999). Evalaution of biting performance with standardized test-foods. *Journal of Oral Rehabilitation,* 26, 447-452.

Slagter, A.P., Hilbert, W., van der Glas, H.W., Bosman, F., H.W., & Olthoff, L.W. (1992). Force-deformation properties of artifical and natural foods for testing chewing efficency. *The Journal of Prosthetic Dentistry,* 68, 790-799.

Sloan, A.E. (2011). Top 10 food trends. *Food Technology,* 65, 24-41.

Truong, V.D., & Daubert, C.R. (2000). Comparative study of large strain methods for assessing failure characteristics of selected food gels. *Journal of Texture Studies,* 31, 335–353.

van der Bilt, A. (2002). Human oral function: a review. *Brazalian Journal of Oral Science,* 1*,* 7-18.

van der Bilt, A., Weijnen, F.G., Ottenhoff, F.A., van der Glas, H.W., & Bosman, F. (1995). The role of sensory information in the control of rhythmic open-close movements in humans. *Journal of Dental Research,* 74,1658-1664.

van der Bilt, A., van der Glas, H.W., Olthoff, L.W., & Bosman, F. (1991). The effect of particle size reduction on the jaw gape in human mastication. *Journal of Dental Research,* 70, 931 937.

Vinyard, C. V., Wall, C. E., Williams, S. H., & Hylander, W. L. (2008). Patterns of variation across primates in jaw-muscle electromyography during mastication. *Integrative and Comparative Biology*, 48, 294–311.

Woda, A., Foster, K., Mishellany, A., & Peyron, M.A. (2006). Adaptation of healthy mastication to factors pertaining to the individual or to the food. *Physiology & Behavior,* 89*,* 28–35.

Table 1. Mastication parameters extracted from oral processing analysis and their definitions.

Parameter	Definition
n_chews	Number of chews from placement into mouth until last swallow
t_chews (s)	Total duration of the chewing sequence
Frequency (n_chews/s)	Number of cycle/seconds
Cycle Duration (ms)	Time required for a single cycle of mandible. Includes opening, closing and occlusal phases.
Opening Duration (ms)	Time required for opening phase of cycle
Closing Duration (ms)	Time required for closing phase of cycle.
Occlusal Duration (ms)	Time required for occlusal phase of cycle.
Vertical amplitude (mm) (VertAmp)	The total inferior movement of mandible during jaw opening for a chewing cycle
Lateral amplitude(mm) (LatAmp)	The total mediolateral movement of mandible during jaw a chewing cycle
Anterior/posterior amplitude (mm) (A/PAmp)	The total anterior and posterior excursion of the jaw during a chewing cycle.
Maximum working side movement (Max WS)	Value of the maximum movement of jaw toward the working side during the chewing cycle. This value is dependent on if the cycle is left or right-side chew.
Opening velocity (mm/s) (OpenVel)	Average jaw opening speed. Calculated as VertAmp divided by time from start of opening to maximum jaw opening
Closing velocity (mm/s) (CloseVel)	Average jaw closing speed. Calculated as VertAmp divided by time from maximum jaw opening to beginning of occlusal phase
wk	Total muscle activity: integrated area under the curve describing the rms EMG versus time relationship for the entire chewing sequence.
wkAT, wkM and wkAD	Total muscle activity calculated separately for right (R) and left (L) AT, M and AD muscles and also for their total (R+L)
wk/chew	Mean muscle activity per chew: the total muscle work values divided by the number of chew in the sequence to adjust differences in number of chews

Table 2. Correlation coefficients between rheological parameters

	Fracture Stress (kPa)	Fracture Strain	Stress Intensity ($Pa.m^{1/2}$)	Fracture Energy ($J.m^2$)	Fracture Modulus (kPa)	Young's Modulus (kPa)
F. Stress	1.00*	0.00	0.87*	0.08	0.87*	0.86*
F. Strain		1.00*	0.44	0.95*	-0.47	-0.46
S. Intensity			1.00*	0.55	0.57	0.59
F. Energy				1.00*	-0.34	-0.30
F. Modulus					1.00*	0.99*
Y. Modulus						1.00*

*Correlation coefficients are significant at $P < 0.05$

Table 3. Minimum and maximum mean values obtained from all subjects while 3% (w/w) agar gels were chewed

3%(w/w) Agar	Min	Max
n-chews	14	85
t-chews (s)	10	51
Frequency (#cycle/s)	1.2	1.9
Cycle Duration(ms)	513	827
Opening Duration (ms)	177	271
Closing Duration (ms)	188	366
Occlusal Duration (ms)	57	235
OpenVel (mm/s)	47	72
CloseVel (mm/s)	35	64
VertAmp (mm)	10	17
A/PAmp (mm)	2	6
LatAmp (mm)	3	6
Max WS (mm)	3	5

Table 4. Effects of increased fracture stress of agar gels on mastication parameters. Mean values for the treatments and standard error (SE) are presented together with the results of ANOVA and Tukey mean separation test ($p<0.05$). Different letters in the same row showed that treatments were different effects on parameters. Mean values were calculated from the data of 14 subjects chewing 3 replicates of each treatment in a single session (n= 42 for each level of hardness).

	Samples			Statistical Parameters		
	1A	**3A**	**5A**	**SE**	**F ratio**	**p values**
Durations						
n-chews	16^{c}	31^{b}	38^{a}	3.86	36.35	<.0001
t-chews (s)	10^{c}	19^{b}	24^{a}	2.28	38.37	<.0001
Frequency(#cycle/s)	1.6	1.6	1.6	0.06	2.84	0.0769
Cycle Duration(ms)	637	636	650	25.25	2.36	0.1142
Opening Duration(ms)	232^{a}	221^{b}	223^{ab}	10.48	4.17	0.0269
Closing Duration(ms)	268	271	278	16.02	2.09	0.1434
Occlusal Duration(ms)	137^{b}	144^{ab}	149^{a}	15.26	3.20	0.0573
JT parameters						
OpenVel (mm/s)	56^{b}	63^{a}	65^{a}	1.84	41.45	<.0001
CloseVel (mm/s)	49^{b}	52^{a}	53^{a}	2.23	14.42	0.0001
VertAmp (mm)	13^{c}	14^{b}	15^{a}	0.50	24.06	<.0001
A/PAmp (mm)	3.1^{b}	3.3^{b}	3.6^{a}	0.38	7.58	0.0026
LatAmp (mm)	4.3^{b}	4.6^{ab}	4.9^{a}	0.28	9.21	0.0009
Max WS (mm)	3.4^{b}	3.8^{a}	4.0^{a}	0.23	10.70	0.0004
EMG parameters						
TA Peak(μV)	0.5^{c}	0.8^{b}	1.0^{a}	0.08	54.40	<.0001
MM Peak	0.5^{c}	0.8^{b}	0.9^{a}	0.07	74.68	<.0001
DA Peak	0.7^{b}	0.7^{b}	0.8^{a}	0.05	13.97	0.0001
wkAT	8^{c}	22^{b}	34^{a}	3.08	72.92	<.0001
wkM	8^{c}	22^{b}	32^{a}	2.87	85.65	<.0001
wkAD	10^{c}	21^{b}	28^{a}	2.90	42.92	<.0001
wkTotal	26^{c}	65^{b}	94^{a}	7.87	83.23	<.0001
wk/chewTotal	1.6^{c}	2.1^{b}	2.5^{a}	0.15	72.61	<.0001

Table 5. Effects of increased deformability of κ-carrageenan–locust bean gum gels on mastication parameters. Mean values for the treatments and standard error (SE) are presented together with the results of ANOVA and Tukey mean separation test. Different letters in the same row showed that treatments were different effects on parameters. Mean values were calculated from the data of 14 subjects chewing 3 replicates of each treatment in a single session (n= 42 for each level of hardness).

Mastication parameters	Samples			Statistical Parameters		
	C:LB(1.0)	**C:LB(3.1)**	**C:LB(1.1)**	**SE**	**F ratio**	**p values**
Durations						
n-chews	29^{c}	34^{b}	37^{a}	3.36	37.28	<.0001
t-chews (s)	17^{c}	20^{b}	22^{a}	1.95	43.84	<.0001
frequency(#cyc/t)	1.7	1.7	1.7	0.06	2.34	0.1163
Cycle Duration(ms)	591	604	597	20.08	1.66	0.2094
Opening Duration(ms)	212^{a}	210^{a}	200^{b}	9.70	6.50	0.0051
Closing Duration (ms)	244	244	237	15.42	1.73	0.1963
Occlusal Duration(ms)	136^{c}	150^{b}	161^{a}	14.35	23.70	<.0001
JT parameters						
OpenVel(mm/s)	62	62	63	2.21	1.41	0.2628
CloseVel (mm/s)	54	53	54	2.53	0.72	0.4969
VertAmp (mm)	13.2^{a}	12.9^{ab}	12.6^{b}	0.47	5.31	0.0117
A/PAmp (mm)	3.5	3.5	3.5	0.42	0.01	0.9945
LatAmp (mm)	4.3^{a}	4.2^{ab}	4.0^{b}	0.24	5.82	0.0082
MaxWS (mm)	3.6^{a}	3.5^{ab}	3.3^{b}	0.21	8.01	0.0019
EMG parameters						
TA Peak(μV)	0.7^{c}	0.9^{b}	1.0^{a}	0.08	72.28	<.0001
MM Peak	0.7^{c}	0.9^{b}	1.0^{a}	0.07	51.94	<.0001
DA Peak	0.8	0.8	0.8	0.03	0.03	0.9748
wkAT	21^{c}	30^{b}	36^{a}	3.97	69.51	<.0001
wkM	22^{c}	31^{b}	37^{a}	3.78	87.14	<.0001
wkAD	23^{b}	27^{a}	29^{a}	3.28	21.63	<.0001
wkTotal	66^{c}	89^{b}	102^{a}	10.23	75.30	<.0001
wk/chewTotal	2.3^{c}	2.6^{b}	2.8^{a}	0.12	61.52	<.0001

Table 6. Significant correlation coefficients between rheological and mastication parameters ($p<0.05$)

Attributes	Fracture Stress	Fracture Strain	Stress Intensity	Fracture Energy	Fracture modulus
Durations					
n-chews	0.84		0.91		
t-chews (s)	0.91		0.93		
Cycle Duration(ms)					
Opening Duration		-0.88			
Closing Duration		-0.81			
Occlusal Duration		0.83	0.83	0.90	
JT parameters					
OpenVel(mm/s)	-0.85				
CloseVel					
VertAmp					0.95
A/PAmp					
LatAmp					0.94
MaxWS					0.96
EMG parameters					
wk/chewAT			0.90		
wk/chewM			0.81		
wk/chewAD					
wk/chewTotal			0.81		
TA Peak(μV)	0.82		0.98		
MM Peak			0.93		
DA Peak	0.81				
wkAT	0.81		0.93		
wkM			0.89		
wkAD			0.84		
wkTotal			0.84		

Table 7. Significant correlation coefficients between rheological and mastication parameters of different phases

Attributes	Fracture Stress	Fracture Strain	Stress Intensity Factor	Fracture Energy	Fracture Modulus
			INITIAL PHASE		
Cycle D.	0.92				0.96
Opening D.	0.92				0.97
Closing D.	0.88				0.97
Occlusal				0.84	
OpenVel					
VertAmp	0.93			0.92	
A/PAmp	0.90				
LatAmp	0.82				
TA Peak	0.91		0.90		
M Peak	0.86		0.85		
DA Peak	0.85				
wkAT	0.86		0.90		
wkM			0.85		
			MIDDLE PHASE		
Cycle D.					
Opening D.		-0.88			
Closing D.		-0.82			
Occlusal		0.80	0.87	0.85	
OpenVel	-0.91		-0.83		
VertAmp					0.94
A/PAmp	0.86		0.84		
LatAmp		-0.84			0.87
TA Peak	0.85		0.99		
M Peak			0.95		
DA Peak					
wkAT			0.93		
wkM			0.83		
			LAST PHASE		
Cycle D.					
Opening D.					
Closing D.		-0.83			
Occlusal		0.92		0.90	
OpenVel					
VertAmp					0.94
A/PAmp					
LatAmp					0.82
TA Peak			0.94		
M Peak			0.90		
DA Peak	0.90		0.83		
wkAT		0.83			
wkM		0.85			

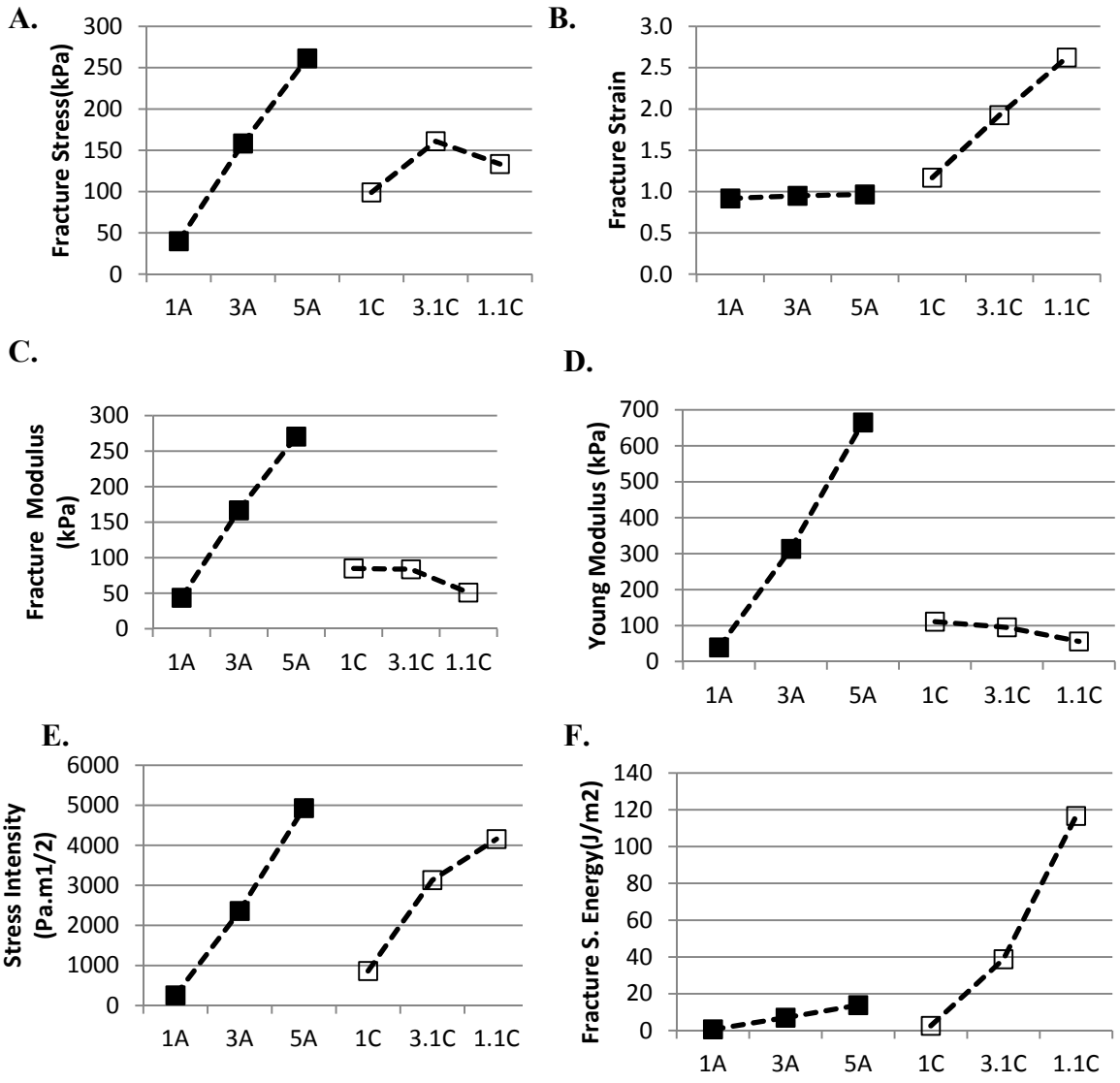


Figure 1. Fracture properties of agar (1A, 3A, 5A) and κ-carrageenan- locust bean gum gels (1C, 3.1C, 1.1C). Each data point is the average of eight samples.

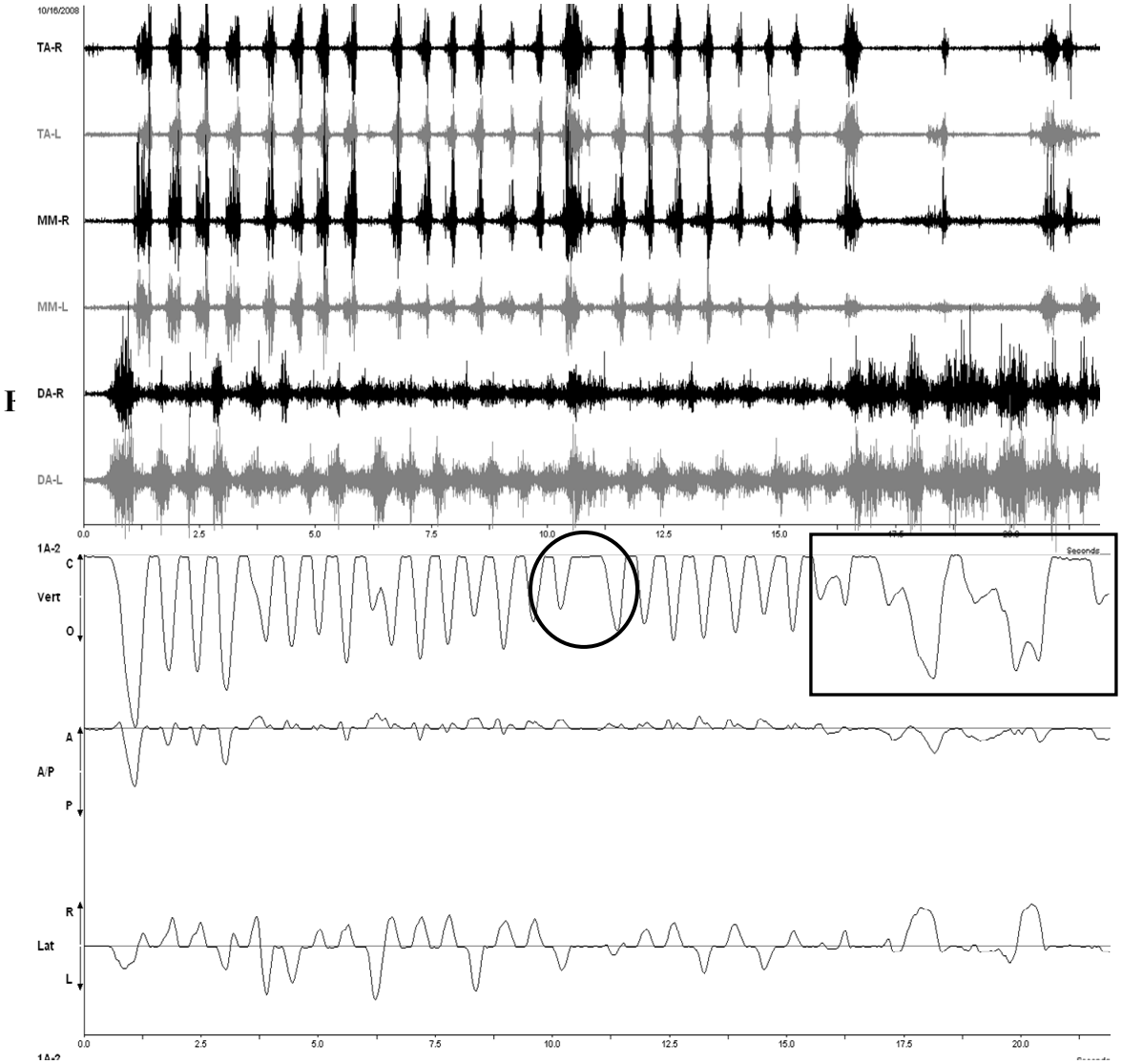


Figure 2. Example of a chewing sequence showing changes through the sequence. Interpose swallow (in circle), and clearance and swallowing section (in rectangle) C:Close, O:Open, A:Anterior, P:Posterior, R:right, L:left

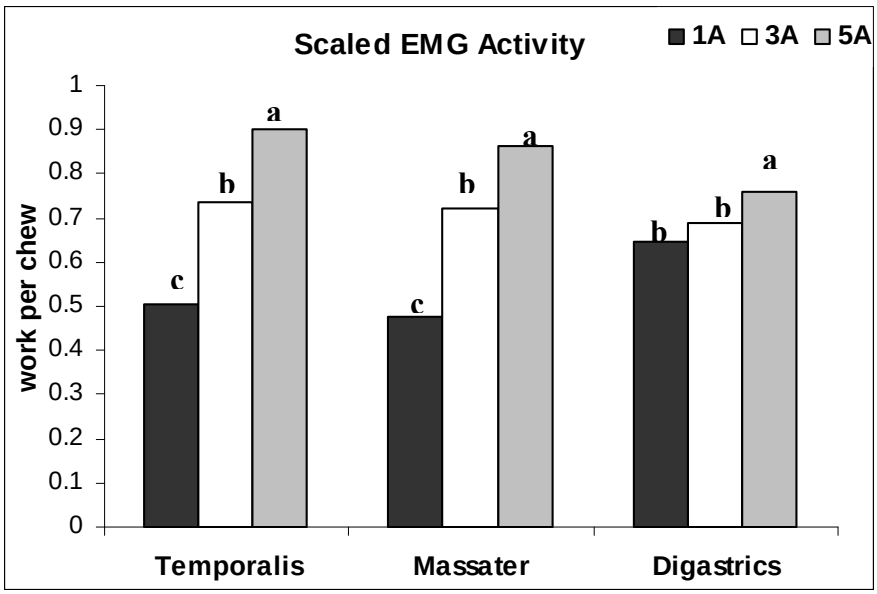


Figure 3. Mean values obtained for muscle activities for agar gels.

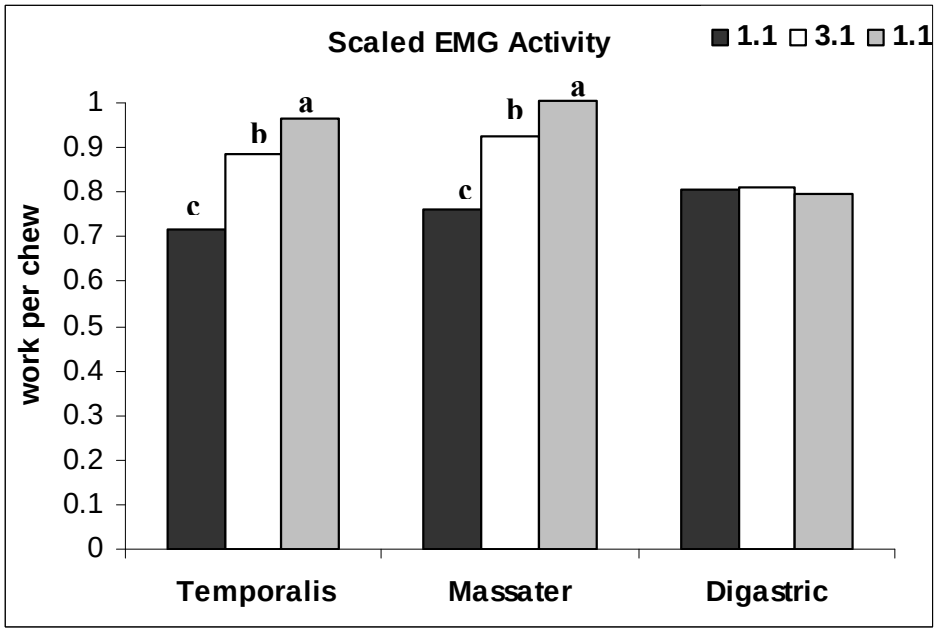
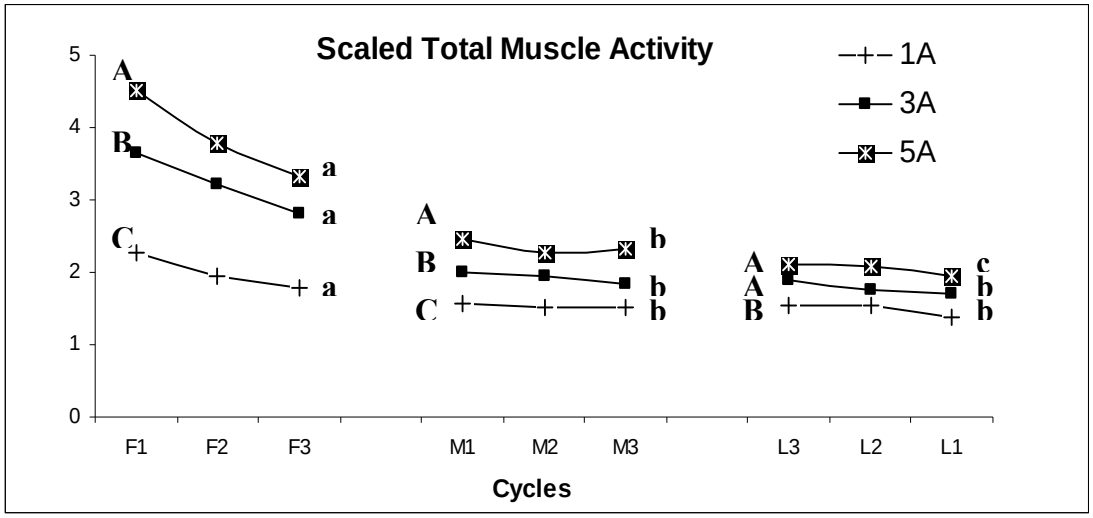


Figure 4. Mean values obtained for muscle activities for κ-carrageenan-locust bean gum gels

A.



B.

