Characterisation of battered and breaded coatings for food systems

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Abstract

Texture perception is due to a foods structural and mechanical properties detected through our senses. The texture of deep-fried battered and breaded coatings are recognised for their crisp outer crust contrasting a tender core. Crispness is a textural parameter used to assess the quality and freshness of deep-fried goods, it is therefore a fundamental attribute. The ultimate goal of this research is to understand the main drivers of crispness, thereby allowing an understanding of how crispness can be controlled from a formulation perspective. The ability to manipulate crispness is advantageous for developing a product to suit a desired specification or market niche.

The focus of this thesis is firstly directed towards gaining an understanding of the microstructure of deep-fried battered and breaded coatings. By characterising the microstructure of the entire coating, it was then possible to study the physical and mechanical properties and relate this to textural properties. The layers of a standard deep-fried coating consisted of predust flour, liquid batter layer followed by panko breadcrumbs. The breadcrumb layer is the first point of contact when biting and assessing texture, this initiated an incentive to investigate the effect of breadcrumb size on the physical and mechanical properties of the coating layer. Eight breadcrumb fractions were investigated for their effect on mechanical and physical properties of the deep-fried coating.

Instrumental characterisation was carried out using X-ray MicroCT, texture analysis, acoustics, confocal microscopy, Cryo-SEM, moisture and oil quantification. This concept was further explored by carrying out sensory studies. This consisted of using a trained sensory panel to develop a tailored lexicon for descriptive profiling. Results showed a significant difference in physical and mechanical properties as well as sensory attributes when breadcrumb size varied. These structural parameters were correlated with sensory parameters to develop a predictive statistical model for crispness. By using both instrumental and sensory characterisation methods, this provided a full representation of the contributors to crispness.

In the final chapter, consumer studies were carried out to understand consumer acceptance and preference. Cluster analysis confirmed that deep-fried battered and breaded coatings were grouping into three clusters (coarse, medium, fine). These clusters were based on dissimilarities instrumentally and sensorially. These three clusters of batter and breadcrumb coatings were carried forward for liking and acceptance testing. Consumers assessed these three samples on four hedonic and nine sensory attributes (9-point scale and JAR-scale). Penalty analysis confirmed significant mean drops within all three samples, highlighting which attributes can be focused on to improve overall hedonic score. Further cluster analysis confirmed consumers grouping into three clusters, each with a higher liking score for either coarse, medium or fine. Although crispness is a known important attribute for deep-fried coatings, results showed that when crispness is scored too high, overall liking score decreases. The results also highlight the microstructural differences in coatings that exceed the crispness limit. These microstructural properties explain why quality may be perceived as lower. It is also a combination of texture, flavour and appearance related attribute that significantly reduce overall liking score.

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Nomenclature

	Capillary pressure
	Interfacial tension liquid-gas
	Wetting angle
	Radius
	Interfacial tension solid-liquid
	Length
	energy supplied to the material during deformation
	elastically stored energy
	dissipated energy
	fracture energy

Abbreviations

MicroCT	Micro Computed Tomography
SEM	Scanning electron microscopy
CSLM	Confocal scanning laser microscopy
AED	Acoustic envelope detector
SPL	Sound pressure level
ANOVA	Analysis of variance
PCA	Principle component analysis
fps	Frames per second
MFA	Multiple factor analysis
AHC	Agglomerative hierarchical clustering
RV	Relative variance
PLS	Partial least squares
pps	Points per second

Chapter 1 : Introduction

1.1 Context for this study

The United States National Marine Fisheries Services reported an increase of shrimp consumption from 1.0 kg/year in 1989 to 1.8kg/year in 2005 (Norhana et al., 2010). These figures suggest an increasing demand for seafood products, which is due in part to their high nutritional content, palatable taste and affordability (Pawar et al., 2020). Shrimp in particular, are a rich source of protein, minerals, vitamins and polyunsaturated fatty acids (Nasiri et al., 2012). However, they are a perishable product, therefore, the use of deep-fat frying has been employed as it is a well-recognised method to prolong shelf-life.

The process of deep-fat frying is a common unit operation with an annual production of more than 20 million tonnes of frying oil, as reported in 2006 (Dana & Saguy, 2006a). Deep-fried foods are clearly very popular and are prepared in household kitchens, restaurants, catering and fast-food chains (Chang et al., 2019). Deep-fat frying as a cooking method is favoured for enhancing flavour, texture, aroma, reducing moisture loss and thereby prolonging shelf-life.

Coated deep-fried products can range from poultry, vegetables, cheeses and seafood but the coating system will be similar. A core is coated in a predust flour to allow adhesion to a liquid batter latter, this is then coated with a layer of breadcrumbs. It is during the deep-fat frying process that a dry crisp texture develops. Crispness is recognised as a key sensory attribute in deep-fried goods and is used to assess quality and freshness. A deep-fried crisp material is firm and brittle in nature, but will rupture under low strain and will emit an acoustic emission upon deformation (Saeleaw & Schleining, 2011).

In order to understand the major contributors to a crisp texture, a microstructural approach can be applied. This is represented schematically in Figure 1.0, which highlights that the sensory perception is largely due to the function of a products material properties. These properties are in turn dependent on its microstructure, which is determined by ingredients and processing. The process of deep-fat frying has many variables (temperature, frying time and frying oil). This research focuses on a specific frying procedure for deep-fried battered and breaded shrimp.

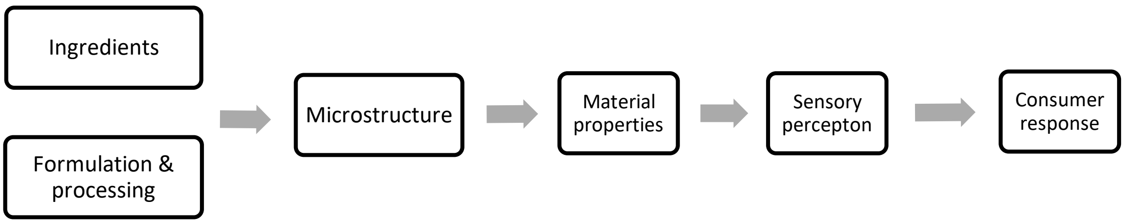

Figure 1.0 Schematic representation of formulation engineering from a microstructural approach.

1.2 Relevance to Rich Products Corporation & Kerry Ingredients

Rich Products Corporation, one of the industrial collaborators in this project, is a privately owned company headquartered in Buffalo, New York, USA. Founded in 1945, Rich's now operate globally and are a leading food supplier, specialising in baked goods, desserts, toppings, beverages, savoury snacks and deep-fried goods.

Kerry Group is the second industrial collaborator in this project and is a public food company headquartered in Ireland. Kerry Ingredients are global suppliers of functional ingredients and actives, with over 26,000 employees and 151 manufacturing sites. They are leaders in food processing, ingredients, taste and nutrition technologies. Kerry are one of Rich's ingredient suppliers and supply to Seapak, one of Rich's consumer brands.

Seapak