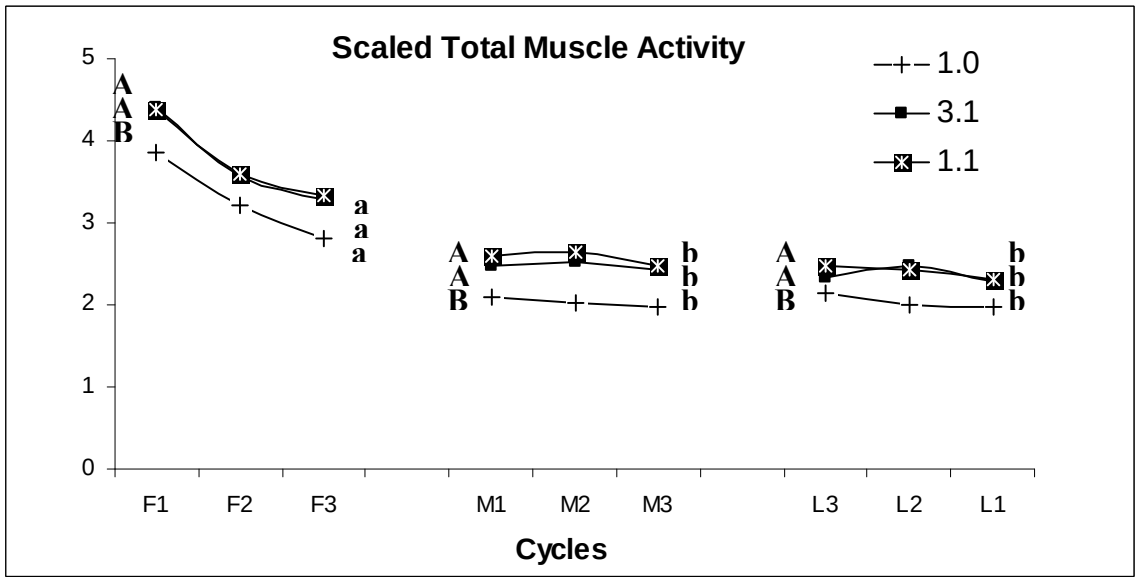
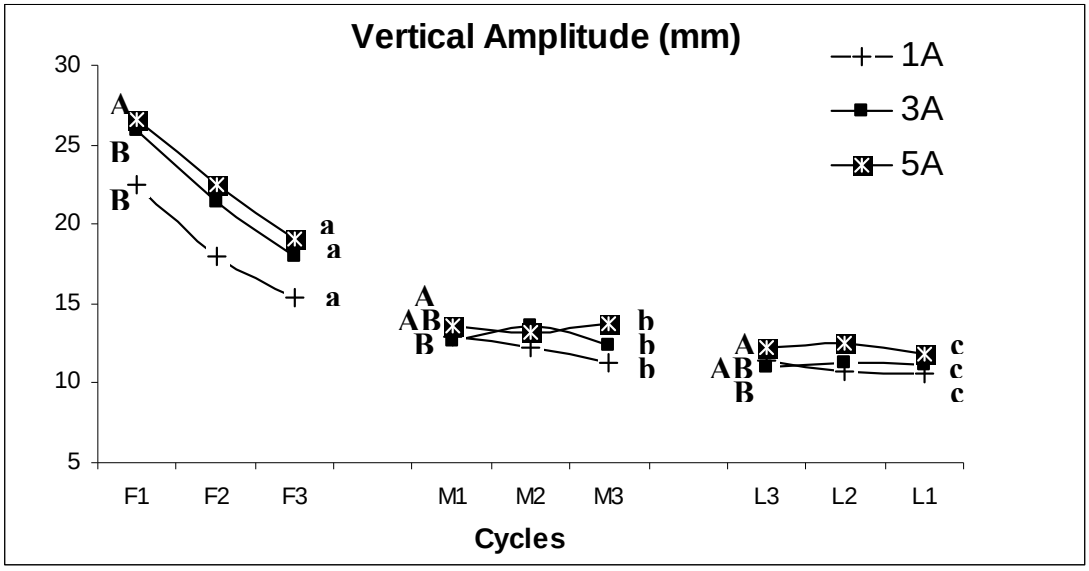


Figure 5. Changes in muscle activities along the chewing sequence. (A) agar gels (B) κ-carrageenan-locust bean gum gels. Mean values for 14 subjects and 3 replicates were used**.** Changes along the sequence were represented with first 3 cycles (F1-F3), middle 3 (M1-M3) and last 3 cycles (L1-L3) of the sequence. Upper case letters indicates differences among different level of treatments, while lower case letters show differences among first, middle, and last sections of same hardness.

A.



B.

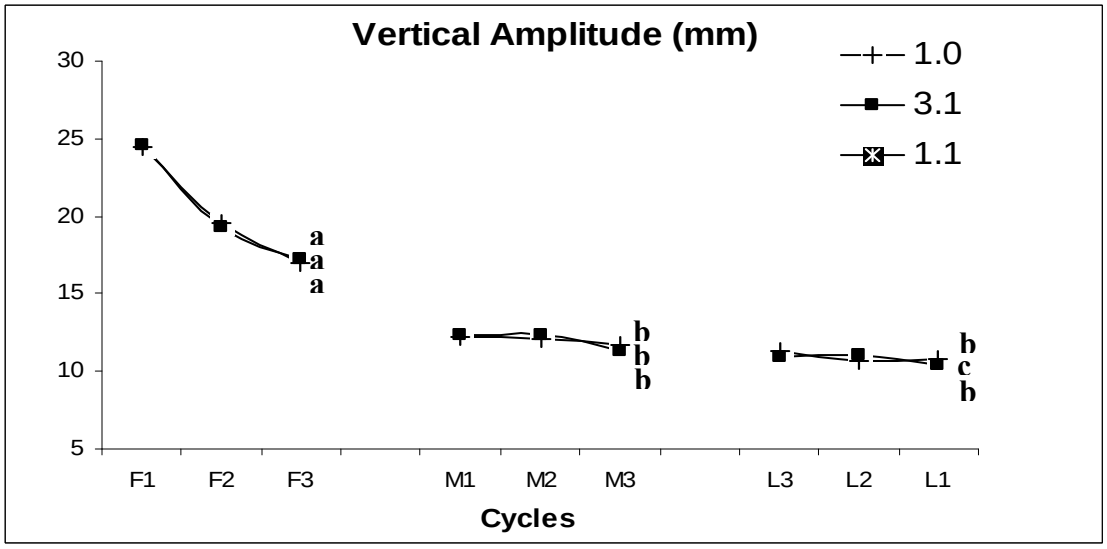


Figure 6. Changes in vertical movements along the chewing sequence. (A) agar gels (B) κ-carrageenan-locust bean gum gels. Mean values for 14 subjects and 3 replicates were used**.** Changes along the sequence were represented with first 3 cycles (F1-F3), middle 3 (M1-M3) and last 3 cycles (L1-L3) of the sequence. Upper case letters indicates differences among different level of treatments, while lower case letters show differences among first, middle, and last sections of same hardness.

CHAPTER 3

Sensory Texture of Model Foods Based on Large Deformation Rheological Properties and Oral Processing

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Abstract

The texture of model foods with increased hardness (agar gels) or increased deformability (κ-carrageenan-locust bean gum gels) was characterized by descriptive sensory analysis and explained based on previously determined gel mechanical properties and oral processing parameters. Tongue-palate compression, first chew, mastication and residual sensory attributes of model foods were evaluated. Model foods were differentiated ($p<0.05$) based on hardness, deformability, size of breakdown particles, rate of breakdown, particle mouthcoating and total number of chews. Significant correlation was obtained between: 1) sensory hardness and fracture stress ($r = 0.92$, $p<0.05$), 2) sensory deformability (hand) and fracture strain ($r = 0.94$), particle mouthcoating and fracture strain ($r = -0.93$) and 3) compressibility and fracture modulus ($r = -0.98$). Among oral processing parameters, muscles activities and number of chewing cycles were closely related to sensory hardness and duration of occlusion to deformability. Harder foods required more chewing cycles and greater muscle activity in preparation for swallowing. This was associated with a decreased rate of breakdown during mastication evaluated by descriptive analysis. Changes in sensory attributes resulted in modification of jaw movement amplitudes. Analysis of the relations of sensory, rheology and oral processing parameters suggests that fracture stress/stress intensity factor, hardness and muscle activities are closely associated. Moreover, fracture strain, deformability and occlusal durations exhibit strong correlations. Particle mouthcoating is related to fracture strain and jaw movements. Hardness, fracture stress or stress intensity factor are the best indicators of number of chews required to process a food material for swallowing and also affect the rate of breakdown and size of the particles. The results show

that sensory textural properties of model foods are adequately reconciled taking into consideration food mechanical properties and alterations in oral processing.

Keywords: hardness, deformability, gel texture, mastication, EMG, JT

1. Introduction

Texture is an important sensory attribute related to food structure and contributes to the quality and acceptability of foods. Sensory perception of texture is a complex and dynamic process which involves continuous changes in food structure with the applied force and lubrication during mastication (Hutchings and Lillford, 1988). Descriptive sensory analysis is used to provide a human assessment of texture. Trained individuals identify and quantify specific textural attributes (Foegeding and Drake, 2007), starting with those associated with surface properties and first chew, followed by properties sensed during chewing and ending with residual sensations after swallowing. There is a long-standing desire to determine which mechanical properties of foods are involved in sensory perception of texture (Blair, 1958). Towards that end, large-strain testing, deforming the material to an extent which causes damage or fracture, has been used to examine food texture (van Vliet and Walstra, 1995; Diehl and Hamann, 1980; Montejano et al., 1985). However, instrumental techniques designed to determine large-strain and fracture properties do not account for factors such as oral motion, rates of force application and effects of temperature and saliva (van Vliet, 2002; Meullenet et al., 2002).

The way humans perceive textural properties and how mastication functions can be related to mechanical parameters responsible for texture perception is not fully understood (Meullenet et al., 2002; Chen, 2009). For a complete understanding of food texture, a comprehensive approach should be used which combines characterization of the physical and chemical properties of the food, sensory perception and oral processing (Foegeding, 2007). Oral processing, which considers all the physiological processes in first bite, mastication and swallowing, is an important step in texture assessment (Peyron et al., 1996). During chewing, food undergoes structural transformations related to food structure and changes in sensory perception modulate oral processing (Gambareli et al., 2007). Textural characteristics of food influence mastication parameters such as muscle force and mandibular jaw movements, along with the duration and number of mastication cycles. These mastication parameters have been investigated via electromyography (EMG) and movements of the jaw in three dimensions (electrognathography).

Oral processing of a range of foods and the effect of mechanical properties on the mastication process has been studied (Agrawal et al., 1998; Foster et al., 2006). Mechanical hardness, toughness and Young's modulus are some of the food properties that appear to cause modulation of oral processing parameters. However, there are few studies that have investigated the interrelationships among food structure (as reflected in mechanical properties), oral processing and a complete characterization of sensory texture. Some sensory attributes, such as hardness are perceived in the initial phase of the chewing process, while others are perceived at latter stages. For example, in evaluating biscuit texture, the chewing effort in the first 5 chews is related to hardness while crunchiness is more explained

by the chewing effort in the subsequent 5 chews (Brown et al., 1998). Sensory tenderness of meat is perceived not only during the first chew but also during subsequent chews (Mioche and Martin, 1998). Increased sensory hardness of gelatin gels is associated with increased mastication time, muscle activity, and vertical amplitude of jaw movement (Peyron et al., 2002). In most of these studies, perception of one or two sensory properties has been examined in relation to oral processing. A complete description of texture and the understanding of the perception of different sensory attributes with oral processing across a wide range of textures have been limited.

In the preceding manuscript (Koc et al., 2012), model foods varying in strength (fracture stress) or deformability (fracture strain) were developed. Increasing agar concentration in the presence of glycerol produced agar gels with varied levels of fracture stress at constant strain and combinations of κ-carrageenan and locust bean gums at different ratios produced gels with different levels of fracture strain at similar fracture stress. These model foods also varied in other mechanical properties. Fracture and Young's modulus of agar gels showed 3-10 fold increase with concentration, while they were decreased slightly in κ-carrageenan-locust bean gels. Stress intensity factor increased similarly for both model foods, while fracture energy was much higher for more deformable κ-carrageenan-locust bean gum network, but increased in both gels. Jaw movement maintained a rhythmic movement while adjusting other parameters to changes in textural properties. Muscle activities increased with fracture stress and stress intensity factor. Fracture strain related to duration of occlusion. Jaw movements scaled with fracture modulus. The goal of this study

was to use the same model foods to understand how sensory perception of texture is related to fundamental fracture properties and oral processing parameters.

2. Materials and Methods

2.1. Materials

Food grade agar powder (TIC Gums, Belcamp, MD), glycerol (Protector Gamble Chemicals, New Milford, CT), κ-carrageenan (GenuGel® CHP-2, CP Kelco, Denmark), locust bean gum (Genu®Gum RL-200Z, CP Kelco, Atlanta, GA), crystalline potassium chloride (KCl) (Fisher Scientific, Fair Lawn, NJ), strawberry flavor and Dulce De Leche flavor (Mother's Murphy, Greensboro, NC). Mineral analysis of κ-carrageenan and locust bean gum powders were done by inductively coupled plasma spectroscopy; κ-carrageenan has P (24.81 mg/kg), Ca (569.10 mg/kg), K (16.93 %w/w), Mg (1220.44 mg/kg), Na (4978 mg/kg), S (5.77 mg/kg). Locust bean gum has P (165.12 mg/kg), Ca (420.61 mg/kg), K (0.18 %w/w), Mg (63.27 mg/kg), Na (921 mg/kg), S (0.16 mg/kg).

2.2. Sample Preparation

Following Koc et al. (2012), agar gels were prepared at three different concentrations (1, 3 and 5% w/w) containing 60% glycerol and 0.2% (w/w) artificial Dulce De Leche flavor. Briefly, a solution of water, glycerol and agar powder was mixed at 250 rpm for 30 min and followed by heat treatment in microwave for one minute and in water bath at 85 ^{o}C for 30 min. After cooling 2 h at room temperature (22 ± 2 ^{o}C), samples were stored at 4 ± 2 ^{o}C for 16-24 h for gelling. κ-carrageenan(C) and locust bean gum (LB) gels containing 10%

sucrose were prepared at varying ratios of 1:0, 3:1 and 1:1(C-LB (w/w)) with 0.2% (w/w) strawberry flavor in 0.02M KCl solution. The gel solution was mixed for 15 min and held in a water bath at 90 ^{o}C for 15 min. Solution was subsequently boiled and then held in a water bath at 90 ^{o}C for 30 min. Samples were gelled at room temperature (22 ± 2 ^{o}C) for 16-24 h and then stored at 4 ± 2 ^{o}C until testing. The gels were equilibrated at room temperature (22 ± 2 ^{o}C) 2 h prior to testing and were cut into 15 mm long and 19 mm diameter cylinders for the analyses.

2.3. Large Deformation Rheological Tests

Fracture properties of agar gels and κ-carrageenan-locust bean gum gels were determined by uniaxial compression and torsional fracture, respectively, following Koc et al. (2012). Agar gels (22 ± 2 °C) were compressed to 20% of the original height at a constant cross-head speed of 50 mm/min using a universal testing machine (Instron Model 5565 Instron Engineering Corp., Canton, MA, U.S.A.) equipped with a 5 kN load cell. Capstan shaped κ-carrageenan-locust bean gum gels were mounted vertically in a Haake VT550 Viscometer (Paramrus, NJ) and twisted to failure at a rotational speed of 4.5 rpm (Diehl, 1979). Fracture stress, fracture strain, and fracture modulus (fracture stress/ fracture strain) were reported from these analyses. Stress intensity factor and fracture surface energy of the gels were obtained from center crack tension test (Koc et al., 2012). Samples (5x18x120 mm) with a 9-mm-wide notch in the middle were glued to tension measurement fixtures attached to an Instron 5540 universal testing machine (Inston Engineering Corporation, Canton, MA)

equipped with a 50-N load cell. Tests were conducted at a constant speed of 10 mm/min at room temperature (22 ± 2 °C).

2.3. Masticatory Recordings and Data Analysis

Muscular activity and three dimensional jaw movements of fourteen subjects (8 female, 6 male, 18-35 years old, mean 25) were recorded simultaneously while subjects were chewing the agar and κ-carrageenan-locust bean gum gels following Cakir et al. (2011). Electromyographic activities of masseter (M), anterior temporalis (AT) and anterior digastric (AD) muscles were measured by surface electrodes (BioFLEX, BioRESEARCH Assoc., Inc., Milwaukee, WI) while a ground electrode on the subjects' neck minimized electrical background noise. Three dimensional movements of the mandible (anterior-posterior, vertical, lateral) were recorded within an electromagnetic field by a small magnet attached to the lower frontal incisors. In addition to muscle activities and jaw movements, durations of opening, closing, occlusion phase, closing and opening velocities, number of chews were obtained.

2.4. Descriptive Sensory Analysis

Descriptive sensory analysis with a highly trained (>500 hr experience on food texture) panel was used to describe sensory texture of model foods. The panel consisted of 7 women ranging in age from 45 to 60. Textural attributes previously established for protein and polysaccharide gels (Gwartney et al., 2004; Barrangou et al., 2006) were evaluated by the panel using the Spectrum method (Table 1). A 15-point reference scale was used for the

analysis and two gel samples (a whey protein gel and an agar gel with attributes previously defined by panelists) were presented as references. Samples were cut into cylinders 19 mm diameter and 15 mm long and served at room temperature in 2 oz. plastic cups marked with 3-digit random numbers. Panelists expectorated gels after evaluation and rinsed the mouth with water between samples. Sample assessments were conducted in triplicate. Initial, tongue-palate compression, first chew, mastication and residual sensory attributes were evaluated (Table 1).

2.5. Statistical Analysis

Sensory and mechanical tests results were analyzed by Proc GLM for treatment effects. Tukey test were conducted for mean separation at $\alpha = 0.05$ significance levels. Analysis of variance on oral processing data was conducted with Proc Mixed of SAS (version 9.2, SAS, Cary, NC) by treating treatment as a fixed effect and subjects and subject treatment interaction as random effects. The relations between rheology, sensory and mastication parameters were studied by correlation coefficients (Proc CORR, SAS).

3. Results

3.1. Descriptive Sensory Analysis

Mean values of sensory attributes of model foods are presented in Table 2. Some of the attributes are also shown in Figure 1a-b to emphasize the main attributes differentiating model foods.

Initial and tongue-palate compression:

All gels had a similar level of surface smoothness, so the initial textural impression was the same among all treatments (Table 2). Likewise, there was not difference in springiness. Gels with the lowest concentration of agar were compressible between the tongue and hard palate to some extent, but gels with higher concentrations of agar could not be compressed to fracture. κ-Carrageenan-locust bean gels had a detectable but low level of compressibility. The high springiness values (14.6 to 15.0), all gels showing essentially 100% recovery, and low compressibility indicate a gel stiffness that is around the upper limit of tongue-palate sensing (Table 2).

First chew:

Hardness of agar gels increased with increasing polymer concentration, as reported previously on different gel networks (Gwartney et al., 2004; Munoz et al., 1986), while deformability at first chew and by hand were generally similar among agar gels (Fig. 1a). Hardness was very sensitive to agar concentration, covering 67% of the 15-point scale (1.7 to 11.7) (Table 2). Agar gels exhibited some moisture release at first chew. Although gels had low amounts of moisture released, there was a significantly higher amount released in the 1% agar gels. In the first chew sensory evaluation of κ-carrageenan-locust bean gum gels, differences in hardness, moisture release and deformability were perceived, with κ-carrageenan gels being different than κ-carrageenan-locust bean gum gels. Deformability (first chew and hand) generally increased as locust bean gum content increased. Evaluation of deformability properties of gels with fingers was more discriminating than the evaluation in the mouth (Fig. 1b). Both mouth and hand evaluation of texture has been showed to be

appropriate in texture determination of foods such as cheese (Drake et al., 1999) and agar gels (Barrangou et al., 2006).

Mastication:

There was not a noteworthy level of adhesiveness or cohesiveness perceived during chewing of agar gels. All gels were broken down into uniform particles. As the concentration of agar increased, it was broken down into larger particles at a slower rate, thus requiring an increased number of chewing cycles (Fig. 1a). Moisture release of agar gels during mastication decreased with increased concentration of agar. As with the agar gels, κ-carrageenan-locust gels exhibited very low adhesiveness and cohesiveness. The gel with a 1:1 ratio of polymers was perceived more cohesive than the others, albeit at a low overall level. The size of particles increased and the rate of breakdown decreased significantly with the addition of locust bean gum. Gels with locust bean gum required more chews to prepare the sample for swallowing. There was slight moisture release in the first chew and during chewing; however moisture release was generally the same among κ-carrageenan gels.

Residual:

After sample expectoration, some degree of particle and moisture mouthcoating was perceived for both model foods. There were no differences among agar gels, particle mouthcoating of κ-carrageenan gels decreased slightly with the increased ratio of locust bean gum.

Overall, main differences in sensory properties of model foods were obtained in first chew and mastication parameters, with minimal effects on *initial*, *tongue-palate compression* and *residual* terms. There were significant correlations among sensory attributes (Table 3).

When the hardness of gels increased, they were broken down to larger particles (r = 0.97) and the rate of breakdown (r = -0.98) was slower. The number of chews required to prepare the samples for swallowing was highly correlated with hardness (r = 1), moisture release (r = -0.99), particle size (r = 0.98) and rate of breakdown (r = -0.98). This relationship obtained between hardness and number of chews has also been established by Barrangou et al. (2006) on agar/glycerol gels. Moreover, study by Meullenet et al. (1998) on various types of 21 food samples also indicated a good relation between sensory hardness and chewiness (total amount of work required to prepare sample for swallowing) as r = 0.77. It can be concluded that sensory hardness evaluated after the first chew can predict number of cycles required to process these model foods before swallowing. There was also a significant negative correlation between particle mouthcoating and hand deformability (r = -0.97). This most likely reflects the brittle nature of agar gels, resulting in more particles after a "shattering" type of fracture. Another significant correlation was obtained between particles size and rate of breakdown (r = -0.99). As a result of fast breakdown, smaller particles are formed.

3.2. Sensory Texture Related to Large Deformation Rheological Properties

Fracture properties (stress, strain, modulus, stress intensity factor, surface energy) and Young's modulus of the gels are presented in Table 4 (data from Koc et al., 2012). Increasing the concentration of agar in the presence of glycerol resulted in gels with increased fracture stress and constant fracture strain. Change in fracture stress at constant strain resulted in a gradual increase in fracture modulus from 44 to 271 kPa. κ-Carrageenan-locust bean gum gels had varying fracture strain levels and fracture stresses were kept in the

100-160 kPa range. Fracture modulus of these model foods did not vary to a great extent (51-85 kPa). Stress intensity factors for both model foods were in similar range and showed an increase with greater agar concentration or the addition of locust bean gum. Model foods also had increased fracture surface energy values, however highly deformable gels required much greater energies for formation of new surfaces during crack propagation. Fracture surface energy was calculated based on a linear elastic fracture behavior assumption. During the extension of the deformable κ-carrageenan-locust bean gum gels, some degree of necking was observed. Thus, high fracture surface energy obtained may include energy spent for plastic deformation in addition to that creating new surface area. Changes in Young's modulus showed a similar pattern to fracture modulus. Correlations among sensory attributes and fracture properties are presented in Table 5. Gels with high fracture or Young's modulus were less compressible between the tongue and hard palate before fracture ($r = -0.99$ and $r = -0.94$, $p<0.05$). Hardness was strongly correlated to fracture stress and stress intensity factor ($r = 0.91$, 0.92, respectively); as expected because both properties reflect the general strength of the gels. Approximately a six fold increase in fracture stress resulted in change of perceived hardness from 2 to 12 in a-15 point scale. Deformability, via hand or first chew, was correlated to fracture strain and fracture surface energy ($r = 0.80$, 0.94, respectively). High correlations were also obtained between sensory firmness (hardness) and fracture stress of different foods (Gwartney et al., 2004; Wium et al., 1997; Cakir et al., 2011). Fracture strain of protein gels (Montejano et al., 1985) was reported to correlate with sensory cohesiveness; defined as the "degree to which sample deforms before it ruptures". This definition is the same as the way "deformability" was defined in our study.

Thus, the relationship between fracture strain and deformability is in agreement with the previous work on protein gels. Moisture release in the first chew and during mastication had negative correlations with fracture properties. Increased fracture stress was significantly negatively correlated ($r = -0.98$) with moisture release. This is a coincidental correlation (mainly seen in agar gels) as fracture stress does not directly determine how moisture is held in gels. Gels with greater material strengths (i.e., fracture stress and stress intensity factor) had larger particles during mastication and a slower rate of breakdown. Thus, more chews were made before swallowing. Gels with high fracture strain exhibited less particle mouthcoating ($r = -0.93$), which supports the relationship obtained between deformability and mouthcoating of sensory attributes. This negative relationship between particle mouthcoating and fracture strain ($r = -0.81$) has been also observed with mixed whey protein-carregeenan gels having different microstructures (Cakir et al., 2011).

3.3. Sensory Texture in Relation to Oral Processing

Oral processing results of agar and κ-carrageenan-locust bean gum gels reported previously (Koc et al., 2012) was used to determine relationships between sensory attributes and oral processing parameters. The number of chewing cycles and time for a chewing sequence increased for agar gels and κ-carreegenan-locust bean gum gels (Fig. 2a) with changes in sensory properties mainly at first chew. Frequency of chewing was not affected by changes in hardness or deformability (Fig. 2b). Muscle activities of the main masticatory muscles increased for both model foods; with jaw closing muscles (temporalis and masseter) showing

greater differences than the opening muscle (digastrics) (Fig. 3). Jaw movement patterns were altered differently for agar and κ-carrageenan-locust bean gum gels (Fig. 4).

Correlations among sensory attributes and mastication parameters for a complete chewing sequence are given in Tables 6-8. Hardness was positively correlated with the number of chewing cycles and muscle activities. This shows that hardness is associated with extra masticatory effort required for oral processing. Foster et al. (2006) also reported that most of the mastication parameters increased with sensory hardness on gelatin based model systems. Longer occlusal durations were obtained for more deformable gels ($r = 0.93$). Among mastication attributes, particle size and number of chews were positively correlated to temporalis muscle peak value and temporalis muscle activity for whole sequence, while moisture release and rate breakdown were negatively correlated. When the gels became softer, less time was required for a chewing cycle, less jaw movements were observed and there was a decrease in muscle activity. Particle mouthcoating attribute was positively related to vertical and lateral jaw movements. When model foods exhibited more particle mouthcoating, greater jaw movements were required to manipulate the particles. Mastication frequency did not adapt to changes in hardness or deformability (Fig. 2)

In the previous study (Koc et al., 2012), differences in correlations between mechanical properties and oral processing were observed when oral processing was separated into stages. In similar way, different phases of sensory evaluation were compared with corresponding phases of oral processing. Tables 6-8 shows correlations (reported in parenthesis) of initial, first compression and first bite sensory terms with the first 3 chews (initial phase), mastication attributes with middle 3 chews and residual terms with last three

chews. Considering the first three chews alone generally increased the correlations among mastication parameters and hardness. Brown et al. (1998) also found a relationship between hardness and chewing effort for the first 5 chews. Deformability was correlated with occlusal duration as stated previously. On the other hand, sensory deformability showed better correlation when whole chewing sequence data was used. When mastication sensory attributes were compared to the middle phase of oral processing, correlation between temporalis muscle peak and particle size and rate of breakdown improved slightly. Smoothness of pieces was also negatively related to vertical and lateral movements. Residual attribute particle mouthcoating showed good relation with jaw movements of last cycles of chewing sequence, however better correlations with jaw movements were observed when compared with mean values for the whole sequence. A strong relation between residual attributes and jaw movements in the last cycles of chewing sequence for mixed whey protein / κ-carrageenan gels has also been observed (Cakir et al., 2011).

4. Discussion

Descriptive texture attributes established in previous studies to evaluate texture of cheese and model protein and polysaccharide gels were used to describe the texture of model polysaccharide gels with different levels of strength and deformability. Evaluating the deformability term was relatively new to this panel; and thus, it was evaluated at first chew and by hand. Gel deformability detected with fingers was more discriminating than evaluation at first chew, although both attributes were defined as the level of deformation before fracture. The difference can be due to the differences in sensivity or surface

properties of molars and fingers. However, sensory attributes of cheese such as firmness, adhesiveness when evaluated by hand or mouth shows strong correlations (Drake et al., 1999). Deformability can be a difficult attribute to evaluate by panel.

Sensory terms hardness and firmness have been used interchangeably in sensory studies with the same definition "force required to fracture the sample with molars". Properties associated with material strength (e.g., fracture stress and stress intensity factor) logically were correlated with first chew hardness but also dictate the number of chews required to chew model foods. Harder gels were broken in larger pieces and decreased in size at slower rates, thus the number of chews was greater. Having model foods with minimal adhesive and cohesive properties demonstrated that these attributes were not complicated by other oral processes (i.e., removal of food particles adhering to the teeth).

Fracture stress is the best indicator of oral and non-oral firmness of cheeses (Wium et al., 1997) among the mechanical parameters of fracture stress, Young's modulus, and work for fracture. In agar gels (Barrangou et al., 2006), hand fracture force is more related to fracture modulus than fracture stress; suggesting a coupling of stress and strain in the perception of force to evaluate hardness. Similarly, fracture modulus correlated better with firmness of mixed whey protein/ κ-carrageenan gels (Cakir et al., 2011); although fracture stress, critical stress intensity factor and fracture surface energy also showed also good correlations. Although our study did not show that fracture mechanics terms (stress intensity factor and surface energy) explained more than fracture stress and strain, their importance in the predicting hardness and crunchiness of hard/brittle solids such as fruits and vegetables (Vincent et al., 2002) and biscuits (Kim et al., 2011) have been demonstrated.

Changes in some sensory texture attributes coincide with modifications in oral processing. Association between hardness and muscle activities are well established (Foster et al., 2006) and our findings support the general trends. It was also shown that deformability was related to occlusal duration. Model foods with high deformability required more energy to be broken into pieces which may explain the increase in occlusal durations. Oral processing and sensory texture terms were compared on coinciding temporal scales. Comparing mean mastication parameters for overall sequence and also initial, middle, and last phases with sensory attributes gave similar results, although phase to phase comparison improved some of the correlations. Residual particle and moisture mouthcoating were showed to be related to magnitude of jaw movements. Since these attributes are evaluated after the sample is expectorated, it suggests a coupling between movement for mouth clearance and residual material.

5. Conclusions

A comprehensive texture study of agar and κ-carrageenan-locust bean gum gels were reported by combining descriptive sensory analysis, oral processing and rheology/fracture mechanics. Increasing fracture stress or strain resulted in increased hardness and deformability, respectively. Both changes in fracture properties caused increased number of chews, larger particles and a slower rate of breakdown. Harder gels were chewed longer and required more muscles activity. More deformable gels resulted in longer occlusal durations. Morever, jaw movements were altered based on the amount of particles that coated oral

surfaces. Sensory attributes and fracture properties showed similar trends and altered oral processing.

References

Agrawal, K. R., Lucas, P. W., Bruce, J. C., & Prinz, J. F. (1998). Food properties that influence neuromuscular activity during human mastication. *Journal of Dental Research,* 77(11), 1931-1938.

Blair, G.W. (1958). Rheology in Food Research. *Advances in Food Research.* 8, 1-61.

Barrangou, L. M., Drake, M. A., Daubert, C. R., & Foegeding, E. A. (2006). Sensory texture related to large-strain rheological properties of agar/glycerol gels as a model food. *Journal of Texture Studies,* 37(3), 241-262.

Brown, W. E., Langley, K. R., & Braxton, D. (1998). Insight into consumers'assessments of biscuit texture based on mastication analysis-hardness versus crunchiness. *Journal of Texture Studies,* 29(5), 481-497.

Chen, J. (2009). Food oral processing—A review. *Food Hydrocolloids,* 23(1), 1-25.

Cakir, E., Koc, H., Daubert, C., Drake, M., Essick, G., Vinyard, C., & Foegeding, E.A. (2011). Evaluation of texture changes due to compositional differences using oral processing. *Journal of Texture Studies.*

Çakır, E., Daubert, C. R., Drake, M. A., Vinyard, C. J., Essick, G., & Foegeding, E. A. (2012). The effect of microstructure on the sensory perception and textural characteristics of whey protein/κ-carrageenan mixed gels. *Food Hydrocolloids,* 26(1), 33-43.

Diehl, K. C., & Hamann, D. D. (1980). Relationships between sensory profile parameters and fundamental mechanical parameters for raw potatoes, melons and apples. *Journal of Texture Studies*, 10 (4), 401-420.

Drake, M. A., Gerard, P. D., & Civille, G. V. (1999). Ability of hand evaluation versus mouth evaluation to differentiate texture of cheese. *Journal of Sensory Studies*, 14(4), 425-441.

Foegeding, E. A., & Drake, M. A. (2007). Invited Review: Sensory and Mechanical Properties of Cheese Texture. *Journal of Dairy Science*, 90(4), 1611-1624.

Foegeding, E.A. (2007). Rheology and sensory texture of biopolymer gels. *Current Opinion in Colloid & Interface Science*, 12(4–5), 242-250.

Foster, K. D., Woda, A., & Peyron, M. A. (2006). Effect of texture of plastic and elastic model foods on the parameters of mastication. *Journal of Neurophysiology,* 95(6), 3469-3479.

Gambareli, F. R., Sera, M.D., Pereira, L.J., & Gavio, M.B.D. (2007). Influence of measurement technique, test food, teeth and muscle force interactions in masticatory performance. *Journal of Texture Studies,* 38(1), 2-20.

Gwartney, E. A., Larick, D. K., & Foegeding. E. A. (2004). Sensory texture and mechanical properties of stranded and particulate whey protein emulsion gels. *Journal of Food Science,* 69(9), 333-339.

Hutchings, J. B., & Lillford, P. J. (1988). The perception of food texture - the philosophy of the breakdown path. *Journal of Texture Studies,* 19(2), 103-115.

Kim, E. H-J., Corrigan, V., Waters, I., Wilson, A., Hedderley, D., & Morgenstern, M.P. (2011). Fundamental fracture properties associated with sensory hardness of brittle solid foods. *Journal of Texture Studies.*

Koc, H., Cakir, E., Daubert, C., Drake, M., Essick, G., Vinyard, C., Osborne, J., & Foegeding, E.A. (2012). Alteration of oral processing with increased fracture stress and fracture strain of model foods (to be submitted to *Journal of Texture Studies*).

Meullenet, J. F., Finney, M.L., & Gaud, M. (2002). Measurement of biting velocities, and predetermined and individual crosshead speed instrumental imitative tests for predicting cheese hardness. *Journal of Texture Studies,* 33(1), 45-58.

Meullenet, J. F, Lyon, B.G., Carpenter, J. A., & Lyon, C. E. (1998). Relationship between sensory and instrumental texture profile attributes. *Journal of Sensory Studies,* 13(1), 77-93.

Mioche, L., & Martin, J. F. (1998). Training and sensory judgment effects on mastication as studied by electromyography. *Journal of Food Science,* 63(1), 1-5.

Montejano, J. G., Hamann, D. D., & Lanier, T. C. (1985). Comparison of two instrumental methods with sensory texture of protein gels. *Journal of Texture Studies,* 16(4), 403-424.

Munoz, A.M., Pangborn, R.M., & Noble A.C. (1986) Sensory and mechanical attributes of gel texture. 1. Effect of gelatin concentration. *Journal of Texture Studies,* 17(1), 1-16.

Peyron, M.A., Mioche, L, Renon, P., & Abouelkaram, S. (1996). Masticatory jaw movement recordings: a new method to investigate food texture. *Food Quality and Preference,* 7(3-4), 229-237.

Peyron, M. A., Lassauzay, C., & Woda, A. (2002). Effects of increased hardness on jaw movement and muscle activity during chewing of visco-elastic model foods. *Experimental Brain Research,* 142(1), 41-51.

van Vliet, T., & Walstra, P. (1995). Large deformation and fracture behaviour of gels. *Faraday Discussions*, 101(0), 359-370.

van Vliet, T. (2002). On the relation between texture perception and fundamental mechanical parameters for liquids and time dependent solids. *Food Quality and Preference,*13(4), 227-236.

Vincent, J. F. V., Saunders, D. E. J., & Beyts, P. (2002). The use of critical stress intensity factor to quantify hardness and crunchiness objectively. *Journal of Texture Studies,* 33(2), 149-159.

Wium, H., Qvist, K. B., & Gross, M. (1997). Uniaxial compression of UF-feta cheese related to sensory texture analysis. *Journal of Texture Studies,* 28 (4), 455-476.

Table 1. Evaluation techniques and definitions of sensory texture attributes

Initial	**Technique:** Move gel in mouth without chewing
Smoothness	Degree to which sample perceived as smooth when evaluated with tongue
Tongue-Palate Compression	**Technique:** Compress the sample between the tongue and hard palate
Springiness	Degree to which the sample returns to the original shape after partial compression between the tongue and hard palate
Compressibility	Degree to which the sample deforms or compresses before fracture using the tongue and hard palate
First Chew	**Technique:** Bite completely through with the molars
Hardness	Force required to fracture the sample with the molars
Fracturability	Degree to which the sample fractures into pieces on the first bite with the molars
Moisture release	Extent to which moisture is released from the sample during the 1st bite with the molars
Deformability	The degree to which the sample deforms or compresses before fracture
Mastication	**Technique:** Chew 5-8 times and evaluate
Particle size	Size of breakdown particles (small to large)
Particle size dist.	Degree of homogeneity in the particle distribution size distribution
Cohesiveness	Degree to which the sample mass stays together as chewing progresses
Adhesiveness	Degree to which the mass or pieces stick to any mouth surfaces
Smoothness of pcs	Degree to which the mass or particles feel smooth
Chalkiness	Degree to which fine chalk-like particles are perceived
Moisture release	Degree to which moisture is released during mastication
Rate of breakdown	Rate at which the sample breaks into breakdown smaller and smaller particles (slow to fast)
# chews	Number of chews required to prepare the sample for swallowing when chewing at a rate of 1 chew per second
Residual	**Technique:** Expectorate the sample and evaluate
Particle mouthcoat	Amount of particles remaining in the mouth after expectoration
Moisture mouthc.	Amount of moisture remaining in the mouth after expectoration
Other	
Deformability (hand)	The deformation % of sample at fracture by pressing the sample between thumb and first two fingers until sample fractures

Table 2. Mean values of sensory texture attributes of agar gels and κ-carrageenan-locustbean gum gels. (Samples with the same letter within a row are not significantly different, $p<0.05$).

Attributes	1A	3A	5A	1.0	3.1	1.1
Initial						
Smoothness	14.8a	14.8a	15.0a	15.0a	15.0a	15.0a
Tongue-Palate Compression						
Springiness	14.9a	14.8a	15.0a	15.0a	14.6a	15.0a
Compressibility	3.9a	NA*	NA	2.9bc	2.7c	3.6ab
First Chew						
Hardness	1.7e	9.8b	11.7a	4.0d	8.1c	9.1bc
Fracturability	12.9a	12.5a	5.9c	9.3b	9.0b	8.8b
Moisture release	1.8a	1.0c	0.6c	1.7ab	1.1bc	1.2bc
Deformability	1.4c	3.5ab	2.7bc	1.4c	4.0ab	5.0a
Mastication						
Particle size	4.8e	9.5b	10.8a	6.1d	7.4c	8.5bc
Particle size dist.	8.7ab	7.9b	9.2ab	8.0b	8.5ab	9.5a
Cohesiveness	0.5b	0.3b	0.5b	0.3b	0.1b	1.7a
Adhesiveness	0.5a	0.4a	0.4a	0.4a	0.5a	0.5a
Smoothness of pcs	13.2a	12.0bc	11.0c	12.6ab	12.8ab	13.0ab
Moisture release	3.0a	2.0c	1.2d	2.8ab	2.2bc	2.2bc
Rate of breakdown	10.7a	3.4c	2.1d	9.8a	6.4b	5.5b
# chews	16.0c	27.4a	31.5a	18.7bc	25.1ab	26.4a
Residual						
Particle mouthcoat	3.0ab	3.4a	3.6a	3.1ab	2.4bc	2.0c
Moisture mouthc.	1.9a	1.8a	1.3a	2.1a	1.8a	2.0a
Additional						
Deformability (hand)	3.3bc	3.6bc	1c	3.8bc	6.4ab	8.9a

*NA- Not applicable

Table 3. Correlation coefficients among sensory attributes ($p<0.05$)

Attributes	Moisture release (1st chew)	Particle size	Smooth. of pcs	Moisture release (mast.)	Rate of breakdown	Chews	Moisture mouthcoating	Deform-ability (hand)
Tongue-Palate Compression								
Compressibility		0.82	0.92		0.82			
First Chew								
Hardness	-0.97	0.97		-0.95	-0.98	1		
Moisture release		-0.97		0.99	0.97	-0.99		
Mastication								
Particle size			-0.81	-0.96	-0.99	0.98		
Adhesiveness			0.85					
Smoothness of pcs				0.84			0.86	
Chalkiness								
Moisture release					0.96	-0.97	0.83	
Rate of breakdown						-0.98		
Residual								
Particle mouthcoat								-0.97

Table 4. Fracture properties of agar (1A, 3A, 5A) and κ-carrageenan-locust bean gum gels (1C, 3.1C, 1.1C) (data from Koc et al., 2012a). Each data point is the average of minimum eight samples.

Sample	Fracture Stress (kPa)	Fracture Strain	Stress Intensity Factor ($Pa.m^{1/2}$)	Fracture Surface Energy (J/m^2)	Fracture Modulus (kPa)	Young's Modulus (kPa)
1A	40	0.9	253	1	44	39
3A	158	0.9	2359	7	167	313
5A	261	1.0	4929	14	271	665
1C	99	1.2	862	3	85	111
3.1C	161	1.9	3132	39	84	95
1.1C	133	2.6	4156	117	51	56

Table 5. Correlation coefficients between sensory attributes and rheological parameters

Attributes	Fracture Stress	Fracture Strain	Intensity Factor	Fracture Energy	Fracture modulus	Young modulus
Initial						
Smoothness	0.39	0.62	0.51	0.51	0.01	0.01
Tongue-Palate Comp.						
Springiness	0.00	-0.04	0.09	0.16	0.12	0.21
Compressibility	-0.69	0.08	-0.19	0.17	**-0.99***	**-0.94***
First Chew						
Hardness	**0.91***	0.23	**0.92***	0.34	0.71	0.69
Fracturability	-0.75	-0.28	-0.76	-0.29	-0.52	-0.55
Moisture release	**-0.97***	-0.08	**-0.90***	-0.19	**-0.82***	**-0.81***
Deformability	0.38	**0.79***	0.70	**0.82***	-0.03	-0.05
Mastication						
Particle size	**0.92***	0.06	**0.87***	0.21	**0.82***	**0.81***
Particle size dist.	0.27	0.50	0.62	0.66	0.06	0.17
Cohesiveness	-0.07	0.72	0.39	**0.88***	-0.30	-0.23
Adhesiveness	-0.71	0.32	-0.41	0.27	-0.79	-0.76
Smoothness of pcs Chalkiness	**-0.86***	0.47	-0.55	0.33	**-0.99***	**-0.99***
Moisture release	**-0.98***	-0.02	**-0.90***	-0.15	**-0.86***	**-0.86***
Rate of breakdown	**-0.91***	-0.05	**-0.85***	-0.20	-0.79	-0.78
# chews	**0.94***	0.19	**0.93***	0.31	0.75	0.74
Residual						
Particle mouthcoat	0.33	**-0.93***	-0.12	**-0.83***	0.75	0.73
Moisture mouthc.	**-0.82***	0.39	-0.61	0.27	**-0.90***	**-0.92***
Additional						
Deformability (hand)	-0.27	**0.94***	0.16	**0.86***	-0.69	-0.69

*($p<0.05$)

Table 6. Significant correlation coefficients between rheological and mastication parameters averaged over a complete chewing cycle ($p<0.05$). Significant correlation coefficients in parenthesis are between first compression sensory attributes and average mastication parameters for initial phase of chewing (first three cycles) ($p<0.05$)

Attributes	Hardness	Fractr.	Moist. release	Deformability (1st chew)	Deformability (Hand)
Durations					
n-chews	0.90		-0.83		
Cycle Duration(ms)	(0.82)		(-0.91)		
Opening Duration			(-0.83)		-0.82
Closing Duration			(-0.87)		-0.85
Occlusal Duration				0.93(0.85)	
JT parameters					
OpenVel(mm/s)	-0.85				
CloseVel					
VertAmp	(0.87)		(-0.90)		-0.85
A/PAmp	(0.84)	-0.92	(-0.82)		
LatAmp	(0.87)		(-0.84)		
EMG parameters					
wk/chewAT	0.81				
wk/chewM					
wk/chewAD					
wk/chewTotal					
TA Peak(μV)	0.91(0.95)		-0.86(-0.91)		
MM Peak	0.87(0.90)		(-0.84)		
DA Peak		-0.92			
wkAT	0.83(0.89)		(-0.84)		
wkM	(0.81)				
wkAD		-0.81			
wkTotal	0.81(0.81)		- 0.83(-0.83)		

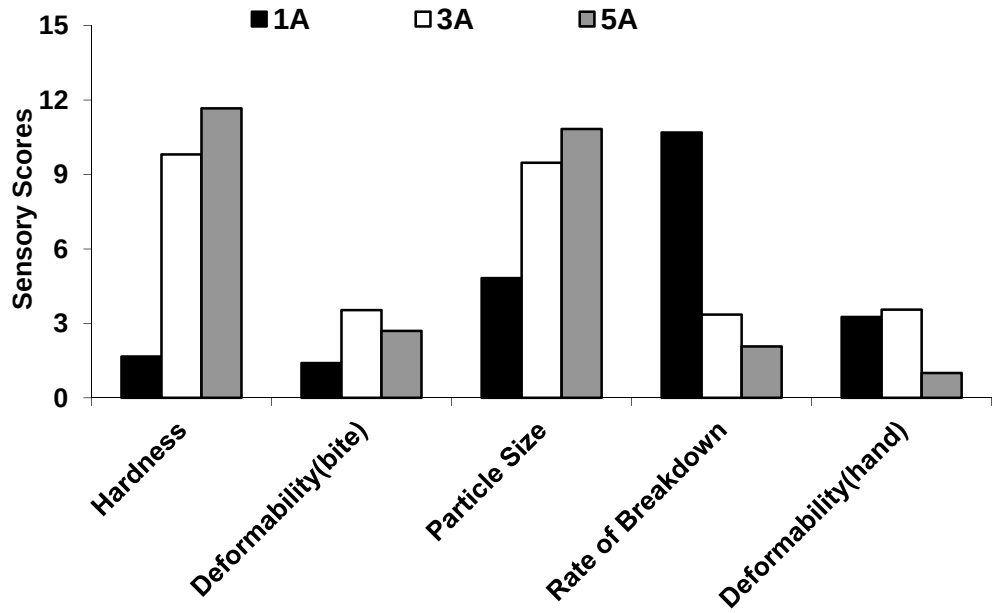
Table 7. Significant correlation coefficients between rheological and mastication parameters averaged over a complete chewing cycle ($p<0.05$). Significant correlation coefficients in parenthesis are between mastication sensory attributes and average mastication parameters for middle phase of chewing (middle three cycles) ($p<0.05$)

Attributes	Particle Size	Adhesive-ness	Smooth ness	Moisture release	Rate of breakdown	Chews
Durations						
n-chews	0.83			-0.81		0.88
Cycle Duration(ms)						
Opening Duration						
Closing Duration						
Occlusal Duration					0.93	
JT parameters						
OpenVel(mm/s)	-0.84	0.81		(0.83)		-0.83
CloseVel						
VertAmp			-0.94(-0.92)			
A/PAmp						
LatAmp			-0.94(-0.86)			
EMG parameters						
wk/chewAT						
wk/chewM						
wk/chewAD						
wk/chewTotal						
TA Peak(μV)	0.85(0.86)			-0.84(-0.87)	-0.82(-0.84)	0.91
MM Peak						0.85
DA Peak			-0.92			
wkAT						0.82
wkM						
wkAD			-0.81			
wkTotal				-0.83		

Table 8. Significant correlation coefficients between rheological and mastication parameters averaged over a complete chewing cycle ($p<0.05$). Significant correlation coefficients in parenthesis are between residual sensory attributes and average mastication parameters for last phase of chewing (last three cycles) ($p<0.05$)

Attributes	Particle Mouthcouting	Moisture Mouthcoating
Durations		
n-chews		
Cycle Duration(ms)		
Opening Duration		
Closing Duration	0.85	
Occlusal Duration		
JT parameters		
OpenVel(mm/s)		
CloseVel		
VertAmp	0.89 (0.81)	-0.85(-0.94)
A/PAmp		
LatAmp	0.92	-0.84 (-0.90)

a.



b.

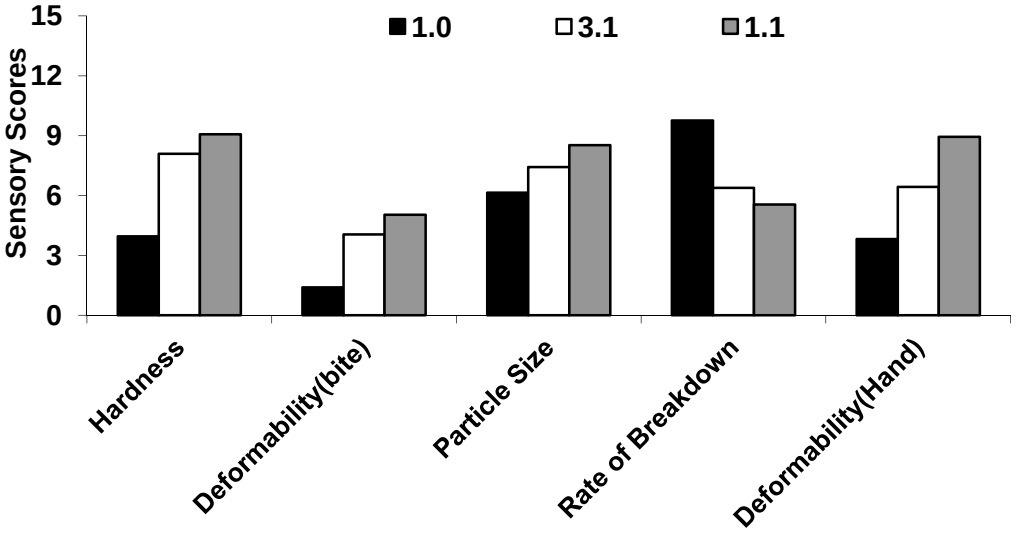
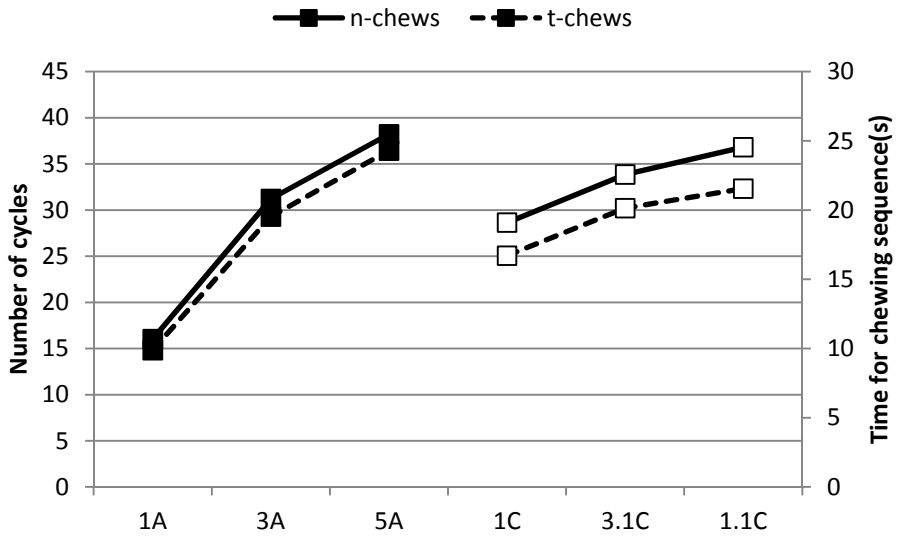


Figure 1. Sensory scores of hardness, deformability, particle size and rate of breakdown for agar gels (a) and κ- carrageenan-locust bean gum gels (b).

a.



b.

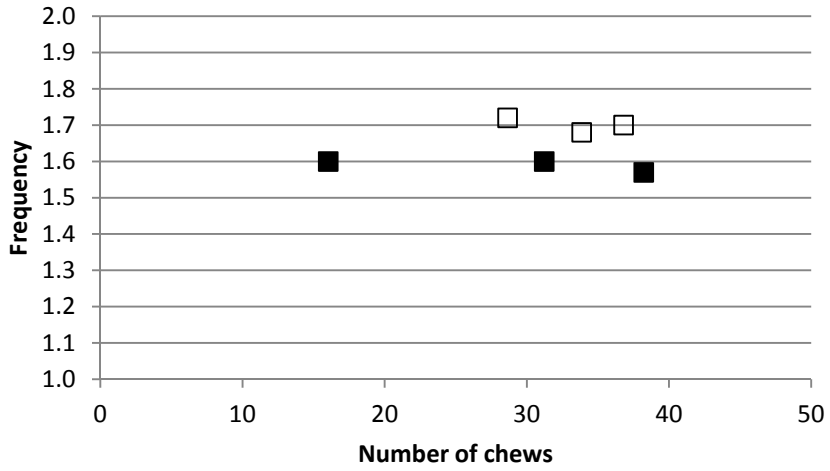
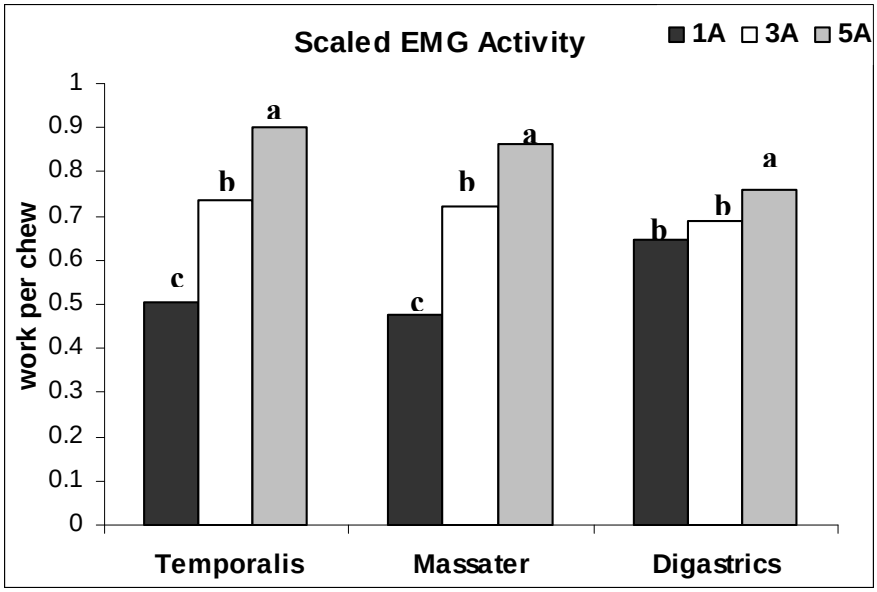


Figure 2. (a)Number of chews and chewing time for agar (filled squares) and κ-carrageenan-locust bean gum gels (unfilled squares) (b) Chewing frequency for agar (filled squares) and κ-carrageenan-locust bean gum gels (unfilled squares).



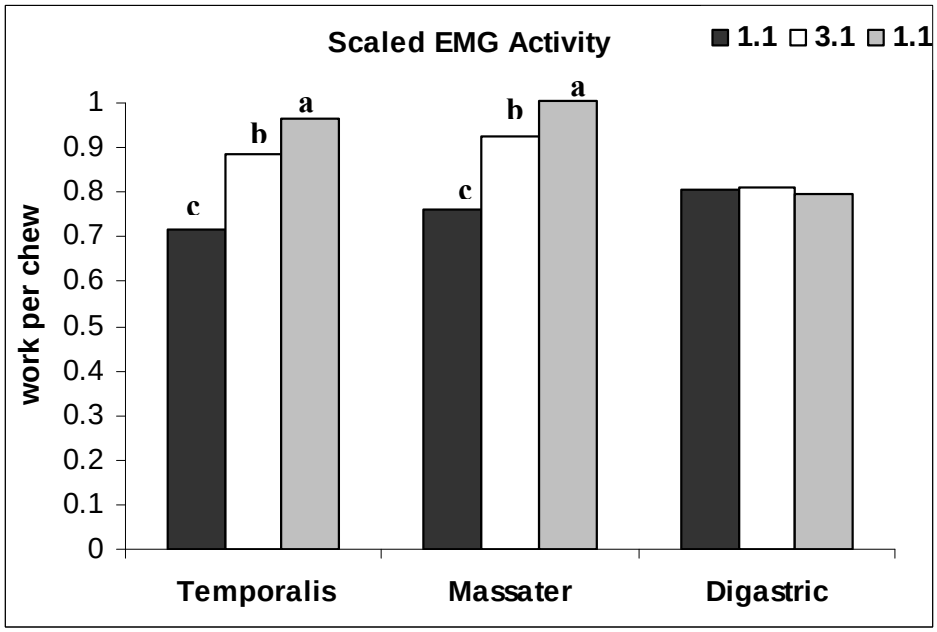
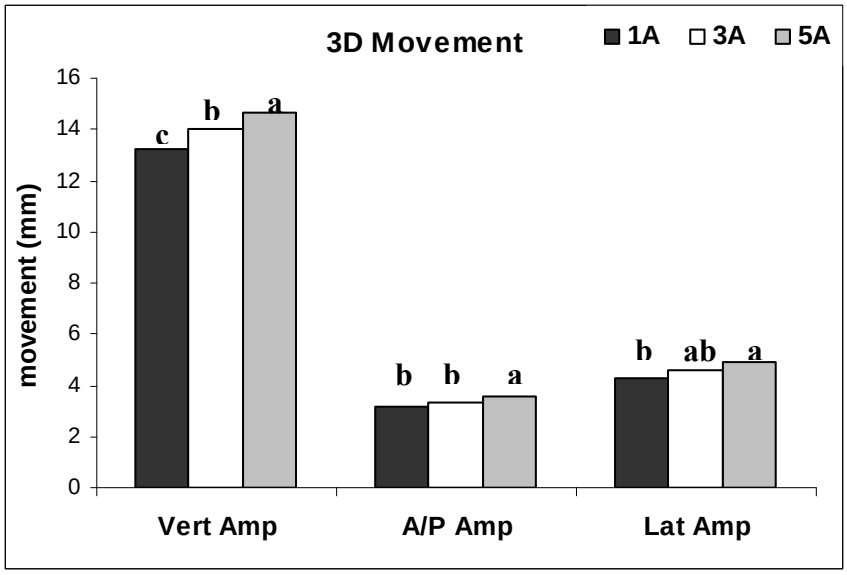


Figure 3. Mean values obtained for muscle activities for agar gels and κ-carrageenan-locust bean gum gels. Significant differences ($p<0.05$) among treatments for each muscle are showed with letters.



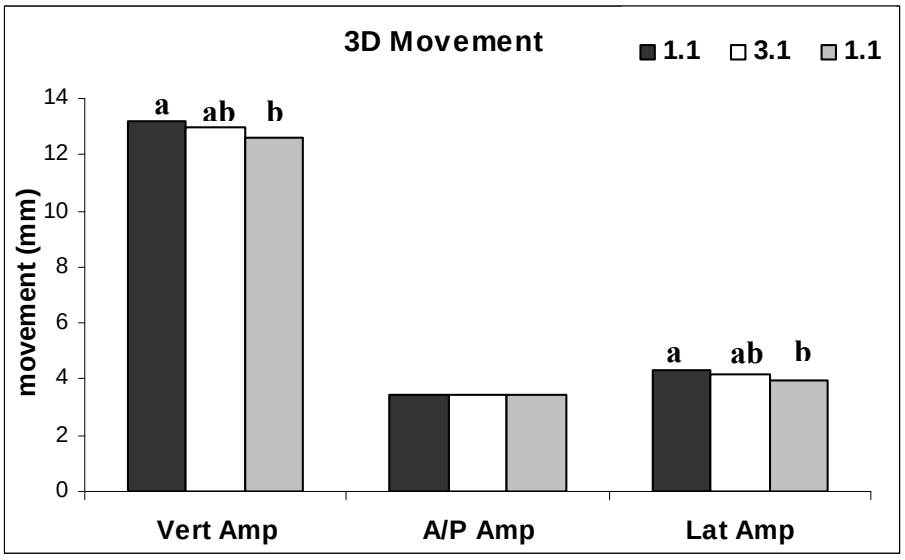


Figure 4. Mean values observed for three dimensional movements of mandibular for agar and κ-carrageenan-locust bean gum gels.

CHAPTER 4

Effect of Filler Type and Concentration on Small and Large Strain Rheological Properties of Emulsion Filled Polysaccharide Gels

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Abstract

The effect of the fillers on material properties of model foods was investigated to understand the effects of fat content on food texture. Agar gels and κ-carrageenan-locust bean gum gels were formulated to have similar strength (fracture stress) but different deformability (fracture strain) with various phase volume of corn oil. Corn oil droplets (approximately 1 μm) were stabilized by surfactants that had no charge (Tween 20), negative (β-lactoglobulin) or positive (lactoferrin) charge at neutral pH. Oil droplet size and distribution were examined by confocal laser scanning microscopy. All solutions started with stabilized oil droplets but flocculation and/or coalescence occurred during gelation. All fillers behaved as inactive fillers and decreased storage modulus (G′), except lactoferrin stabilized oil droplets in the κ-carrageenan gel network. Lack of interaction between fillers (neutral and negatively charged) and the gel networks weakened gels because the filler particle replaced the gel network. Reinforcement of κ-carrageenan gel network by lactoferrin stabilized droplets was due to interaction between positively charged filler and the negatively charged polymer. Changes in G′ were well predicted by van der Poel's theory. Increasing the phase volume of oil droplets decreased fracture stress and stress intensity factor of both filled gels, while the main effect on fracture strain and fracture surface energy was observed for the highly deformable κ-carrageenan gels. Tween 20 stabilized fillers had greater effect on fracture properties than protein stabilized fillers which can be explained by the lower estimated modulus of these fillers. It was shown that oil droplets with different surface properties significantly affected the small and large strain rheological properties of polysaccharide gels

which can be explained by combined effects of filler-network interactions and the mechanical properties of the gel network and filler droplets.

Keywords: Emulsion filled gel, rheology, fracture mechanics

1. Introduction

Soft solid foods with dispersed oil particles, such as cheese and processed meats, can be considered as filled gels (Tolstoguzov and Braudo, 1983; Sala et al., 2008) where particles are entrapped in a biopolymer network. The effect of particles on mechanical properties of filled gels depends on the volumes of the filler and gel phases, rheological properties of both phases, and filler-gel network interactions (Richardson et al., 1981; van Vliet 1988; Chen and Dickinson, 1998). Filler particles can be classified in two groups depending on their interaction with gel networks. Active fillers are defined as those that interact with the gel network, whereas inactive filler are distributed within the gel network but do not interact with the network (Ring and Stainsby, 1982; Rosa et al., 2006). The interaction between the gel network and the filler particles can be controlled by the surface properties of filler (Chen and Dickinson, 1999). If filler particles are bound to the gel network, they can increase or decrease the modulus of the filled gel depending on the ratio of modulus of filler droplets and modulus of gel network. If the filler droplets are unbound to the network, droplets decrease the modulus of gels in all circumstances (van Vliet, 1988; Sala et al., 2009).

Several model systems, differing in gel network (continuous phase) and dispersed particles, have been developed to investigate the effect of the dispersed phase and to improve the understanding of food structure. The effects of size, shape, phase volume and surface

properties of filler particles on small and large rheological properties of gels have been investigated by several research groups. Initially, glass or Sephadex were used as fillers in gelatin (Ross-Murphy and Todd, 1983; Brownsey et al., 1987) and whey protein gels (Langley and Green, 1989). In whey protein gels, hydrophilic glass spheres (clean or protein coated surface) cause larger increase in fracture stress than hydrophobic spheres (paraffin and silicon coated surface) (Langley and Green, 1989); indicating the importance of filler surface properties. Gels with hydrophilic spheres fracture through gel matrix, whereas gels with hydrophobic spheres fracture adjacent to spheres. Fracture adjacent to a filler particle indicates a weak interaction between particle and matrix. The reinforcement effect of series of filler particles at equal phase volume but different shapes changed in the order of rods> plates> cubes> spheres (Richardson et al., 1981). Anisometric shaped filler particles have more effect on the matrix properties than spherical particles (van Vliet, 1988). In addition to glass and Sephadex, oil droplets have been used to understand the effects filler particles on rheological properties of whey protein (Dickinson and Yamamoto, 1996; Chen and Dickinson, 1998; McClements et al., 1993; Yost and Kinsella, 1992; Gwartney et al., 2004; Rosa et al., 2006; Sala et al., 2008), egg yolk (Anton et al., 2001), soy protein (Matsumura et al., 1993; Kim et al., 2001), casein (Chen et al., 1999; Manski et al., 2007) and some polysaccharide gels (Kim et al., 1996; Sala et al., 2008). These types of systems are an example of filled gels having emulsified oil in a gel network (called emulsion droplets filled gels or emulsion filled gels).

Addition of 11-45% emulsified triolein oil to whey protein isolate (WPI) gels as an active filler shows an increase in G′ (elastic modulus) with increased lipid content (Chen and

Dickinson, 1998). Similary, soy oil reinforces a soy protein gel network (Kim et al., 2001). The van der Poel and the Kerner theories have been commonly used to model the small strain rheological data of filled gels to predict the effect of filler phase fraction on modulus (Sala et al., 2007). The effect of ratio of storage modulus of filler to matrix (M) on small deformation properties was studied by van Vliet (1988) based on van der Poel theory. If the droplet is bound, the effect of volume fraction of filler on the modulus of the gel matrix is related to M. When filler is stiffer than matrix (M>1), the larger the ratio the larger the increase in G′ with increased volume fraction. When matrix is stiffer than droplet (M<1), the lower the ratio, the larger the decrease of G′ with increasing oil fraction.

The effect of filler particles on fracture properties has been investigated because of the association between fracture properties and sensory texture (Rosa et al., 2006). Langley and Green (1989) showed that fracture stress increased and fracture strain decreased with increased lipid content in whey protein gels. Similar changes in fracture stress and strain of WPI gels were observed by Gwartney et al. (2004) for fine stranded gels, while fracture stress increased but fracture strain did not change in particulate gels. Fracture strain was also independent on phase volume of oil droplets in soy protein gels (Kim et al., 2001). Sala et al. (2007, 2008) studied the effect of matrix properties of emulsion filled WPI, gelatin and carrageenan gels. Fracture strain decreased when the filler volume increased for bound droplets, while there was no change in fracture strain for unbound particles. The effect on fracture stress was different than that of strain. Fracture stress was not affected by bound droplets whereas it decreased with unbound droplets (Sala et al., 2007). Models used to describe the effect of filler phase fraction on fracture properties are the Nielsen theory

predicting the effect on fracture strain, and a model proposed by Ross-Murphy and Todd (1983) and Langley and Green (1989) predicting the effect on fracture stress. According to these models, fracture strain decreases with the increase phase volume regardless of if particle is active or inactive. Fracture stress can either decrease or increase depending on phase volume of filler. The theories on the effect of filler on fracture properties do not seem to predict the observations.

The size of particle is also an important factor affecting the gel properties. Decrease in droplet diameter caused an increase in compressive stress in corn oil filled WPI gels when emulsion was stabilized with WPI particles (McClement et al., 1993). In contrast, oil droplets stabilized with Tween 20 and sodium dodecyl sulfate did not show any effect of particle size on gel properties. Filled agar gels with increasing oil content (0.1, 0.2, 0.3% phase fraction in 1% Agar) and particle size (1.5, 6.5, and 12.2 μm) showed a decrease in fracture stress and strain coinciding with increased filler volume and particle size (Kim et al., 1996). It has been suggested that if the particle size is larger than the average void size of gel matrix, then they disrupt the gel network. Using sodium caseinate gels filled with palm fat or glass spheres, Manski et al. (2007) showed that particle size, type of filler and surface properties had minimal effect on viscoelastic or tensile properties but filler phase volume was the most important.

Most investigations have concerned the effect of fillers in protein gels and the effect of filler particles in polysaccharide gels is less understood. Moreover, knowledge on filler effect on gel networks with different physical properties is limited. This study investigated the effect of phase fraction and surface properties of fillers on two different types of

polysaccharide gels. Agar gels show a brittle fracture pattern and increasing polymer concentration causes an increase in fracture stress and no change in fracture strain. κ-Carrageenan-locust bean gum gels show a ductile fracture pattern and fracture strain can be altered by varying the ratio of κ-carrageenan to locust bean gum. These gels were filled with varying levels of oil droplets stabilized with neutral, anionic or cationic surfactants. Gels were characterized by small and large deformation properties in addition to fracture mechanics.

2. Materials and Methods

2.1. Materials

Agar powder (110 FCC/NF) was donated by TIC Gums (Belcamp, MD). κ-carrageenan (GenuGel® CHP-2, Denmark), and locust bean gum (Genu®Gum RL-200Z, Atlanta, GA) was donated by CP Kelco. Crystalline potassium chloride (KCl) and pellets of sodium hydroxide (NaOH) were purchased from Fisher Scientific (Fair Lawn, NJ). Corn oil (Mazola ®) was purchased from a local grocery store. Hydrochloric acid (HCl) was obtained from Mallinckrodt Baker Inc. (Paris, KY). Tween 20 (Polysorbate 20, W291501) was obtained from Sigma-Aldrich (St.Louis, MO). Beta-lactoglobulin and lactoferrin (Bioferrin® 2000) was donated by Davisco Foods International Inc. (Le Sueur, MN) and Glanbia Nutritionals Inc. (Twin Falls, ID), respectively. The nitrogen contents of the powders were obtained by inductively coupled plasma spectroscopy and converted to protein using % Protein = 6.38 x % Nitrogen. The β-lactoglobulin powder contained 97.90% protein

and lactoferrin contained 98.57% protein. Nile Blue A Sulfate was obtained from MP Biomedicals LCC (Solon, OH).

2.2. Sample Preparation

2.2.1. Emulsion Formation and Particle Size Analysis

Oil in water stock emulsions (40% w/w) stabilized with different types of surfactants (Tween 20, β-lactoglobulin, lactoferrin) were prepared with corn oil and deionized water. Firstly, the surfactant was dissolved in water. The pH of β-lactoglobulin and lactoferrin solutions were adjusted to pH 7 and 6, respectively, using either 1 N NaOH or 1 N HCl. The surfactant solution was added into corn oil and mixed and blended using a blender (Kitchen Aid) for 15 min to form a coarse emulsion. Coarse emulsions were deaerated under vacuum for 30 min to remove gas incorporated during mixing, then homogenized using a Niro-Soavi Panda 2K lab scale homogenizer (GEA Niro-Soavia, Parma, Italy). Pressure (400 or 250 ±20 Bar) and number of cycles passed through the system (6 or 4 cycles) were adjusted to produce a particle size of approximately one micrometer diameter for all surfactants.

The median and modal oil droplet size and specific surface area of droplets in the 40% (w/w) o/w stock emulsion was analyzed by Shimadzu SA-CP4 Centrifugal Particle Size Analyzer (Shimadzu Corporation, Kyoto, Japan). The analyses were conducted under 240 rpm constant acceleration to predict a particle size over a range of 0.05-50 μm. The density of dispersed and continuous phase and viscosity of continuous were required for the analysis. The density of corn oil was measured as 0.9172 g/cm^3 at room temperature (22 ± 2 °C) using a Mettler-Toledo DE40 density meter (Mettler-Toledo, Columbus, OH). The density and

viscosity of water at 23 °C were 0.9976 g/cm^3 and 0.938 mPa.s, respectively, provided by the Shimadzu SA-CP4 Instructions Manual.

2.2.2. Gel Preparation

Agar (3% w/w) and κ-carrageenan-locust bean gum (1.8% w/w in 0.02 KCl solution) were prepared with different oil concentrations (0, 5, 10, 20 and 25% w/w). Double concentrated polymer solution was mixed with double concentrated emulsion at 1:1 ratio for all samples except 25% oil (0.6:1 ratio). Gelling agent concentration in the water phase was kept constant for all samples.

Agar powder was mixed into deionized water and stirred at room temperature (22 ± 2 °C) for 1 h. Following a 1 min boiling step by microwave heating, the solution was heated in a water bath at 85 °C for 1 hr. The solution was then mixed with heated emulsion (85 °C) and poured into cylindrical glass tubes (i.d.=19 mm) and held for 2 hr at room temperature (22 ± 2 ^{o}C) and then stored at 4 ± 2 ^{o}C for 16-24 h for gelling. The gels were equilibrated at room temperature (22 ± 2 ^{o}C) for 2 hr prior to mechanical tests.

Premixed κ-carrageenan and locust bean gum powders was hydrated for 1 hr at room temperature and then held in a water bath at 90 ^{o}C for 1 hr. Solutions were subsequently boiled on a heated stirrer plate and then held in a water bath at 90 ^{o}C for another hour. The solution was mixed with heated emulsion (90 ^{o}C), poured into cylindrical glass tubes (i.d.=19 mm) and gelled at room temperature (22 ± 2 ^{o}C) for 16-24 h.

After gelation, all samples were stored at 4 ± 2 ^{o}C until testing. The gels were equilibrated at room temperature (22 ± 2 ^{o}C) for 2 hr prior to analysis.

2.3. Small Strain Rheology

Dynamic oscillatory testing was conducted at 25 ^{o}C using a Stress Tech controlled stress rheometer (ATS Rheosystems, Bordentown, NJ) equipped with 20-mm serrated parallel plate geometry. Gel samples were cut into 4 mm thickness and trimmed to the size of the plate. Mineral oil was applied to exposed edges of the gels to avoid moisture loss during analysis. After linear viscoelastic regions of each gel were determined by stress sweeps tests, frequency sweeps were conducted within the linear region from 0.01 to 10 Hz at 10 Pa.

2.4. Large Strain Rheology

Torsional Fracture

Fracture properties of filled agar gels and κ-carrageenan-locust bean gum gels were determined by torsional fracture as previously described (Diehl, 1979; Barrangou et al, 2006; Koc et al., 2012). Capstan shaped gels were mounted vertically in a Haake VT550 Viscometer (Paramrus, NJ) and twisted to failure at a rotational speed of 4.5 rpm (corresponding to a shear rate of 0.47 s^{-1}). Fracture stress, fracture strain, and fracture modulus (fracture stress/ fracture strain) were reported.

Compression Test

Recoverable energy was determined by a compression-decompression test using a universal testing machine (Instron Model 5565 Instron Engineering Corp., Canton, MA, U.S.A.) equipped with a 5 kN load cell. Samples (19 mm diameter, 21.5 mm height) were

compressed to 80% of the original height at 50 mm/min and decompressed at same speed. The test was also conducted by compressing to 90% of the height to understand the effect of different deformation rates on recoverable energy. Area under force-deformation curve during compression (W_1) and decompression (W_2) were calculated and %RE were expressed as

$$\%RE = \frac{W_2}{W_1} \; x \; 100$$

which represents the ratio of recoverable work to total work (Kaletunc et al., 1991).

Young's modulus was obtained from the initial normal true stress and strain values determined during compression. It was calculated from the initial slope of the true stress and true strain curve by applying linear regression in the range of 0.02-0.1 true strain.

Center Crack Tension Test

Stress intensity factor and fracture surface energy of the gels were obtained from center crack tension tests (Koc et al., 2012). Samples (5x18x120 mm) with a 9-mm-wide notch in the middle were glued to tension measurement fixtures attached to an Instron 5540 universal testing machine (Inston Engineering Corporation, Canton, MA) equipped with a 50-N load cell. Tests were conducted at a constant speed of 10 mm/min at room temperature (22 ± 2 °C).

2.5. Confocal Scanning Laser Microscopy (CSLM)

Oil droplet size and distribution of emulsions and emulsion filled gels were examined by CSLM using a Zeiss LSM 710 confocal microscope equipped with an inverted microscope (Zeiss Axio Observer Z1). Gel samples were stained with Nile Blue A Sulfate

solution (0.2% w/w) and excited with 488 nm argon laser. Emission spectrum was collected between 500 and 650 nm to visualize the oil phase. Images were collected with a water immersion objective lens (LD C-Apochromat 40x/1.1W Korr M27) at 1024x1024 pixel resolution.

3. Results and Discussion

3.1. Emulsion Stability and Droplet Size

Emulsions containing oil droplets with no charge, negative charge and positive charge were obtained by stabilizing droplets with Tween 20, β-lactoglobulin (isoelectric point (pI) 5) and lactoferrin (pI 8), respectively. Solutions of β-lactoglobulin and lactoferrin were adjusted to pH 7 and 6, respectively, before emulsion preparation. The particle size analysis data is reported in Table 1. Average median diameters of oil droplets varied between 0.7 and 1.6 μm. Average median diameters were very similar to modal diameters which indicated a unimodal distribution of droplets. Size and distribution of the droplets were also confirmed by confocal microscopy images. Stability of droplets, over time and with heating, was examined by particle size analysis, by visual observation in a graduated cylinder and also by confocal microscopy images (unreported data). Emulsions did not show a significant change in particle size with time or increased temperatures during heat treatment, assuring that they should be stable during the process required for gel formation. However, flocculation and/or coalescence of particles occurred when emulsions were mixed with polymer solutions and during gelation. This increased their effective volume due to the entrapped polysaccharide solution/gel and formed anisometric particles (Fig. 1).

The degree of coalescence of particles was greater in protein stabilized fillers compared to fillers stabilized with Tween 20. These changes in droplet size and shape can affect the rheological results and bring some difficulties in the application of theoretical models to the experimental data due to increased phase volume (van Vliet 1988, Walstra 2003, Dickinson and Chen, 1999).

3.2. Small Strain Rheology

Frequency dependency of viscoelastic parameters (G′ storage modulus and G″ loss modulus) of agar gels and κ-carrageenan-locust bean gum gels without oil and with 25% oil are presented in Fig. 2a and Fig. 3a. When oil droplets stabilized with different emulsifying agents were incorporated in the agar gel network, both storage and loss moduli decreased (Fig. 2a). The differences in loss modulus became more apparent at higher frequencies. The effect of Tween 20 on viscoelastic parameters was greater than other surfactants (Fig. 2b). Oil droplets stabilized with lactoferrin affected G′ significantly, however all levels of oil incorporation (10, 20, 25%) were close to the each other. β-Lactoglobulin stabilized fillers did not change the relative modulus significantly at lower concentrations.

Neutral, positively and negatively charged oil droplets affected κ-carrageenan-locust bean gum gel network in different ways (Fig. 3a). Tween 20 stabilized fillers reduced G′ and G″; while lactoferrin stabilized fillers caused an increase in both moduli. β-Lactoglobulin stabilized filler did not show a significant effect on moduli. With an increase in oil concentration, effect of lactoferrin stabilized fillers became more apparent and caused approximately a 50% increase in G′ at 20-25% concentrations (Fig. 3b). The increase in G′

with addition of oil showed oil droplets reinforce the network structure, most plausible through the interaction between positively charged lactoferrin molecules on the surface of oil droplets and the negatively charged gel network. Storage modulus of κ-carrageenan-locust bean gum varied between 5-12 kPa and loss modulus varied between 0.4-2 kPa, which were smaller than agar gel network moduli (G′: 30-60 kPa, G″: 1-7kPa).

Phase angles for agar gels with and without oil ranged between 2 and 8, and ranged between 4 and 10 for κ-carrageenan gels indicating predominantly elastic behavior for both gel network (Fig. 4). At lower frequencies, emulsion gel was more viscous whereas at higher frequencies it was more elastic than gels without emulsion based on the change in phase angle with frequency (unreported data). This observation was also coincides with data reported for casein gels (Chen et al., 1999). In viscoelastic materials, G′ and G″ appear to be slightly dependent on frequency, which also has been observed previously in different foods as cheese (Rogers et al., 2009), whey protein gels (Chen et al., 2000), mixed κ-carrageenan and β-lactoglobulin (Eleya and Turgeon, 2000).

Experimental results of filled agar and κ-carrageenan gels were compared to theoretical modeling based on a simplified van der Poel's theory (Smith, 1975) (Fig. 5). The effect of filler in gel modulus depends on the ratio (M):

$$M = G'_f / G'_m$$

where G'_f is the modulus of filler, G'_m is the modulus of the gel matrix.

The ratio of the storage modulus of filled gels to the storage modulus of matrix as a function of filler phase volume can be predicted by the equation:

$$\frac{G'}{G'_m} = \frac{15(1-\upsilon_m)(M-1)\phi}{(8-10\upsilon_m)M+7-5\upsilon_m-(8-10\upsilon_m)(M-1)\phi} + 1$$

where □ is the phase fraction of filler, υ_m is the Poisson ratio of matrix (which can be assumed as 0.5 for gels), G′ is the modulus of filled gel.

For filled gels, the G'_f of an active filler can be estimated by $G'_f = 2\gamma/R$ (van Vliet, 1988) based on Laplace pressure where γ is the interfacial tension and R is the radius of the filler. If the filler droplets are unbound to the network, the modulus is assumed to be zero. In the prediction for the active fillers, a value of 6 mN/m was used as interfacial tension to calculate the modulus. The value of γ was selected based on results of interfacial tension measurements between peanut oil and WPI aggregate conducted by Rosa et al. (2006). The average particle size for the fillers was assumed to be 1 μm.

Figure 5 shows experimental results and model predictions. The van der Poel's theory predicted the effect of filler particles on the modulus of filled gels. It also correctly predicts the effect of oil droplets on modulus of WPI gels (Rosa et al., 2006). For κ-carrageenan gels, model predictions are presented for active and inactive fillers. Based on the model, the greater effect of Tween 20 stabilized particles on gel modulus can be attributed to the modulus of fillers stabilized by Tween 20. As a small molecular weight surfactant, Tween 20 may have lower surface tension. Thus its modulus is lower than protein stabilized fillers and causes a greater reduction in the storage modulus. Therefore the ratio between modulus of filler and gel matrix is a critical parameter affecting the properties of filled gel.

Investigations of the application of van der Poel's theory on small strain rheological properties of polysaccharide gels have been scarce. The model correctly predicts the effect of filler particles on various protein gel networks (van Vliet, 1988; Rosa et al., 2006; Chen and Dickinson, 1998). We have showed that van der Poel's theory can also predict different types of networks other than protein based.

3.3. Large strain rheology

Young's modulus

Changes in Young's modulus (E), as a function of the oil concentration are given in Figure 6. Young's modulus, calculated from the initial slope of large-strain rheological measurements are calculated at strains beyond those used in oscillatory small-strain tests. Agar gels (Fig. 6a) had greater Young's moduli (110-220 kPa) compared to κ-carrageenan-locust bean gum gels (Fig. 6b) (20-60 kPa). Young's modulus of agar gels decreased linearly with increased concentration of oil droplets stabilized with Tween 20, β-lactoglobulin and lactoferrin. Oil droplets stabilized by Tween 20 showed the largest effect, causing approximately 50% reduction in Young's modulus at the highest oil concentration. This result suggests that filler droplets with no charge, positively and negatively charged did not bind the agar gel network, thus lowering the modulus. Agar is composed of both agarose and agaropectin fractions. The agarose component is mainly responsible for gelation through hydrogen bonding, and it is neutral. The non-gelling component agaropectin fraction has negative charge. While interactions between agaropection and filler particles cannot be dismissed, it clearly did not increase gel stiffness. In the κ-carrageenan-locust bean gels,

β-lactoglobulin and Tween 20 stabilized droplets lowered the Young's modulus (Fig. 6b). When the κ-carrageenan-locust bean gel network was filled with positively charged fillers, gels were reinforced and Young's modulus increased with increased concentration of oil. Attractive interactions between positively charged oil droplets and a negatively charged gel network explain this reinforcement effect. These results are in agreement with previous findings for semi-solid type κ-carrageenan gels filled with WPI, WPI aggregates, lysozyme, and Tween 20 (Sala et al., 2007). It has been shown that the filler effect on Young's modulus can also be predicted by van der Poel theory (Sala et al., 2007). Changes in Young's modulus were similar to what was seen in viscoeleastic parameters. A linear relationship between Young's Modulus (E) and complex modulus (G*) was established when data is combined for all combinations of gel type, surfactant type, and oil concentration (Fig. 6c).

Recoverable energy

Recoverable energy (RE) was expected to vary with network composition due to incorporation of energy dissipating oil droplets. Agar gels showed similar amounts of recoverable energy among treatments varying in % oil, surfactant type or level of compression (Table 2). κ-Carrageenan-locust bean gum gels showed some decrease in RE with the oil addition, although the trends were not consistent other than for the 25% oil level being lower than no oil addition. Based on the energy balance proposed by van Vliet et al. (1993);

$$W = W' + W''_v + W''_c + W_f$$

Energy applied to deform a material (W) can be elastically stored (W′), dissipated either by viscous flow of the material (W''_v), or by friction between components of the system (W''_c) or used for fracture (W_f). Viscous flow and minor micro-cracks can contribute the dissipated energy in agar and κ-carrageenan-locust bean gum gels without oil droplets. Slight decrease in recoverable energy when the oil was incorporated into the gel network can be due to increased energy dissipation by friction between oil droplets and gel network and also by favoring micro-crack formation. Interestingly, if the gels were compressed to 80% of initial height, recoverable energy for all the treatments varied between 43-57%, which is less than energy levels recovered after compression to 90% which indicates formation of microcracks in the structure and possibly some viscous flow. Therefore, there appeared to be no effects on agar gels and just a slight filler volume effect in κ-carrageenan-locust bean gum gels.

According to the study of Sala et al. (2009) on emulsion filled gelatin, WPI and κ-carrageenan gels, filler particles decreased the RE of protein gel networks. However, the effect of filler phase volume was limited for κ-carrageenan gels which supports our results. Recoverable energy is an important physical measure which relates to microstructure and sensory properties of mixed protein-polysaccharide gels (van der Berg et al., 2007; Cakir et al., 2012) and cheese (Rogers et al., 2009). Kaletunc et al. (1991) determined the degree of elasticity (RE) of various foods such as banana, cheese, frankfurter, and jelly candy. Recoverable energy has been showed to be strain dependent and the nature of dependency varies across foods. Therefore, measuring it at different strains is suggested. Another approach would be the determining the strain at which materials fail and conducting the test

at a strain selected according to fracture strain, e.g. 20% of fracture strain. However, this may pose a challenge when comparing different type of materials.

Materials with 60-80% RE are considered "elastic" (i.e. marshmallow) and materials with 20-50% RE are considered "plastic" (i.e. ripe banana). Degree of elasticity for various food products are not related to other mechanical properties such as fracture stress, strain and elastic modulus (Kaletunc et al., 1991).

Fracture properties

All type of fillers caused a decrease in fracture stress of both gel networks (Fig. 7). With addition of 20% oil, the gel strength was reduced by at least 50% for all samples. Fracture strain of agar gels did not change to a large extent, varying between 0.7-0.5 (Fig. 8). On the other hand, there was a significant reduction in the fracture strain of κ-carrageenan-locust bean gum gels (Fig. 8), although the effect of active and inactive fillers was very similar on gel deformability. Fracture modulus decreased gradually as the oil concentration increased, and all three fillers had similar effects on agar gels (Fig. 9). The effect of fillers on fracture modulus of κ-carrageenan-locust bean gum gel networks started after the addition of more than 10% oil to the system. Non-ionic filler, Tween 20, had the greatest effect overall in agar gel and κ-carrageenan-locust bean gum gel networks. Filler particles act as stress concentration nuclei causing a decrease in fracture stress and strain. Slight variations in fracture strain and decrease in stress of κ-carrageenan gels filled with WPI stabilized oil droplets were reported by Sala et al. (2007); however, the effect of oil droplets on fracture strain was not as significant as observed in this study. In reported results of different types of gel networks by Sala et al., (2007), oil droplets had a minor effect on fracture properties but

showed greater influence on Young's modulus. Theories (Neilsen theory for strain and Ross-Murphy and Langley and Green for stress) did not predict the observed effects on fracture properties (Sala et al., 2007). In this study, significant changes in fracture properties have also been observed. The ranges of fracture stress and fracture strain of various gels in this study are approximately 5-10 kPa and 0.6-1.3, respectively, indicating a very weak gel network. Agar and κ-carrageenan gels are stronger gels with fracture stresses of 70-90 kPa and fracture strains are 0.7 and 2.8 respectively. Differences in observed results of studies can be originated from the differences in the initial mechanical properties.

Stress intensity factor of κ-carrageenan gels was approximately four fold higher than agar gels (Fig. 10). With the addition of oil, both networks showed a decrease in stress intensity factor. The effects of fillers on the κ-carrageenan gels were very similar, as a linear decrease in stress intensity factor with increased concentration of oil was observed. In agar gel networks, both Tween 20 and β-lactoglobulin stabilized fillers caused a reduction in stress intensity factor when the filler concentration was more than 5%. Although, Tween 20 stabilized fillers caused a larger reduction in stress intensity factor than β-lactoglobulin. On the other hand, lactoferrin stabilized fillers had a smaller effect on the stress intensity factor of agar network. Filler droplets did not change the fracture surface energy of agar gels to a great extent; however it reduced the fracture energy significantly in κ-carrageenan gels (Fig. 11). This effect is similar to the effect of fillers on fracture strain.

4. Conclusions

Based on the effect of filler on the storage and Young's moduli, Tween 20 and β-lactoglobulin stabilized fillers behaved as inactive fillers in both gel networks. Lactoferrin stabilized fillers were active in κ-carrageenan gels and inactive in agar gels. Fracture stresses of gel networks decreased with increase concentration of fillers while fracture strain decreased significantly only in κ-carrageenan gels. When the fracture strain of gels without filler is higher, filler has a greater effect on deformability of gel. The effect of fillers on stress intensity factor was similar to fracture stress while the effect on fracture energy was similar to fracture strain. Tween 20 stabilized fillers had the most significant weakening of fracture properties. Oil droplets with different surface properties significantly affected the mechanical properties of polysaccharide gels which show the importance of the interaction between filler and the network, and the structure of continuous phase. Understanding the effect of filler particles on a food gel network is important to control textural properties of products with fat reduction or replacement.

References

Anton, M., Denmat, M. L., Beaumal, V., & Pilet, P. (2001). Filler effects of oil droplets on the rheology of heat-set emulsion gels prepared with egg yolk and egg yolk fractions. *Colloids and Surfaces: Biointerfaces,* 21(1–3), 137-147.

Brownsey, G. J., Ellis, H. S., Ridout, M. J., & Ring, S. G. (1987). Elasticity and Failure in Composite Gels . *Journal of Rheology.* 31(8), 635-649.

Chen, J., & Dickinson, E. (1999). Effect of surface character of filler particles on rheology of heat-set whey protein emulsion gels. *Colloids and Surfaces B: Biointerfaces,* 12(3–6), 373-381.

Chen, J., & Dickinson, E. (1998). Viscoelastic properties of heat-set whey protein emulsion gels. *Journal of Texture Studies,* 29(3), 285-304.

Chen, J., Dickinson, E., & Edwards, M. (1999). Rheology of acid-induced sodium caseinate stabilized emulsion gels. *Journal of Texture Studies*, 30, 377-396.

Chen, J., Dickinson, E., Langton, M., & Hermansson, A-M. (2000). Mechanical properties of heat-set whey protein emulsion gels: Effect of emulsifiers. *Lebensm. Wiss. Technolo.,* 33, 299-307.

Çakır, E., & Foegeding, E. A. (2011). Combining protein micro-phase separation and protein–polysaccharide segregative phase separation to produce gel structures. *Food Hydrocolloids,* 25(6), 1538-1546.

Dickinson, E., & Yamamoto, Y. (1996). Rheology of Milk Protein Gels and Protein-Stabilized Emulsion Gels Cross-Linked with Transglutaminase. *Journal of Agricultural and Food Chemistry,* 44(6), 1371-1377.

Dickinson, E., & Chen, J. (1999). Heat-set whey protein emulsion gels: role of active and inactive filler particles. *Journal of Dispersion Science and Technology*, 20(1-2), 197-203.

Gwartney, E. A., Larick, D. K., & Foegeding. E. A. (2004). Sensory texture and mechanical properties of stranded and particulate whey protein emulsion gels. *Journal of Food Science,* 69(9), 333-339.

Kaletunc, G., Normand, M. D., Johnson, E. A., & Peleg. M. (1991). Degree of elasticity determination in solid foods. *Journal of Food Science,* 56(4), 950-953.

Kim, K., Renkema, J. M. S., & van Vliet, T. (2001). Rheological properties of soybean protein isolate gels containing emulsion droplets. *Food Hydrocolloids,* 15(3), 295-302.

Kim, K., Gohtani, S., & Yamano, Y. (1996). Effects of oil droplets on physical and sensory properties of o/w emulsion agar gel. *Journal of Texture Studies,* 27(6), 655-670.

Koc, H., Cakir, E., Daubert, C., Drake, M., Essick, G., Vinyard, C., Osborne, J., & Foegeding, E.A. (2012). Alteration of oral processing with increased fracture stress and fracture strain of model foods (to be submitted to *Journal of Texture Studies*).

Langley, K. R., Martin, A., & Ogin, S. L. (1994). The effect of filler volume fraction on the fracture toughness of a model food composite. *Composites Science and Technology,* 50(2), 259-264.

Langley, K. R., & Green, M. L. (1989). Compression strength and fracture properties of model particulate food composites in relation to their microstructure and particle-matrix interaction. *Journal of Texture Studies,* 20(2), 191-207.

Manski, J. M., Kretzers, I. M. J., van Brenk, S., van der Goot, A. J., & Boom, R. M. (2007). Influence of dispersed particles on small and large deformation properties of concentrated caseinate composites. *Food Hydrocolloids,* 21(1), 73-84.

Matsumura, Y., Kang, I., Sakamoto, H., Motoki, M., & Mori, T. (1993). Filler effects of oil droplets on the viscoelastic properties of emulsion gels. *Food Hydrocolloids,* 7(3), 227-240.

McClements, D. J., Monahan, F. J., & Kinsella, J. E. (1993). Effect of emulsion droplets on the rheology of whey protein isolate gels. *Journal of Texture Studies,* 24(4), 411-422.

Richardson, R. K., Robinson, G., Ross-Murphy, S. B., & Todd, S. (1981). Mechanical spectroscopy of filled gelatin gels. *Polymer Bulletin,* 4(9), 541-546.

Ring, S., & Stainsby, G. (1982). Filler reinforcement of gels. *Progress in Food and Nutriton Science, 6*, 323-329.

Rogers, N. R., McMahon, D. J., Daubert, C. R., Bletsch, T. K., & Foegeding, E. A. (2010). Rheological properties and microstructure of Cheddar cheese made with different fat contents. *Journal of Dairy Science,* 93, 4565–4576.

Rosa, P., Sala, G., van Vliet, T., & van de Velde, F. (2006). Cold gelation of whey protein emulsions. *Journal of Texture Studies,* 37(5), 516-537.

Ross-Murphy, S. B., & Todd, S. (1983). Ultimate tensile measurements of filled gelatin gels. *Polymer,* 24(4), 481-486.

Sala, G., de Wijk, R. A., van de Velde, F., & van Aken, G. A. (2008). Matrix properties affect the sensory perception of emulsion-filled gels. *Food Hydrocolloids,* 22(3), 353-363.

Sala, G., van Aken, G. A., Stuart, M. A. C., & van de Velde, F. (2007). Effect of droplet matrix interactions on large deformation properties of emulsion-filled gels. *Journal of Texture Studies,* 38(4), 511-535.

Sala, G., F. van de Velde, F., Stuart, M. A. C., & van Aken, G. A (2007). Oil droplet release from emulsion-filled gels in relation to sensory perception. *Food Hydrocolloids,* 21(5–6), 977-985.

Sala, G., van Vliet, T., Stuart, M. A. C., van Aken, G. A., & van de Velde, F. (2009). Deformation and fracture of emulsion-filled gels: Effect of oil content and deformation speed. *Food Hydrocolloids,* 23(5), 1381-1393.

Smith, J.C. (1975). Simplification of the van der Poel's formula for the shear modulus of particulate composite. *J. Res.Natl. Bur.Stand., 79A*, 419–423.

Tolstoguzov, V. B., & Braudo, E. E. (1983). Fabricated foodstuffs as multicomponent gels. *Journal of Texture Studies,* 14(3), 183-212.

van den Berg, L., van Vliet, T., van der Linden, E., van Boekel, M. A. J. S., & van de Velde, F. (2007). Breakdown properties and sensory perception of whey proteins/polysaccharide mixed gels as a function of microstructure. *Food Hydrocolloids,* 21(5–6), 961-976.

van Vliet, T. (1988). Rheological properties of filled gels. Influence of filler matrix interaction. *Colloid & Polymer Science,* 266(6), 518-524.

van Vliet, T., Luyten, H., & Walstra, P. (1993). Time dependent fracture behaviour of food. In *Food Colloids and Polymers: Stability and Mechanical Properties*, E. Dickinson & P. Walstra (Eds.), Royal Society of Chemistry, Cambridge.

Walstra, P. (2003). *Physical chemistry of foods.* New York: Marcel Dekker.

Yost, R. A., & Kinsella. J. E. (1992). Microstructure of Whey Protein Isolate Gels Containing Emulsified Butterfat Droplets. *Journal of Food Science,* 57(4), 892-897.

Table 1. Average median, modal diameters and surface area of the particles stabilized with different emulsifying agents (each data point is the mean value of 2-4 replicates)

Emulsifying agent	Amount (%w/w) in emulsion	Median Diameter (μm)	Modal Diameter (μm)	Surface Area (m^2/g)
Tween	2	0.68 ± 0.12	0.59 ±0.12	13.82 ±1.27
β-lactoglobulin	1	0.92 ± 0.29	0.91 ± 0.35	13.05 ±1.95
Lactoferrin	1	1.56 ± 0.19	1.16 ±0.08	6.88 ±1.55

Table 2. Recoverable energies (RE) for agar (A) and κ-carrageenan-locust bean gum gels (B). Tables on the top represent RE when compression was done to 90% of the original height, tables at the bottom represents RE during compression to 80% of the height.

A. Agar

Oil Conc.(w/w)	Tween	β-lactoglobulin	Lactoferrin
0	80	80	80
5	81	78	80
10	80	78	81
20	79	78	79
25	80	77	79

Oil Conc.(w/w)	Tween	β-lactoglobulin	Lactoferrin
0	52	52	52
5	52	52	53
10	53	52	54
20	53	52	56
25	55	53	57

B. κ-Carregeenan

Oil Conc.(w/w)	Tween	β-lactoglobulin	Lactoferrin
0	78	78	78
5	79	80	75
10	75	80	73
20	74	76	72
25	71	74	66

Oil Conc.(w/w)	Tween	β-lactoglobulin	Lactoferrin
0	48	48	48
5	*47*	*53*	*51*
10	44	53	47
20	45	51	49
25	43	53	45

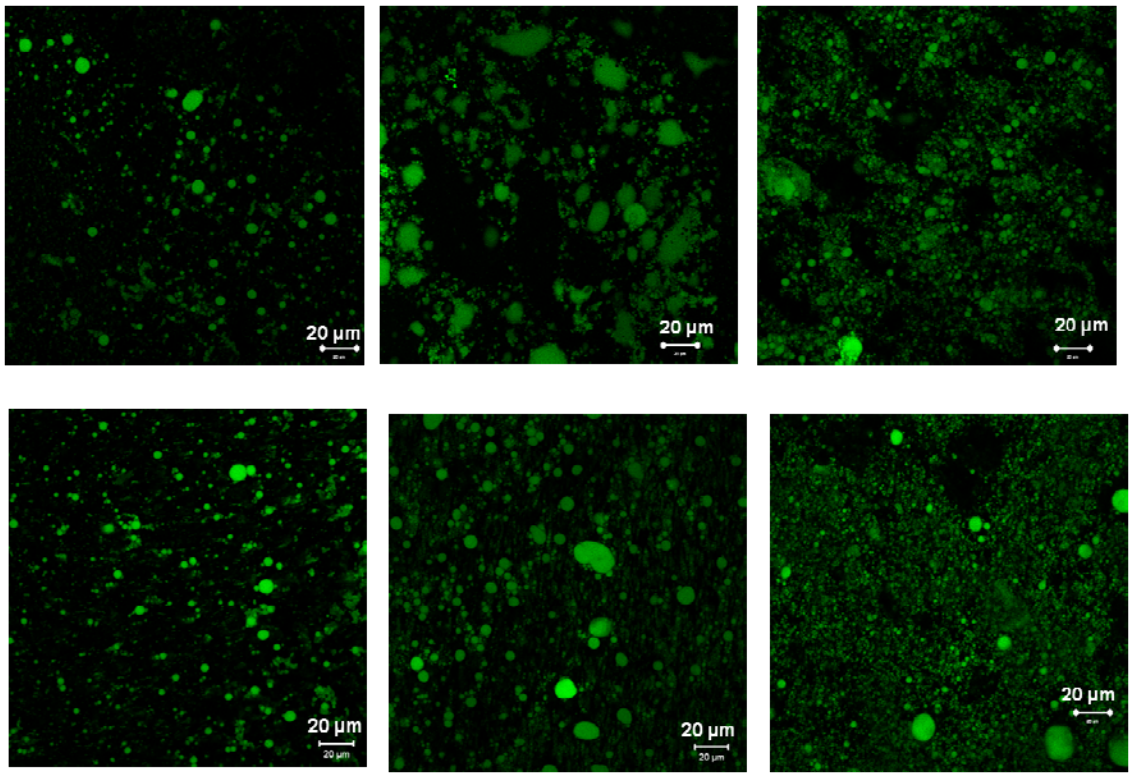


Figure 1. Agar gels (top images) and κ-carrageenan-locust bean gum gels (bottom images) with 20% oil droplets stabilized by Tween 20, β-lactoglobulin, lactoferrin (from left to right)

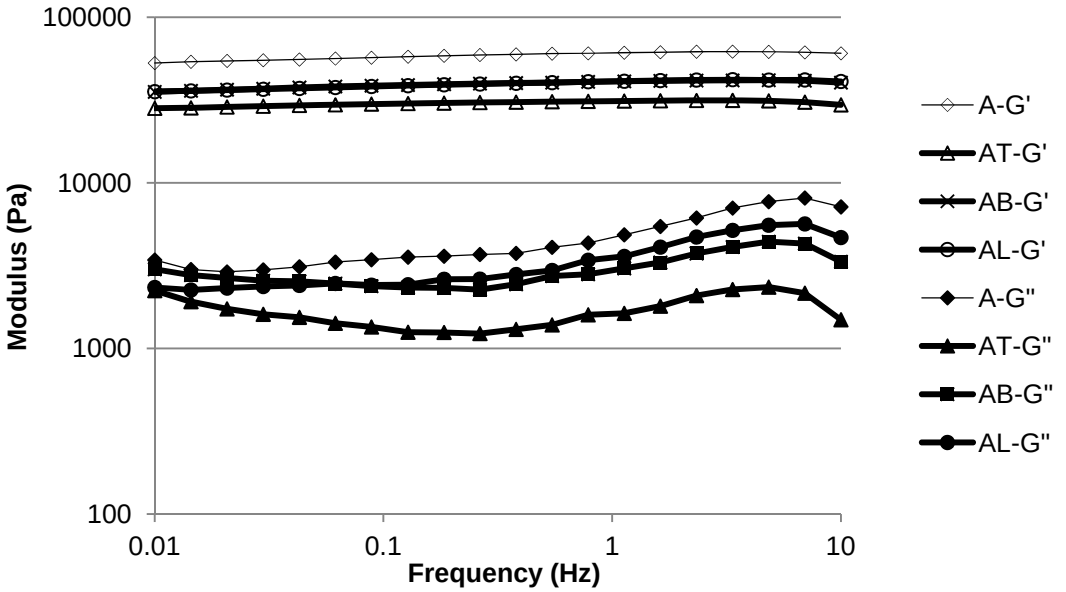


Figure 2a. Storage and loss modulus of agar gels without oil and with 25% oil.
Legend: A-Agar, AT-Agar with Tween 20 stabilized fillers, AB-Agar with β-lactoglobulin stabilized fillers, AL-with lactoferrin stabilized fillers.

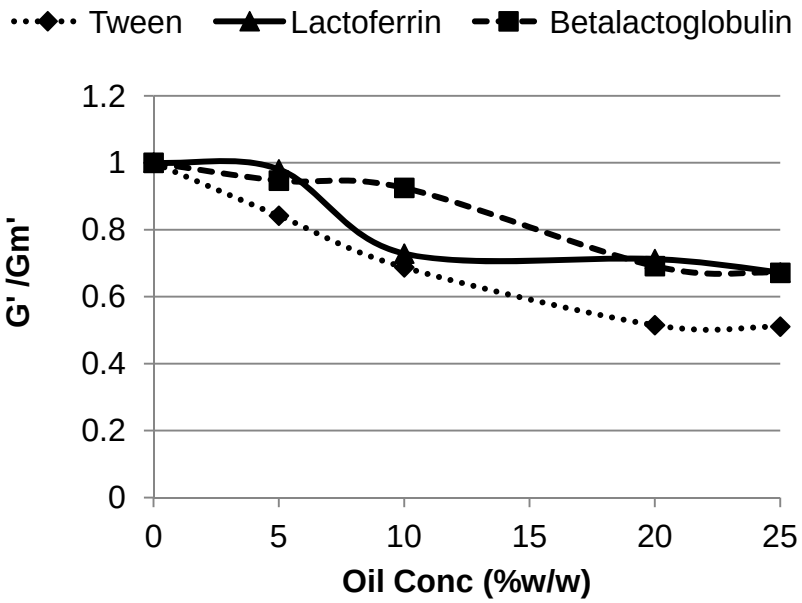


Figure 2b. Relative changes in storage modulus of agar gels at 1 Hz at different oil concentrations (G′ is storage modulus of filled gel, Gm′ is storage modulus of gel matrix)

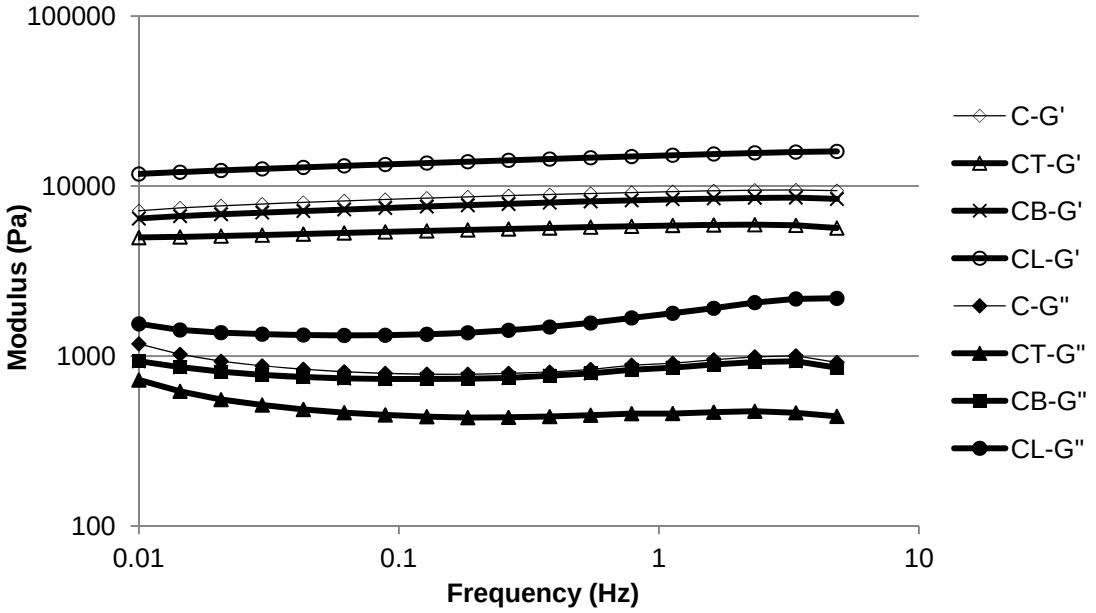


Figure 3a. Storage and loss modulus of κ-carrageenan gels without oil and with 25% oil. C- Agar, CT- κ-carrageenan gels with Tween 20 stabilized fillers, CB- κ-carrageenan gels with β-lactoglobulin stabilized fillers, CL- κ-carrageenan gels with lactoferrin stabilized fillers.

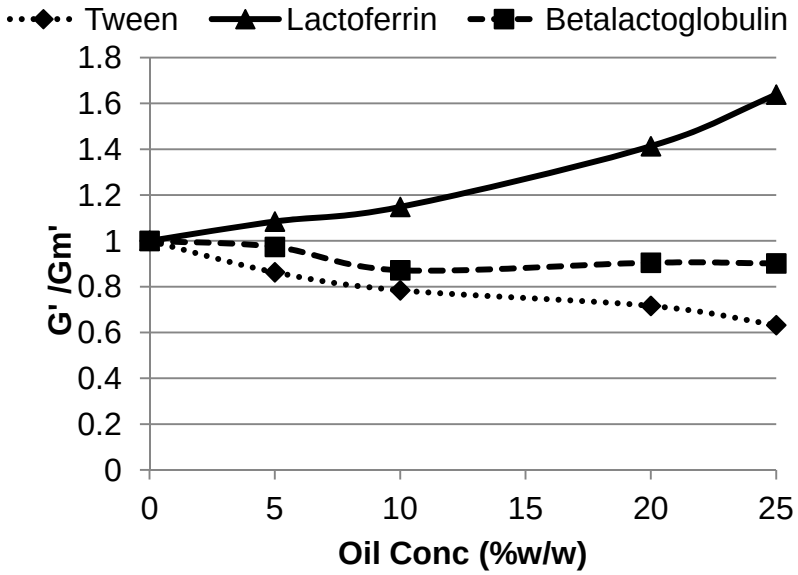


Figure 3b. Relative change in storage modulus of κ-carrageenan gels at 1 Hz at different oil concentrations (G′ is storage modulus of filled gel, Gm′ is storage modulus of gel matrix).

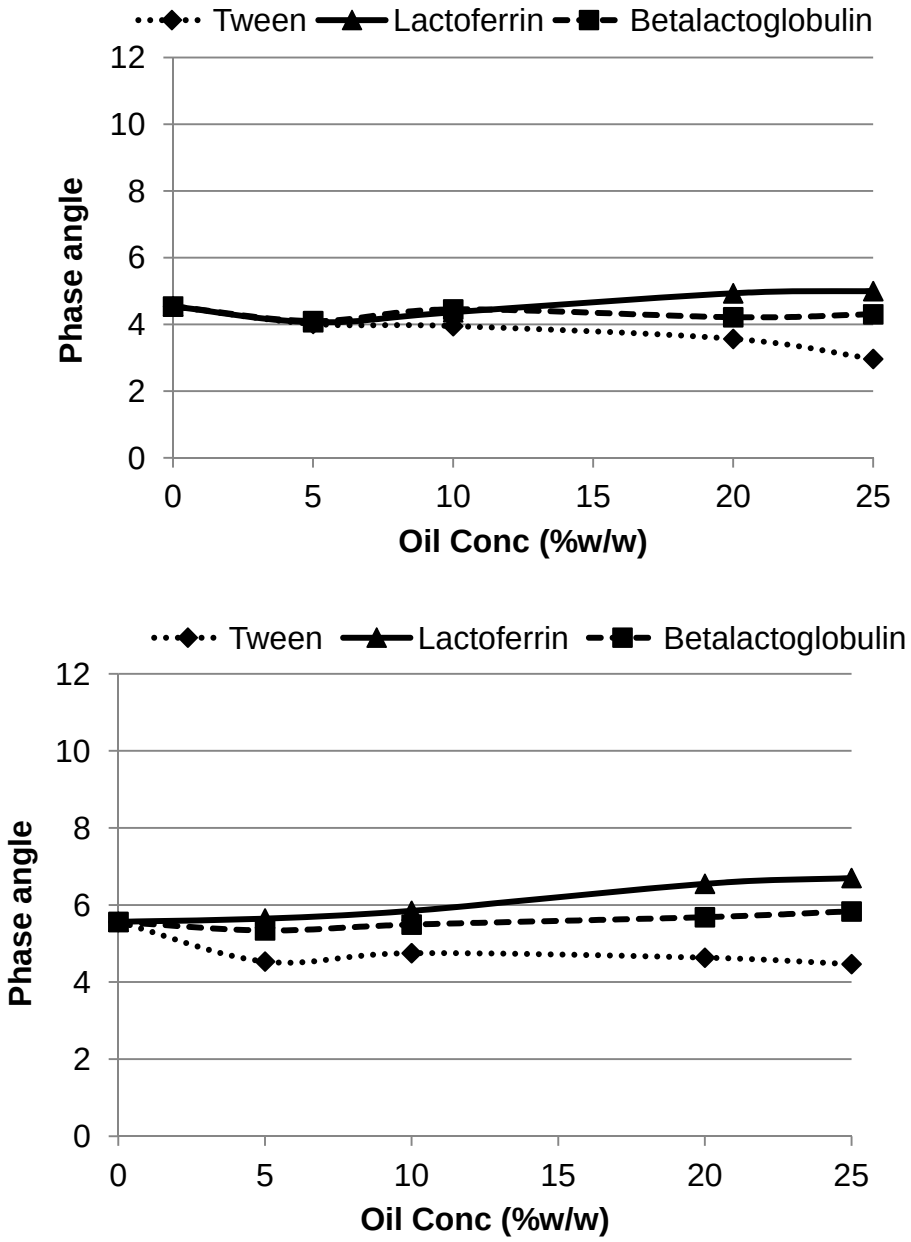


Figure 4. Change in phase angle of agar gels (top) and κ-carrageenan gels (bottom) at 1 Hz at different oil concentrations.

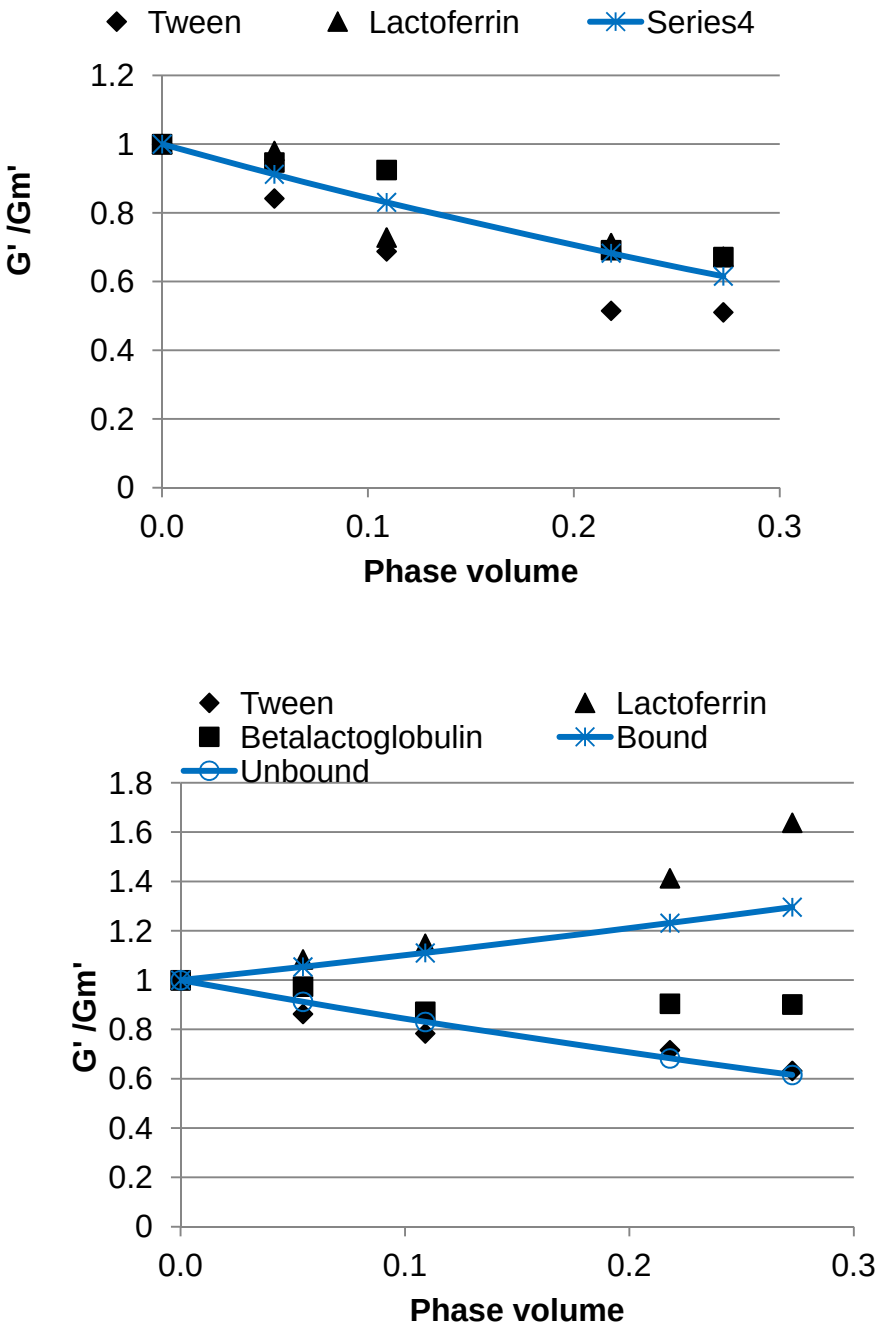
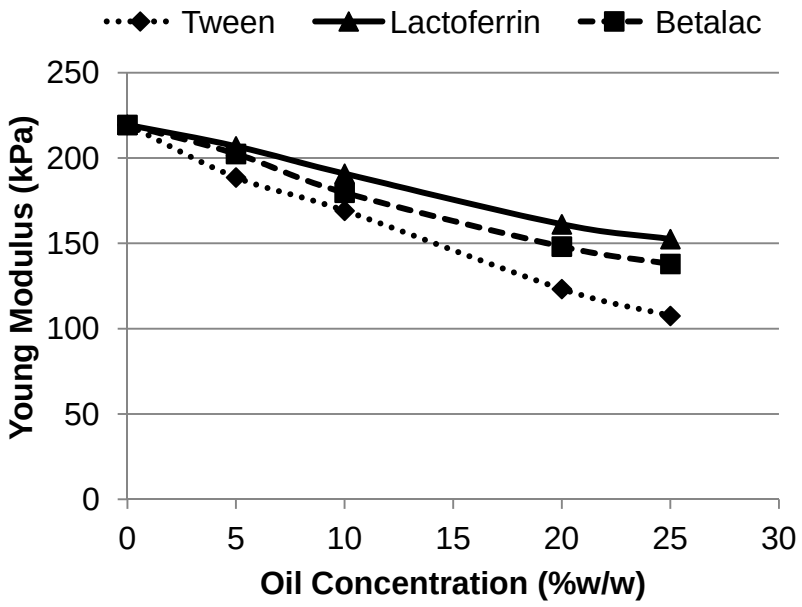


Figure 5. The effect of oil phase fraction on the ratio of storage modulus of filled gel to matrix of agar gels (top) and κ-carrageenan gels (bottom) at 1 Hz at different oil concentrations. Blue lines show modeling based on van der Poel theory assuming $G'_f=0$, surface tension=6 mN/m and poission ratio= 0.5

A. Agar



B. κ-Carrageenan-locust bean gum

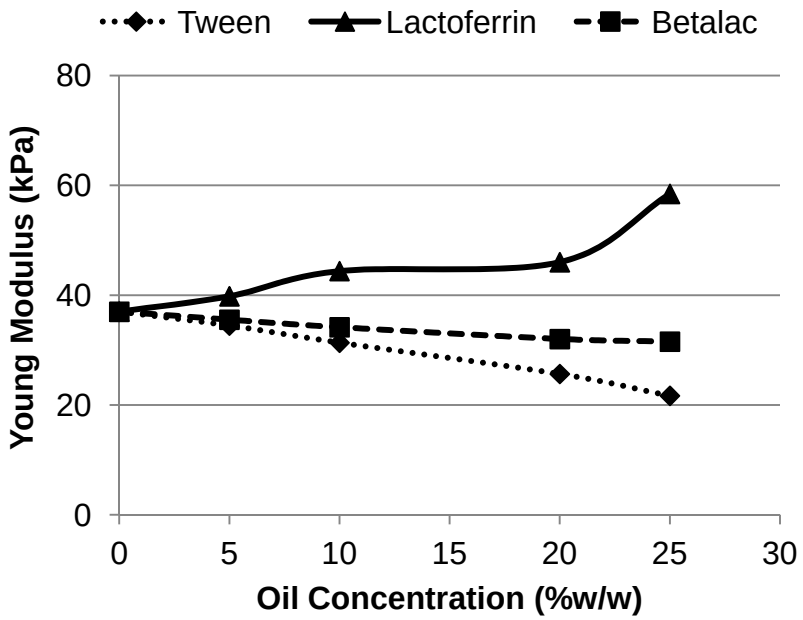


Figure 6. Change in Young's modulus with increase oil concentration for agar gels (a) and for κ-carrageenan gels (b).

C.

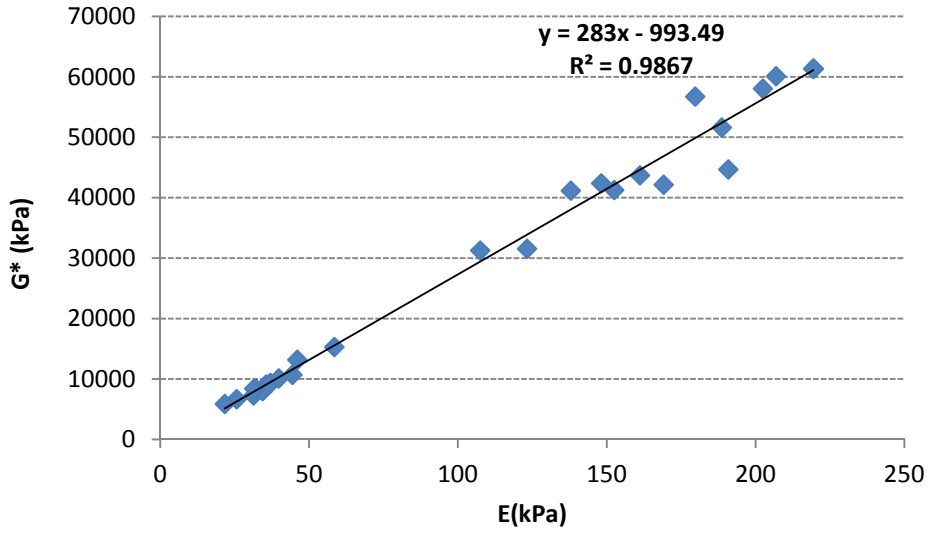
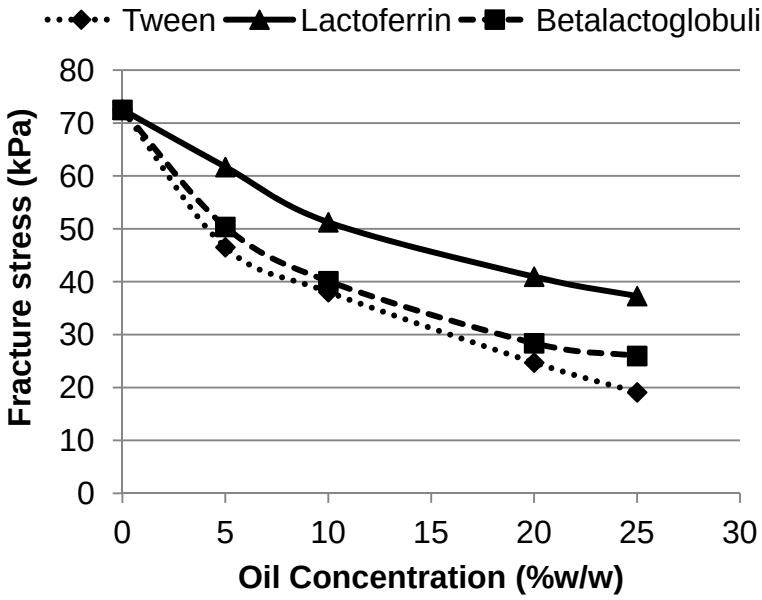


Figure 6c. Relation between complex modulus (G*) and Young's Modulus (E) for all gels.

A. Agar



B. κ-Carrageenan-locust bean gum

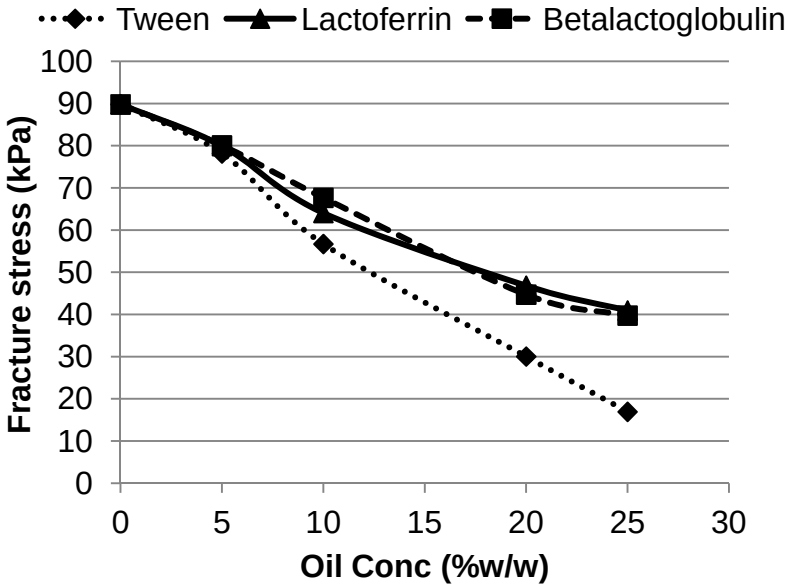
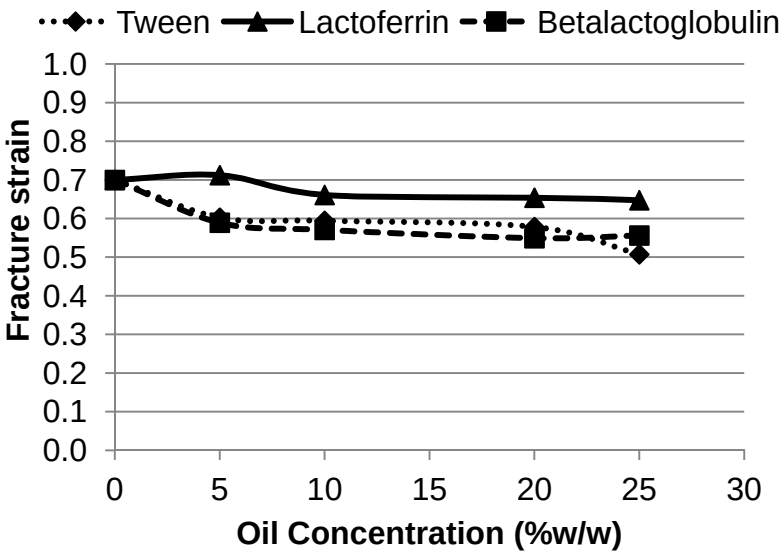


Figure 7. Change in fracture stress with increase oil concentration for agar gels (a) and for κ-carrageenan gels(b).

A.Agar



B. κ-Carrageenan-locust bean gum

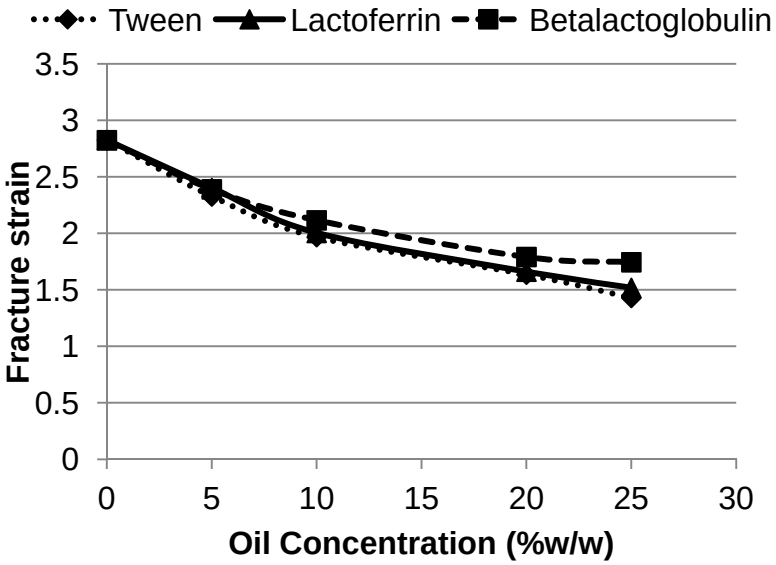
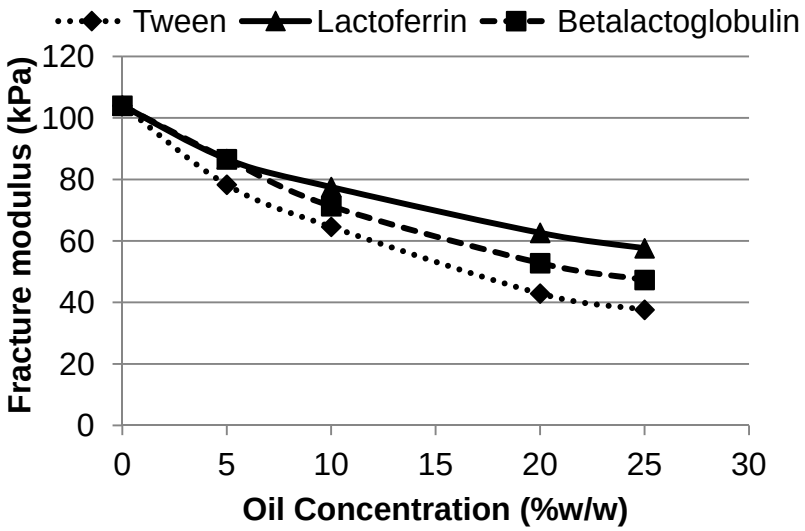


Figure 8. Change in fracture strain with increase oil concentration for agar gels (a) and for κ-carrageenan gels (b).

A. Agar



B. κ-Carrageenan-locust bean gum

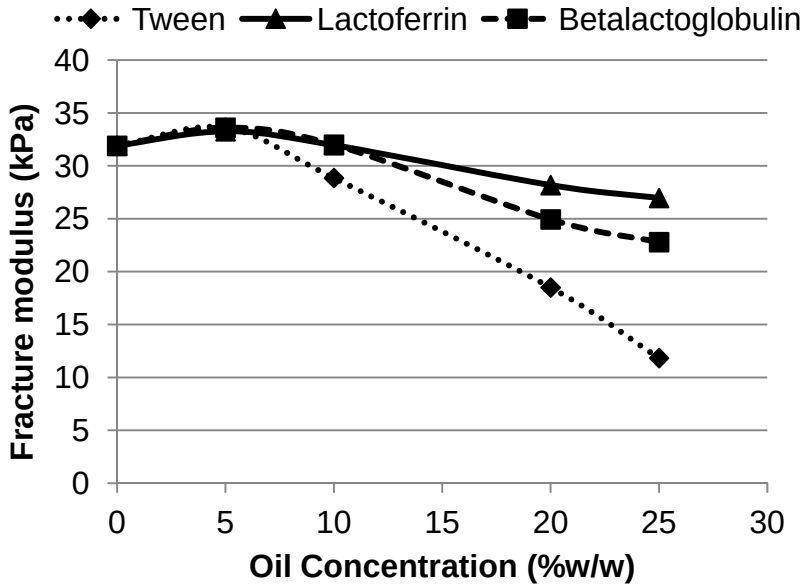
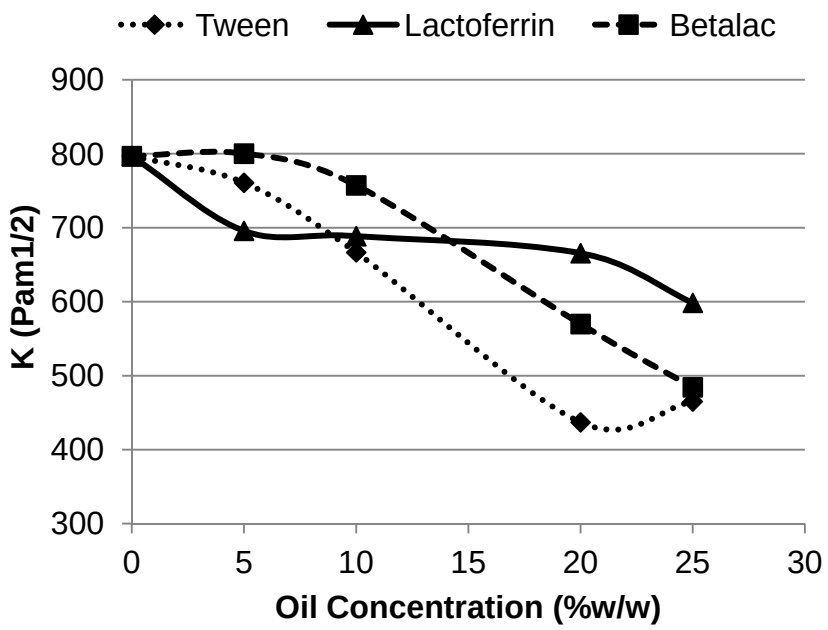


Figure 9. Change in fracture modulus with increase oil concentration for agar gels (a) and for κ-carrageenan gels (b).

A. Agar



B. κ-Carrageenan-locust bean gum

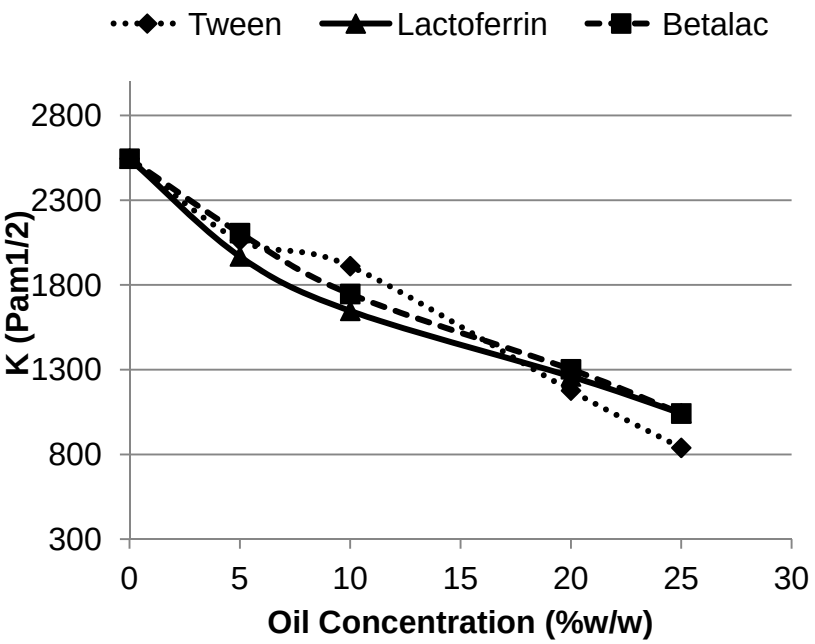
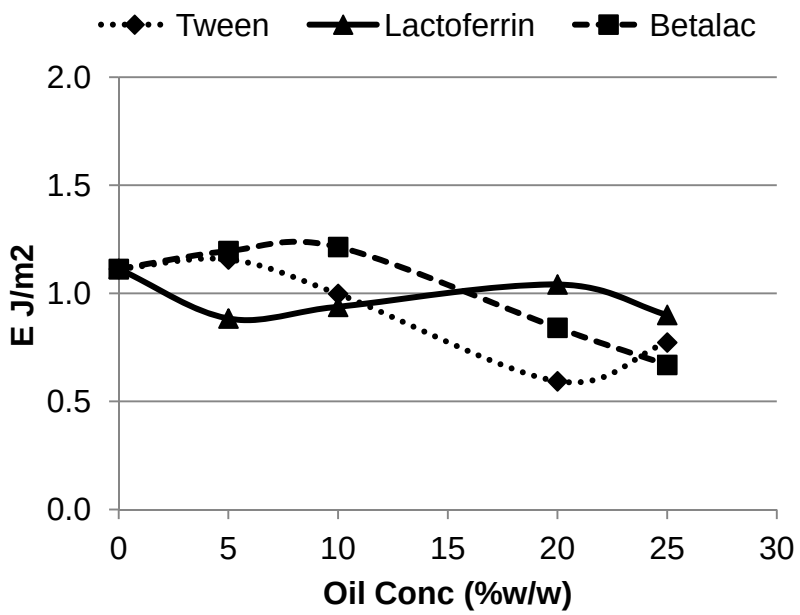


Figure 10. Change in stress intensity factor with increase oil concentration for agar gels (a) and for κ-carrageenan gels (b).

A. Agar



B. κ-Carrageenan-locust bean gum

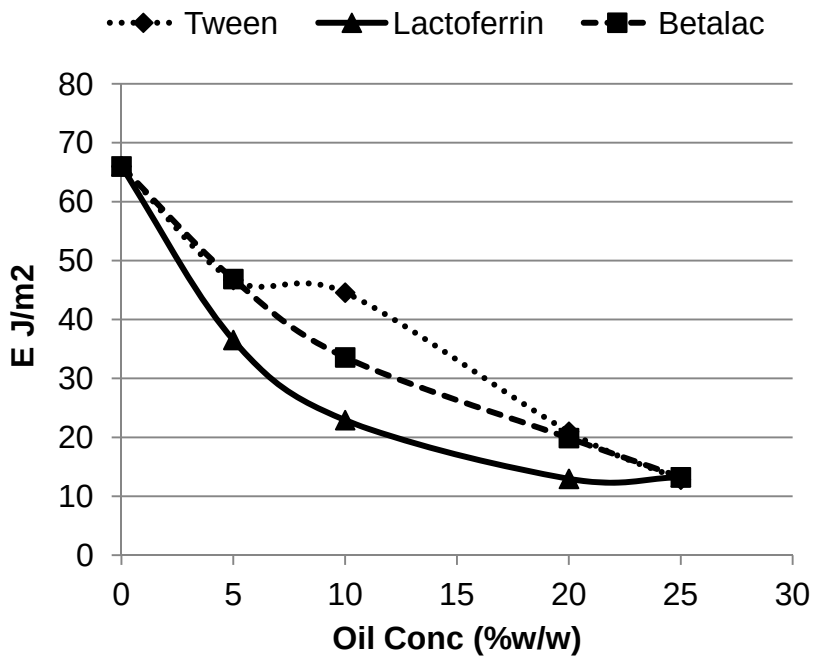


Figure 11. Change in fracture surface energy with increase oil concentration for agar gels (a) and for κ-carrageenan gels (b).

CHAPTER 5

Sensory Texture of Emulsion Filled Polysaccharide Gels Explained by Microrheology and Oral Processing

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Abstract

Low fat products have reduced consumer acceptability due in part to altered flavor and texture sensory attributes. Polysaccharide emulsion gels were studied as a model system to understand the effect of fat on texture. Descriptive sensory analysis was used to evaluate textural properties during tongue-palate compression, first chew, mastication and after expectoration. Agar gels and κ-carrageenan-locust bean gum gels were formulated to have similar strength (fracture stress), but different deformability (fracture strain). Corn oil droplets (1 μm diameter) stabilized by β-lactoglobulin were added at 0, 10 and 20% (w/w). Particles were inactive filler in both gel networks. Changes in textural properties were explained by oral processing and microrheology (compression unit attached to a confocal microscope) images. Agar gels had a brittle fracture pattern while κ-carrageenan-locust bean gum gels displayed elasto-plastic (ductile) fracture. Oil droplets greatly reduced sensory springiness of agar gels but not κ-carrageenan-locust bean gum gels. Sensory hardness of both networks was significantly reduced by oil droplets, while deformability decreased only for the κ-carrageenan-locust bean gum gels. Both gels did not exhibit adhesive or cohesive sensory properties without oil, but agar gels developed some cohesiveness and adhesiveness after 10 and 20% oil were added. Increased adhesiveness and cohesiveness coincided with a greater degree of coalescence of oil droplets during compression. Interestingly, these microstructural and sensory texture changes are also seen when increasing fat content of Cheddar cheese. Change in sensory properties altered the oral manipulation of filled gels. Number of chews and muscle activities during mastication were affected by textural changes caused by oil droplets, while variation in jaw movements mainly reflected the type of gel

being chewed. It was shown that inactive oil droplets significantly affected sensory properties and oral processing of polysaccharide gels and that this may be related to the fracture pattern. Textural properties of gels showing a brittle fracture pattern were the most sensitive to filler particles.

Keywords: Emulsion filled gel, sensory, microrheology, fracture, oral processing

1. Introduction

Fat is an essential part of daily food intake for nutrition and energy. It also has a significant role in sensory quality of food products. Among macronutrients, fat is the most energy dense providing 9 kcal/g. Fat consumption, in most of the developed countries, is above the recommended limit of 30% of energy from fat (WHO, 2003), which is associated with increases in obesity and chronic diseases. The USDA Dietary Guidelines recommends increasing the consumption of fat-free or low-fat milk and milk products, such as milk, yogurt, cheese and also replacing the solid fat from diets (USDA, 2010). However, consumers tend to associate reduced fat products with the poor quality (Hamilton et al., 2000; Porter et al., 1998). Given this perception, fat reduction has a significant negative impact on texture of various products such as baked goods (McEvans and Sharp, 2000), cheese (DMI, 2009), and meat (Mittal and Barbut, 1994). For example, low fat cheeses are characterized by increased hardness, springiness and low intensities of adhesives and cohesiveness, which reduce their consumer acceptability (Bryant et al., 1995; Gwartney et al., 2002; Rogers et al., 2009).

Cheese and processed meats can be considered as filled gels; with a particle phase dispersed in a gel phase. Filler particles can alter the microstructure and physical properties of the gel and result in detrimental effects on sensory perception. To understand these effects of fillers on foods, model foods, such as emulsion filled gels, have been studied. Most of the research in this field focuses on mechanical properties determined at small strains (Chen and Dickinson, 1998; Rosa et al., 2006; van Vliet, 1988) with some investigations on fracture properties (Sala et al., 2007, McClement et al., 1993; Kim et al., 1996). Limited investigation has been conducted that use microstructure and mechanical properties to explain sensory texture. Firmness of whey protein isolate (WPI) gels filled with sunflower oil increases by oil content (Gwartney et al., 2004) at constant protein concentration (i.e., exchanging water and protein). However, filled WPI, gelatin and carrageenan gels are perceived less firm with the increased level of oil content (Sala et al., 2008) at constant polymer concentration in aqueous phase (i.e., removing both protein and water). Changes in number of chews and chewing time are other parameters associated with oil content (Gwartney et al., 2004). Other sensory properties, such as adhesiveness or cohesiveness are affected by gel structure type (fine stranded vs. particulate), and they are not altered with oil incorporation. Another sensory attribute influenced by fillers is creaminess. Creaminess perception of emulsion filled WPI, gelatin and carrageenan gels increases with the level of oil content (Sala et al., 2008). Moreover, creaminess can be affected by the interaction between filler particles and gel network. κ-Carragenan gels with unbound oil droplets are perceived as more creamy compared to WPI gels with bound droplets. Another factor affecting sensory perception is droplet size. When agar gels are filled with different sizes

(1.5, 6.5, and 12.2 μm) of oil droplets, gels with bigger droplets are perceived as oilier and softer (Kim et al., 1996).

Understanding the effect of filler particles on gel sensory and mechanical properties is essential to be able to solve the problems associated with undesirable textures of reduced fat products. Most of the investigations of emulsion filled gels have been done extensively to understand the filler effects on viscoelastic properties or fracture properties. Studies on sensory perception of filled gels are limited. Two comprehensive studies on sensory texture were carried out by Gwartney et al. (2004) on filled WPI gels and by Sala et al. (2008) on filled WPI, gelatin and carrageenan gels. Sala et al. (2008) studied various sensory attributes of emulsion filled WPI, gelatin and carrageenan gels. However these textures are limited to semi-solid type structures and the key attribute is creaminess. Gwartney et al. (2004) has also studied weak protein gels (fracture stress of 11 kPa) but varying in structure, fine stranded vs. particulate. In our previous work (Koc et al., 2012a) stronger polysaccharide gel networks (75-90 kPa) varying at fracture stain (0.7 and 2.8) and having different fracture mechanism (brittle vs. ductile) were developed. In this study, these model foods were characterized by descriptive sensory analysis. Moreover, to explain the sensory texture of filled gels, oral processing analysis and microrheology tests were carried out. The objectives of this study were to understand: 1) the filler effect on sensory perception of strong, soft solid type gels, 2) sensory perception of filled gels which exhibited different types of fracture mechanism, 3) relations between sensory perception of filled gels, oral processing, and microrheology.

2. Materials and Methods

2.1. Materials

Agar powder (110 FCC/NF) was donated by TIC Gums (Belcamp, MD). κ-carrageenan (GenuGel® CHP-2, Denmark), and locust bean gum (Genu®Gum RL-200Z, Atlanta, GA) were donated by CP Kelco. Crystalline potassium chloride (KCl) and pellets of sodium hydroxide (NaOH) were purchased from Fisher Scientific (Fair Lawn, NJ). Corn oil (Mazola ®) was purchased from a local grocery store. Hydrochloric acid (HCl) was obtained from Mallinckrodt Baker Inc. (Paris, KY). Beta-lactoglobulin was donated by Davisco Foods International Inc. (Le Sueur, MN). The protein content (97.9%) of the β-lactoglobulin powder was obtained by nitrogen determination by inductively coupled plasma spectroscopy and using the factor of 6.38 to convert % nitrogen to % protein. Nile Blue A Sulfate was obtained from MP Biomedicals LCC (Solon, OH).

2.2. Sample Preparation

Oil in water stock emulsions (40% w/w) stabilized with β-lactoglobulin was prepared with corn oil and deionized water as described previously (Koc et al., 2012a). Agar (3% w/w) and κ-carrageenan-locust bean gum (1.8% w/w in 0.02 KCl solution) dispersion were prepared with different oil concentrations (0, 10, and 20%). Gelling agent concentration in the water phase was kept constant for all samples. Agar powder was mixed into deionized water and stirred at room temperature (22 ± 2 °C) for 1 h. Following a 1 min boiling by microwave heating, the solution was held in water bath at 85 °C for 1 hr. The solution was mixed with heated emulsion (85 °C) at a 1:1 ratio and poured into cylindrical glass tubes

(i.d.=19 mm) and held for 2 h at room temperature (22 ± 2 °C) and then stored at 4 ± 2C for 16-24 hr for gelling. The gels were equilibrated at room temperature (22 ± 2 °C) for 2 hr prior to analysis.

Premixed κ-carrageenan(C) and locust bean gum (LB) powders were hydrated for 1 hr at room temperature and then held in a water bath at 90 ^{o}C for 1 hr. Solutions were subsequently boiled on a heated stirrer plate and held in a water bath at 90 ^{o}C another hour. The solution was mixed with heated emulsion (90 ^{o}C) in a 1:1 ratio and poured into cylindrical glass tubes (i.d.=19 mm) and gelled at room temperature (22 ± 2 ^{o}C) for 16-24 hr. Samples were stored at 4 ± 2 ^{o}C until testing. The gels were equilibrated at room temperature (22 ± 2 ^{o}C) for 2 hrs prior to analysis.

2.3. Descriptive Sensory Analysis

Descriptive sensory analysis with a highly trained (>500 hr experience on food texture) panel (7 women, aged 45-60 years) was used to describe sensory texture of model foods. Gel textural attributes established by Gwartney et al. (2004) and Barrangou et al. (2006) were slightly modified and used according to the Spectrum method (Table 1). "Oily mouthfeel" attribute was added under mastication attributes. Moisture release during first bite and mastication was changed into moisture/oil release. Moisture mouthcoating was changed into moisture/oil mouthcoating. A 15-point reference scale was used for the analysis with 1 representing "not" and 15 representing "very". Two cheese samples (Harris Teeter mozzarella and Kraft sharp cheddar) and one gel sample (3% Agar with 60% glycerol) were presented as references. Samples were cut into 19 mm diameter and 15 mm long

cylinders and served at room temperature in 2 oz. plastic cups marked with 3-digit random numbers. Panelists were asked to chew samples up to the point of swallowing then expectorate the sample and rinsed the mouth with water between samples. Sample assessments were conducted in three replications.

2.5. Microrheology

Step wise compression was conducted by an Inspec 2000 (Instron Int., Boechout, Belgium) compression unit attached to a Leica TCS SP CSLM (Leica Microsystems, Mannheim, Germany). Details of the microrheology setup were described by van der Berg et al. (2008). Objective used in the imaging was a PL Fluotar L 63.0 x 0.70 dry objective. Samples were cut into 19 mm diameter and 10 mm long cylinders and stained with Nile Blue. Stained samples were placed on a glass cuvette (1 mm thick) which did not bend during compression. Samples were compressed at a constant rate of 20 mm/min in 1 mm steps. After each step, xy-scans of gel microstructure were captured. Stop time between two subsequent compression steps was approximately 5 min. True stress and strain were calculated from load and deformation data following Koc et al. (2012a).

2.6. Oral Processing

Muscle activity and three dimensional jaw movements were used as measurements of oral processing. Subject selection criteria, data collection and data analysis are described in Koc et al. (2012b). Electrical activities of anterior temporalis, superficial masseter, and anterior digastrics were measured simultaneously with the jaw movements in lateral, vertical and

anterior/posterior directions. Agar and κ-carrageenan gels, total of 6 samples, were chewed in duplicate. The complete study was conducted in one session with twelve subjects (6 men, 6 women, aged 25-30 years).

2.7. Statistical Analysis

Data was analyzed with SAS (9.2) to obtain treatment effects, significant differences and pairwise correlation coefficients. Procedures were described previously (Koc et al., 2012b). In addition, principal component analysis was done by JMP 9.0 statistical programming.

3. Results and Discussion

3.1. Descriptive Sensory Analysis

Mean attributes data with statistical differences (Table 2) will be discussed in following sections of tongue-palate compression, first chew, and mastication and residual (after expectoration) corresponding to different phases of oral processing.

Tongue-Palate Compression

In this phase, attributes of springiness and compressibility are evaluated by compression of samples between tongue and hard palate. The main differences in sensory properties are represented in the Fig. 1. Agar (A) and κ-carrageenan-locust bean gum (C) gels without any oil droplets were very springy. They recovered almost fully after a partial compression between the tongue and hard palate. High springiness was expected from these gel networks, since they are predominantly characterized with by their elastic behavior. When oil was incorporated in agar gels, the springiness was reduced at the 10% oil level and

not detected at the 20% oil level. Addition of oil resulted in very low recovery after compression which indicates an energy dissipating process such as friction between oil droplets and the network or disruption of the network. The effect of oil droplets on the springiness was not observed in κ-carrageenan-locust bean gum gels. Gels with 10 % oil (C10) and 20% oil (C20) were perceived to be as springy as gels without oil. Change in springiness of agar gel with oil addition agrees with the decrease in the high intensity springiness of fine stranded WPI gels when oil was added (Gwartney et al., 2004). Similar to κ-carrageenan-locust bean gum gels, oil droplets did not affect the springiness of particulate WPI gels. Particulate WPI gels were characterized with low intensity of springiness. Due to the strength of their mechanical properties, compressibility of gels was not evaluated, except filled agar gels.

First Chew

Hardness, fracturability, deformability and moisture/oil release were evaluated during the first chew with molars. Addition of oil into the gel network caused approximately 50% and 25% reduction in hardness of agar and κ-carrageenan-locust bean gum gels, respectively. The differences between gel hardness of 10% and 20% oil added were small. Hardness of fine-stranded and particulate WPI gel networks increased with oil addition up to 20% (Gwartney et al., 2004). This reinforcement effect of network can be attributed to the interaction between oil droplets and protein networks. Another contributing factor could be the increase in protein concentration in aqueous phase. Hardness of WPI, gelatin, and carrageenan gels decreases with increasing emulsion concentration when the polymer concentration is constant in aqueous phase (Sala et al., 2009). Decrease in sensory hardness

for protein gel networks having active fillers did not correspond to changes in Young's modulus. However, there were slight decreases in fracture stress of WPI and gelatin gels which can explain the change in sensory perception. Deformability of agar gels was low with a score of 2 and decreased slightly with oil. κ-Carrageenan-locust bean gum gels were four times more deformable than agar gels. Addition of oil reduced deformability of these gels; however they were still more deformable than agar gels. A similar decrease in compressibility of WPI gels has been reported (Gwartney et al., 2004). Moisture and oil release with first chew was low for gels varying between 0.7-1.5 (Table 2). Filled agar gels released the least moisture/oil.

Mastication

After chewing 5- 8 times, agar and κ-carrageenan gels did not exhibit cohesive and adhesive properties in the absence of oil. Agar gels developed some cohesiveness and adhesives after 10 % and 20% oil were added into network and were perceived slightly as chalky. On the other hand, filler droplets did not cause the same effect on the deformable κ-carrageenan-locust bean gum gel networks. In comparison with filled polysaccharide gels, the addition of oil to WPI gels did not change cohesiveness and adhesiveness of fine stranded or particulate gel networks (Gwartney et al., 2004). Fine stranded gels are characterized by low intensities of cohesiveness and adhesiveness while particulate gels are perceived as the opposite (Gwartney et al., 2004; Cakir et al., 2012). Moisture/oil release during mastication was very similar to moisture/oil release during the first chew, it was reduced slightly for filled agar gels. After gels were chewed 5-8 times, particle size distribution was relatively homogenous (Table 2). Agar gels broke down into smaller pieces compared to

κ-carrageenan-locust bean gum gels. Filled agar gels formed smaller particles than agar gel during chewing. Rate of breakdown for agar and κ-carrageenan-locust bean gum gels was relatively slow. It increased dramatically once oil was incorporated into the agar gel network. Inversely, there was only a slight increase in the breakdown rate of κ-carrageenan-locust bean gum gels containing oil. Addition of oil caused a faster breakdown of structure, thus resulting in fewer chews need before swallowing. The number of chews for agar gels reduced from 27 to 22, and for κ-carrageenan-locust bean gum gels reduced from 31 to 28 when oil was added. An opposite observation made on WPI gels; oil incorporation to network caused an increase in number of chews (Gwartney et al., 2004). Sensory hardness of filled WPI gels increased in contrast to the decrease observed in filled polysaccharide gels. Hardness could be one of the attributes contributing to the number of chews and would explain the differences between gels. The increase in breakdown rate with addition of oil to WPI gels are in agreement with our findings (Gwartney et al., 2004), although there is some discrepancy between particle size results. While filled polysaccharide gels showed decrease in particle size with oil addition, no change or increase was observed for fine stranded and particulate protein gels, respectively. Oily mouthfeel attribute was evaluated for gels and was perceived as very low (Table 2), although it increased slightly with the addition of oil to the κ-carrageenan-locust bean network. Oily mouthfeel (oily; fatty layer) and creaminess (velvety; warm; full; soft) are different for emulsion filled WPI, carrageenan and gelatin gels (Sala et al., 2009). Creaminess was related to oil concentration and gel type; however, oily mouthfeel was related to gel type only. Perception of creaminess is evaluated with high intensities for networks melting in oral conditions (gelatin) or networks with unbound oil

droplets (carrageenan). The differences in oily mouthfeel perception of κ-carrageenan-locust bean gels and κ-carrageenan gels, both with unbound droplets, can be attributed to the differences in mechanical properties of these networks.

Residual

More particles remained in the mouth after agar gels were chewed than κ-carrageenan-locust bean gum gels, however addition of oil did not cause any difference. Gels without oil had some degree of moisture/oil mouthcoating. Filled agar gels showed the least moisture/oil mouthcoating.

Correlations

Overall, the biggest effect of filler droplets was observed on hardness and deformability of κ-carragenan-locust bean gum gels. Also, there were slight changes in particle size and rate of breakdown. The filler effect on agar gel network was more significant by causing it to be less springy, softer, more adhesive and cohesive. These changes in sensory perception with increased oil in agar gel network corresponded to similar changes in cheese texture with increased fat content. Filled agar gels were broken into smaller pieces at a faster rate resulting in fewer number of chews.

Principal component analysis (PCA) of the sensory data (Fig. 2) showed the clear differences between gel types. Principal component 1 (PC1) explained 78.5% of the variation and discriminated filled agar gels from agar gel without oil and κ-carrageenan gels (with and without oil) by adhesiveness, cohesiveness, chalkiness and rate of breakdown. These attributes characterize the properties of filled agar gels. The second principal

component explained only 12.8% of the variation. All κ-carrageenan gels were clustered together on the PCA biplot indicating small differences among these gels.

Correlations among sensory attributes are presented in Table 3. Hardness and deformability, at first bite and with hand, were related to each other (r = 0.83 and r = 0.86, respectively) which may indicate a coupling effect in the evaluation of these attributes. The harder the gels, the slower the breakdown (r = -0.97) and the larger the particles (r = 0.97). This relationship between hardness, particle size and rate of breakdown was seen when these model gels were adjusted to change in level of strength and deformability (Koc et al., 2012c). In agreement with observed relationship between fracture stress and number of chews in previous works (Gwartney et al., 2002; Cakir et al, 2012, Koc et al., 2012c), hardness predicted number of chews (r = 0.99) made to prepare gels for swallowing. Fracturability was negatively correlated with particle size (r = -0.90) and positively correlated with particle mouthcoating (r = 0.92) showing that highly fracturable gels were broken down in small pieces and had more particle mouthcoating. Deformability at first bite and with hand evaluation were strongly associated with particle mouthcoating (r = -0.87 and r = -0.99, respectively) which is in agreement with previous results on model foods (Koc et al., 2012c).

Relationships among instrumental parameters and sensory attributes are given in Table 4. Hardness was related to fracture stress, stress intensity factor and fracture surface energy. Hardness was also related to fracture strain. And fracture strain was correlated to many other sensory parameters which may indicate the coupling of stress and strain in sensory evaluation. Deformability was correlated to fracture strain, stress intensity factor and

fracture surface energy. The association between particle mouthcoating and fracture strain was significantly similar to relation between particle mouthcoating and deformability.

3.2. Microrheology

Images of gels before compression and after each step of compression are reported in Fig. 3 and Fig. 4. Pink color represents oil droplets against the green background. First images show the distribution of oil droplets in gel before compression. A great degree of coalescence of oil droplets were observed when filled agar gels were compressed stepwise (Fig. 3). At each compression level, degree of coalescence increased, oil droplets clumped into large irregular shaped particles. In the last image of Fig. 3, at 6mm compression, fracture surfaces and also some oil release were observed. Oil droplets moved in the network during compression. Highly deformable κ-carrageenan-locust bean gum gels also had slight coalescence but it was not as dramatic as observed in agar gel networks (Fig. 4). κ-Carrageenan-locust bean gum gels could not be compressed more than a few steps because gel pieces slid during testing. Different heights of samples were compressed to see if sliding could be avoided but none were successful. κ-Carrageenan-locust bean gum gels were too deformable to fracture by compression testing (Koc et al., 2012b).

Stress-strain values observed in step-wise compression (Fig. 5) indicated that starting values of stress at one compression step was lower than end stress values of the previous compression step. There was 5 min stop time between each compression steps and therefore this was essentially a series of stress-relaxation tests. The relaxation of gel networks between compressions steps were found to not cause any change in microstructure or fracture

properties of gels (van der Berg et al., 2008). Filled agar gels had similar fracture strains in stepwise compression and in continuous compression (Koc et al., 2012a). No fracture was observed in κ-carrageenan-locust bean gum gels.

3.3. Oral Processing

Number of chews and total time for chewing sequence decreased approximately 20-25% with addition of oil in both type of gels (Table 5). Average time spent for one cycle varied between 597-612 ms but it was not different significantly for any of the gels. Similarly, frequency was constant for all treatments. Opening duration was longer for agar gels compared to more deformable κ-carrageenan gels, while occlusal duration was shorter. Higher occlusion time with increased level of deformability of κ-carrageenan-locust bean gum gels at varied ratios of concentration for κ-carrageenan to locust bean gum has been reported previously (Koc et al., 2012b). Addition of oil resulted in an increase of opening duration of both gels while decrease in occlusion duration only for κ-carrageenan gels. Decrease in occlusion duration with oil addition to κ-carrageenan gels can be explained by reduced deformability of gels.

Amplitudes of jaw movements were larger for agar gels, however changes in texture with oil did not cause a significant change in jaw movements overall. Differences in jaw movements were mainly caused by gel type, not the effect of filler, which is in agreement with oral processing of cheeses with different fat levels (Cakir et al., 2011). Note the slight increase in vertical and anterior/posterior movements for agar gels with increased oil concentration can be associated with increased chewdown properties such as adhesiveness

and cohesiveness. Temporalis and masseter muscle activities during chewing of agar gels were lower than κ-carrageenan. Activities of jaw closing muscles decreased with addition of oil significantly in both gels. Digastric activity per chew increased with oil in agar, did not change for κ-carrageenan, however total DA activity for a chewing sequence decreased with oil for both. DA activity during agar chewing was slightly higher than κ-carrageenan gels. Total activity of three muscles did not vary to a large extent between gel types, but decreased significantly with oil.

Number of chews and chewing time were associated strongly with the hardness ($r = 0.90$ and $r = 0.88$, respectively) of the gels. Occlusion duration was related to deformability at first bite ($r = 0.90$) and hand deformability ($r = 0.97$). Anterior posterior jaw movements were related to adhesiveness ($r = 0.88$). Muscle activities are closely associated with hardness and some associations between digastrics activity and adhesiveness ($r = 0.90$) and particle mouthcoating ($r = 0.93$) were also present.

4. Conclusions

Inactive oil droplets stabilized by β-lactoglobulin greatly changed first chew sensory attributes of agar gels and κ-carrageenan-locust bean gum gels. Significant changes in chewdown properties were observed mainly for agar gels. Changes in microstructure and sensory perception of agar gels with increased oil content correspond to changes in Cheddar cheese with increased fat. The mastication parameters, number of chews and muscle activities, were affected by textural changes caused by oil droplets, while jaw movements mainly depended on the type of gel. It was shown that inactive oil droplets significantly

affected sensory and oral processing properties of polysaccharide gels; however, the effect depended on the fracture pattern of the primary network. These results have implications in developing low fat, soft solid food products.

References

Bryant, A., Ustunol, Z., & Steffe. J. (1995). Texture of cheddar cheese as influenced by fat reduction. *Journal of Food Science,* 60(6), 1216-1219

Chen, J., & Dickinson, E. (1998). Viscoelastic properties of heat-set whey protein emulsion gels. *Journal of Texture Studies,* 29(3), 285-304.

Cakir, E., Koc, H., Daubert, C., Drake, M., Essick, G., Vinyard, C., & Foegeding, E.A. 2011. Evaluation of texture changes due to compositional differences using oral processing. *Journal of Texture Studies*

Çakır, E., Daubert, C. R., Drake, M. A., Vinyard, C. J., Essick, G., & Foegeding, E. A. (2012). The effect of microstructure on the sensory perception and textural characteristics of whey protein/κ-carrageenan mixed gels. *Food Hydrocolloids,* 26(1), 33-43.

Dairy Management Inc. (DMI). (2009). Low fat cheese research. Special report.

Gwartney, E. A., Foegeding, E. A., & Larick, D. K. (2002). The texture of commercial full-fat and reduced-fat cheese. *Journal of Food Science,* 67(2), 812-816.

Gwartney, E. A., Larick, D. K., & Foegeding. E. A. (2004). Sensory texture and mechanical properties of stranded and particulate whey protein emulsion gels. *Journal of Food Science,* 69(9), 333-339.

Hamilton, J., Knox, B., Desmond, H., & Parr, H. (2000). Reduced fat products – Consumer perceptions and preferences. *British Food Journal*, 102 (7), 494 – 506.

Kim, K., Gohtani, S., & Yamano, Y. (1996). Effects of oil droplets on physical and sensory properties of o/w emulsion agar gel. *Journal of Texture Studies,* 27(6), 655-670.

Koc, H., Khan, S., Daubert, C.R., & Foegeding, E.A. (2012a). Effect of filler type and concentration on small and large strain rheological properties of emulsion filled polysaccharide gels. (Chapter 4).

Koc, H., Cakir, E., Daubert, C.R., Drake, M., Essick, G., Vinyard, C., Osborne, J., & Foegeding, E.A. (2012b). Alteration of oral processing with increased fracture stress and fracture strain of model foods. (Chapter 2).

Koc, H., Cakir, E., Daubert, C., Drake, M., Essick, G., Vinyard, C., & Foegeding, E.A. (2012c). Sensory texture of model foods based on large deformation rheological properties and oral processing. (Chapter 3).

McClements, D. J., Monahan, F. J., & Kinsella, J. E. (1993). Effect of emulsion droplets on the rheology of whey protein isolate gels. *Journal of Texture Studies,* 24(4), 411-422.

McEvans, J. A., & Sharp, T. M. (2000). Technical, economic and consumer barriers to the consumption of reduced fat bakery products. *Nutrition & Food Science,* 30(1), 16 – 18.

Mittal, G. S., & Barbut, S. (1994). Effects of fat reduction on frankfurters' physical and sensory characteristics. *Food Research International,* 27(5), 425-431.

Porter, D., Kris-Etherton, P., Borra, S., Christ-Erwin, M., Foreyt, J., Goldberg, J., Nabors, L. O., Schwartz, N., Lewis, C., Layden, W., & Economos, C. (1998). Educating Consumers Regarding Choices for Fat Reduction. *Nutrition Reviews,* 56(5), 75-92.

Rogers, N. R., Drake, M. A., Daubert, C. R., McMahon, D. J., Bletsch, T. K., & Foegeding, E. A.. (2009). The effect of aging on low-fat, reduced-fat, and full-fat Cheddar cheese texture. *Journal of Dairy Science,* 92(10), 4756-4772.

Rosa, P., Sala, G., van Vliet, T., & van de Velde, F. (2006). Cold gelation of whey protein emulsions. *Journal of Texture Studies,* 37(5), 516-537.

Sala, G., de Wijk, R. A., van de Velde, F., & van Aken, G. A. (2008). Matrix properties affect the sensory perception of emulsion-filled gels. *Food Hydrocolloids,* 22(3), 353-363.

Sala, G., van Aken, G. A., Stuart, M. A. C., & van de Velde, F. (2007). Effect of droplet matrix interactions on large deformation properties of emulsion-filled gels. *Journal of Texture Studies,* 38(4), 511-535.

Sala, G., F. van de Velde, F., Stuart, M. A. C., & van Aken, G. A (2007). Oil droplet release from emulsion-filled gels in relation to sensory perception. *Food Hydrocolloids,* 21(5–6), 977-985.

van Vliet, T. (1988). Rheological properties of filled gels. Influence of filler matrix interaction. *Colloid & Polymer Science,* 266(6), 518-524.

van der Berg, L., Klok, J. H., van Vliet, T., van der Linden, E., van Boekel, M.A.J.S., & van de Velde, F. (2008). Quantification of a 3D structural evolution of food composities under large deformations using microrheology. Food Hydrocolloids, 22, 1574-1583.

World Health Organization (WHO) (2003). Diet, nutrition and the prevention of chronic diseases. WHO technical report series 916, Geneva, Switzerland.

Table 1. Gel texture attributes, evaluation techniques and definitions for filled gels

Tongue-Palate Compression	**Technique:** Compress the sample between the tongue and hard palate
Springiness	Degree to which the sample returns to the original shape after partial compression between the tongue and hard palate
Compressibility	Degree to which the sample deforms or compresses before fracture using the tongue and hard palate
First Bite	**Technique:** Bite completely through with the molars
Hardness	Force required to fracture the sample with the molars
Fracturability	Degree to which the sample fractures into pieces on the first bite with the molars
Moisture, oil release	Extent to which moisture and oil are released from the sample during the 1st bite with the molars
Deformability	The degree to which the sample deforms or compresses before fracture
Mastication	**Technique:** Chew 5-8 times and evaluate
Particle size	Size of breakdown particles (small to large)
Particle size dist.	Degree of homogeneity in the particle distribution size distribution
Cohesiveness	Degree to which the sample mass stays together as chewing progresses
Adhesiveness	Degree to which the mass or pieces stick to any mouth surfaces
Smoothness of pcs	Degree to which the mass or particles feel smooth
Chalkiness	Degree to which fine chalk-like particles are perceived
Moisture,oil release	Degree to which moisture and oil are released during mastication
Rate of breakdown	Rate at which the sample breaks into breakdown smaller and smaller particles (slow to fast)
# chews	Number of chews required to prepare the sample for swallowing when chewing at a rate of 1 chew per second
Oily mouthfeel	Perception of oily, fatty layer
Residual	**Technique:** Expectorate the sample and evaluate
Particle mouthcoat	Amount of particles remaining in the mouth after expectoration
Moisture, oil mouthc.	Amount of moisture and oil remaining in the mouth after expectoration
Other	
Deformability (hand)	The deformation % of sample at fracture by pressing the sample between thumb and first two fingers until sample fractures

Table 2. Mean values of sensory texture attributes of agar gels and κ-carrageenan-locustbean gum gels. (Samples with the same letter within a row are not significantly different, $p<0.05$).

Attributes	A	A10	A20	C	C10	C20
Tongue-Palate Compression						
Springiness	14.5^{a}	1.1^{b}	0.0^{c}	14.6^{a}	14.6^{a}	14.4^{a}
Compressibility	NA	1.8	1.9	NA	NA	NA
First Chew						
Hardness	5.4^{c}	2.6^{d}	2.2^{d}	8.3^{a}	6.5^{b}	5.9^{cb}
Fracturability	11.3^{a}	9.7^{b}	12.0^{a}	6.2^{c}	7.2^{c}	7.1^{c}
Moisture,oil release	1.5^{a}	0.8^{b}	0.7^{b}	1.1^{ba}	1.4^{a}	1.1^{ba}
Deformability	1.9^{d}	1.5^{d}	1.5^{d}	8.7^{a}	4.3^{c}	7.5^{b}
Mastication						
Particle size	6.9^{c}	5.4^{d}	4.8^{d}	10.1^{a}	9.5^{ba}	8.7^{b}
Particle size dist.	8.9^{b}	9.0^{b}	10.6^{a}	10.8^{a}	10.6^{a}	10.0^{a}
Cohesiveness	0.0^{c}	2.2^{b}	2.8^{a}	0.0^{c}	0.0^{c}	0.1^{c}
Adhesiveness	0.3^{c}	2.0^{b}	2.7^{a}	0.1^{c}	0.0^{c}	0.0^{c}
Smoothness of pcs	12.6^{b}	10.6^{c}	10.8^{c}	13.6^{a}	13.8^{a}	13.5^{ba}
Chalkiness	0.0^{b}	0.7^{a}	0.7^{a}	0.0^{b}	0.0^{b}	0.0^{b}
Moisture release	1.8^{a}	1.0^{b}	0.8^{b}	2.0^{a}	2.1^{a}	2.0^{a}
Rate of breakdown	4.6^{b}	9.3^{a}	9.7^{a}	3.0^{d}	3.5^{cd}	4.3^{cb}
# chews	26.5^{bc}	21.5^{d}	22.4^{dc}	31.4^{a}	29.0^{ba}	28.0^{ba}
Oily mouthfeel	0.2^{cb}	0.4^{cb}	0.0^{c}	0.3^{cb}	0.7^{b}	1.3^{a}
Residual						
Particle mouthcoat	4.8^{a}	4.9^{a}	4.6^{a}	2.1^{b}	2.1^{b}	2.5^{b}
Moisture/oil mouthc.	2.9^{a}	1.7^{b}	1.7^{b}	2.9^{a}	2.8^{a}	2.5^{ba}
Additional						
Deformability (hand)	2.9^{c}	2.2^{c}	2.3^{c}	12.6^{a}	11.3^{b}	11.3^{b}

*NA- Not applicable

Table 3. Significant correlation coefficients between sensory attributes ($p<0.05$)

	Comp.	**First bite**			**Mastication**									**Residual**		**Other**
	Spring-ness	Hard-ness	Fractura-bility	Deforma-bility	Moisture release	Particle size	Cohesive-ness	Adhesive-ness	Smooth-ness	Chalki-ness	Moisture release	Rate breakdown	Chews	Particle mct.	Moisture mct.	Hand deform.
Springiness	1.00	0.91			0.89	0.88	-1.00	-0.99	0.96	-1.00	0.98	-0.98	0.90		0.96	
Hardness		1.00		0.83		0.97	-0.91	-0.90	0.94	-0.91	0.92	-0.97	0.99	-0.82	0.91	0.86
Fracturability			1.00	-0.88		-0.90								0.92		-0.94
Deformability				1.00		0.86							0.84	-0.87		0.92
Moistrue r.					1.00		-0.89	-0.86		-0.88	0.83	-0.83			0.89	
Particle size						1.00	-0.87	-0.89	0.96	-0.87	0.93	-0.94	0.97	-0.93	0.83	0.95
Cohesiveness							1.00	0.99	-0.94	0.99	-0.98	0.98	-0.89		-0.95	
Adhesiveness								1.00	-0.95	0.98	-0.99	0.98	-0.89		-0.92	
Smootheness									1.00	-0.96	0.98	-0.98	0.96	-0.86	0.89	0.89
Chalkiness									-0.96	1.00	-0.97	0.98	-0.91		-0.96	
Moisture r.											1.00	-0.98	0.91		0.90	0.83
Rate breakdown												1.00	-0.96		-0.96	-0.82
Chews													1.00	-0.87	0.90	0.89
Particle mct.														1.00		-0.99
Moisture mct.															1.00	
Hand deform.																1.00

Table 4. Significant correlation coefficients between sensory attributes and rheological parameters ($p<0.05$)

	Fracture Stress (kPa)	Fracture Strain	Fracture Modulus (kPa)	Young's Modulus (kPa)	Intensity Factor ($Pa.m^{1/2}$)	Fracture Energy (J/m^2)	RE (%)
Springiness							
Hardness	0.88	0.90			0.90	0.86	
Fracturability		-0.92		0.88	-0.88	-0.84	
Deformability		0.91		-0.84	0.85	0.85	
Moisture r.							
Particle size		0.95		-0.81	0.91	0.87	
Homogeneity			-0.81				
Cohesiveness							
Adhesiveness							
Smoothness		0.84					
Chalkiness							
Moisture r.							
Ratebreakdown	-0.83	-0.81					
Chews	0.83	0.92			0.89	0.86	
Oily moutfeel							
Particle mct.		-0.96	0.84	0.97	-0.88	-0.86	
Moisture mct.	0.90						
Hand deform.		0.96	-0.81	-0.95	0.89	0.86	

Table 5. Oral processing parameters

	A	A10	A20	C	C10	C20	SE	F	p
n-chews	22^{ab}	17^{c}	17^{c}	23^{a}	21^{ab}	19^{bc}	2.25	10.92	<0.0001
t-chews	13^{a}	10^{c}	10^{c}	13^{a}	12^{ab}	11^{bc}	1.21	12.77	<0.0001
Frequency	1.7	1.7	1.7	1.7	1.7	1.7	0.09	1.21	0.3157
Cycle Duration	597	612	611	598	601	604	32.19	0.81	0.5473
Opening Duration	197^{ab}	210^{a}	210^{a}	179^{c}	187^{bc}	191^{bc}	14.91	10.56	<0.0001
Closing Duration	245	253	246	242	243	244	19.64	0.67	0.6469
Occlusal Duration	155^{b}	149^{b}	155^{b}	177^{a}	171^{a}	169^{a}	13.72	13.43	<0.0001
OpenVel	78^{a}	77^{ab}	78^{a}	77^{ab}	75^{ab}	73^{b}	4.64	2.93	0.0205
CloseVel	63^{a}	63^{a}	66^{a}	58^{b}	58^{b}	58^{b}	4.08	10.14	<0.0001
Vertical Amplitude	15.6^{a}	16.2^{a}	16.3^{a}	14.0^{b}	14.1^{b}	13.9^{b}	0.79	21.16	<0.0001
A/P Amplitude	4.1^{ab}	4.3^{a}	4.6^{a}	3.6^{bc}	3.7^{bc}	3.4^{c}	0.44	11.65	<0.0001
Lateral Amplitude	5.6^{a}	5.8^{a}	5.7^{a}	4.8^{b}	5.0^{b}	4.8^{b}	0.25	12.29	<0.0001
MaxWS Movement	4.3^{ab}	4.6^{a}	4.6^{a}	3.9^{bc}	4.0^{bc}	3.7^{c}	0.23	8.84	<0.0001
TAPeak	0.90^{b}	0.78^{dc}	0.76^{dc}	1.09^{a}	0.97^{b}	0.87^{bc}	0.07	16.78	<0.0001
MMPeak	0.90^{b}	0.77^{b}	0.79^{b}	1.03^{a}	0.89^{b}	0.79^{b}	0.07	10.34	<0.0001
DAPeak	0.81ab	0.84a	0.82ab	0.76b	0.74b	0.74b	0.06	5.07	0.0007
TAAUC	0.91^{b}	0.81^{c}	0.80^{c}	1.04^{a}	0.94^{b}	0.83^{c}	0.07	17.24	<0.0001
MMAUC	0.94^{b}	0.85^{bc}	0.86^{bc}	1.04^{a}	0.92^{bc}	0.83^{c}	0.06	8.85	<0.0001
DAAUC	0.88^{ab}	0.93^{a}	0.92^{a}	0.81^{b}	0.81^{b}	0.81^{b}	0.04	5.18	0.0006
TotalAUC	2.73^{ab}	2.59^{bc}	2.59^{bc}	2.89^{a}	2.67^{abc}	2.46^{c}	0.13	6.08	0.0001
TAAUCseq	20^{b}	14^{c}	13^{c}	23^{a}	19^{b}	16^{c}	2.46	30.63	<0.0001
MMAUCseq	21^{ab}	15^{c}	14^{c}	23^{a}	19^{b}	16^{c}	2.57	30.54	<0.0001
DAAUCseq	19^{a}	16^{ab}	15^{b}	18^{a}	17^{ab}	15^{b}	2.02	5.79	0.0002
TotalAUCseq	60^{ab}	45^{c}	42^{c}	65^{a}	56^{b}	47^{c}	6.70	25.67	<0.0001

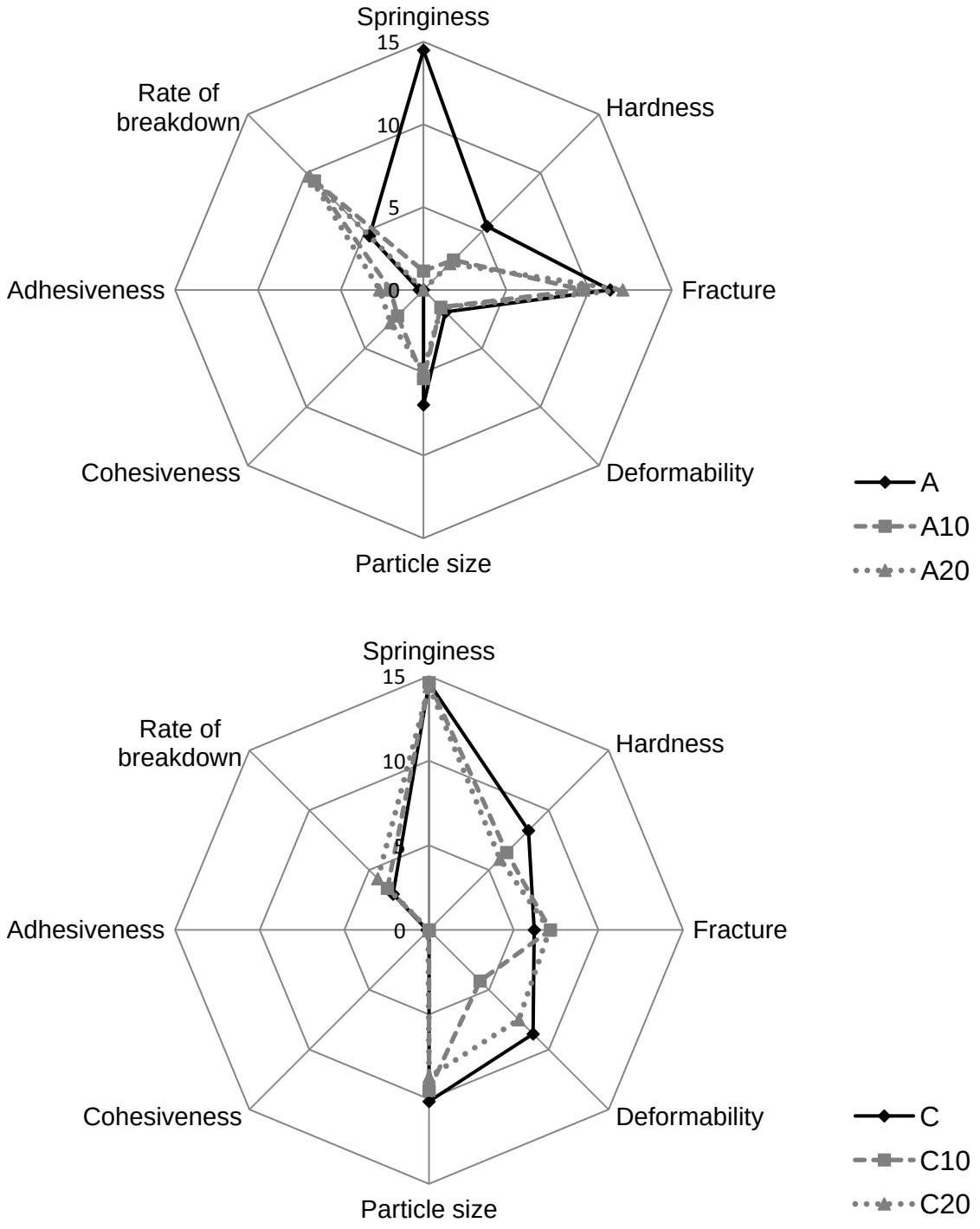

Figure 1. Sensory results of agar gels (top), κ-carrageenan-locust bean gum gels (bottom)

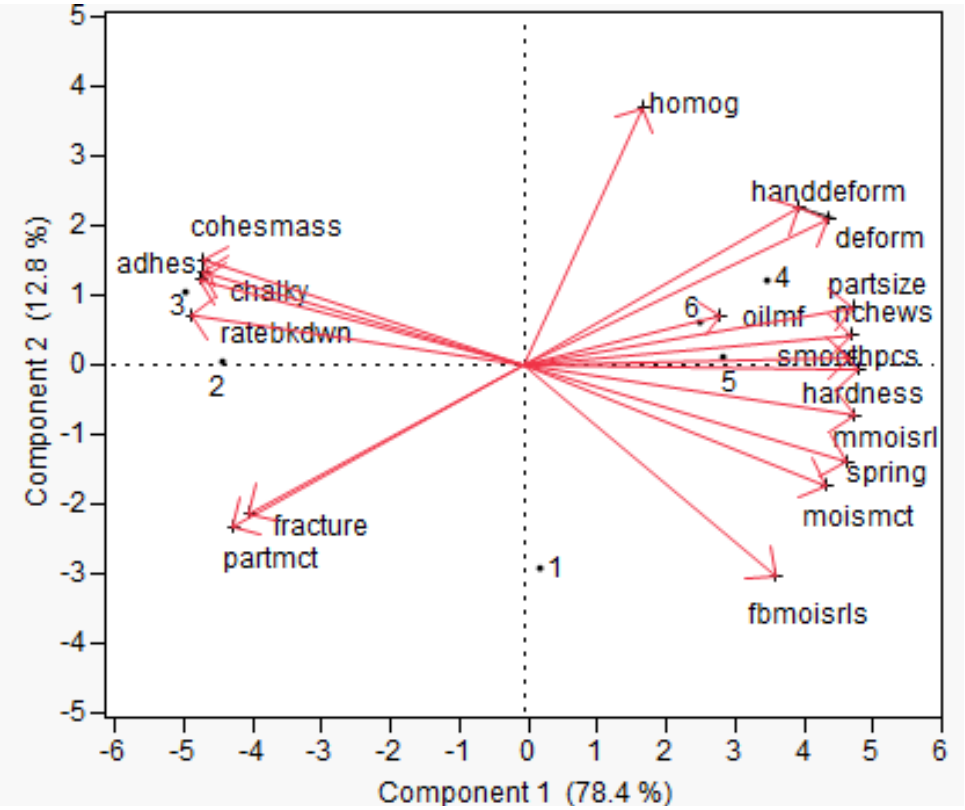

Figure 2. PCA biplot for sensory attributes.
Samples were labeled as: 1. Agar, 2. Agar with 10% oil, 3. Agar with 20 % oil,
4. κ-Carrageenan, 5. κ-Carrageenan with 10% oil, 6. κ-Carrageenan with 20% oil

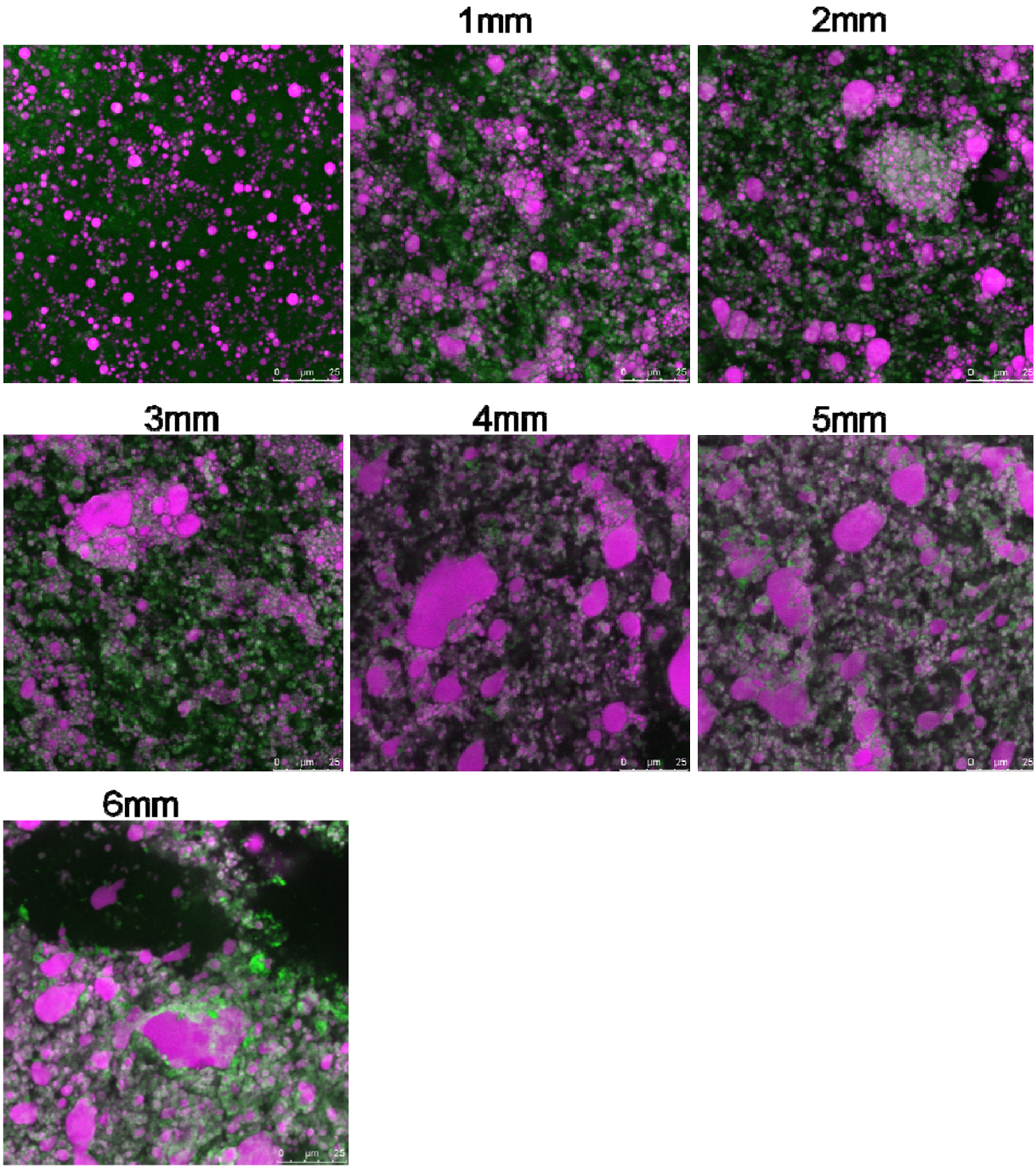

Figure 3. Stepwise compression images of filled agar gels (20% oil)

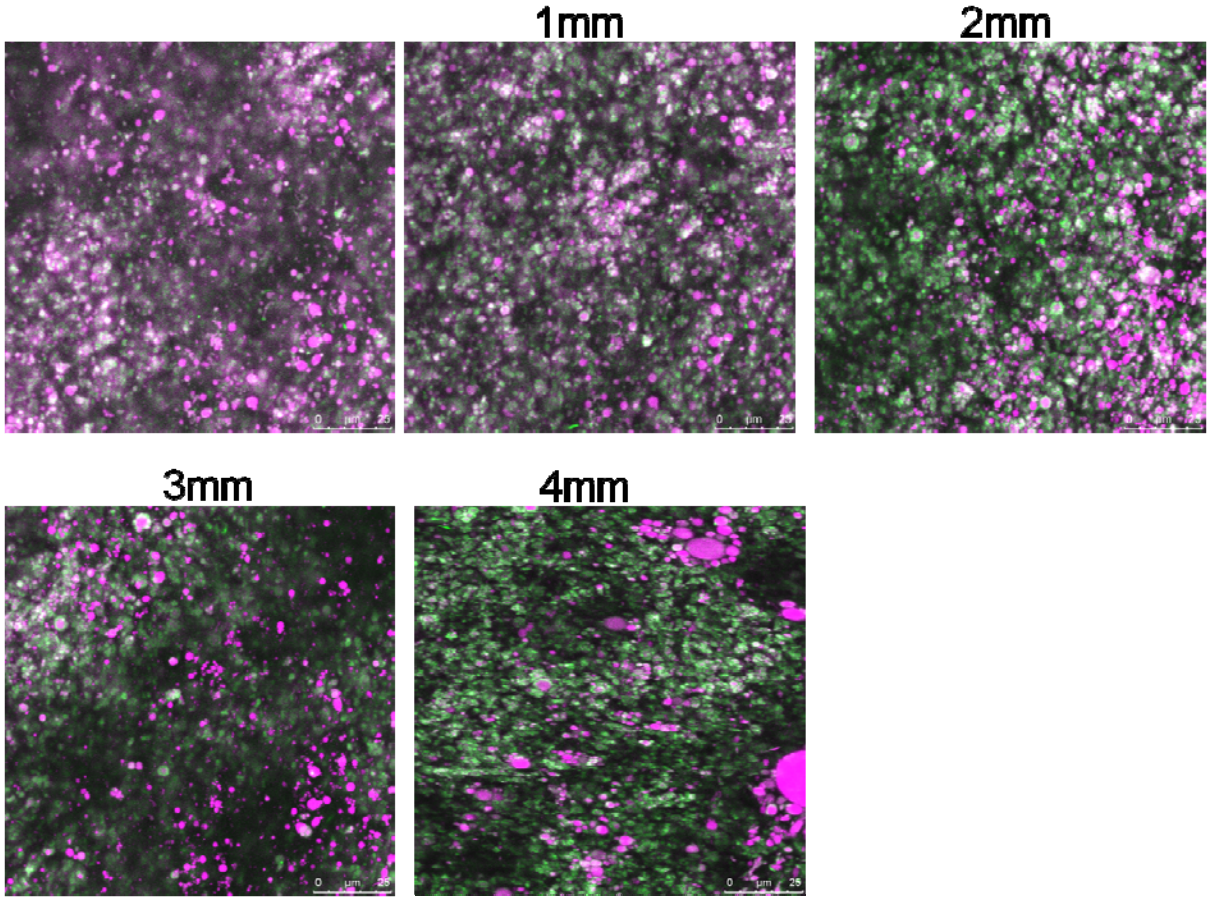

Figure 4. Stepwise compression images of filled κ-carrageenan-locust bean gum gel (20% oil)

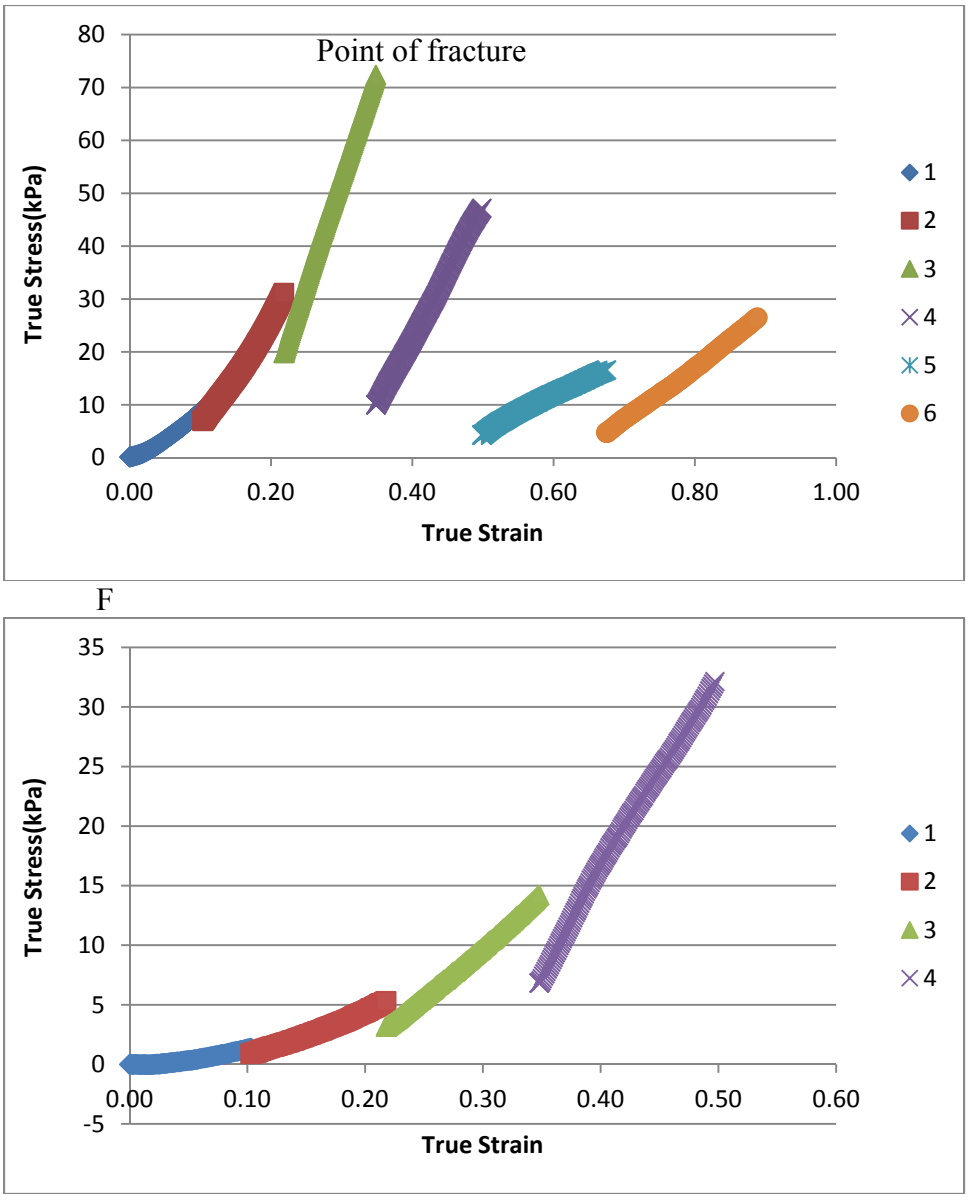

Figure 5. Stress-strain curves of stepwise compression of agar (top), κ-carrageenan-locust bean gum (bottom) gels.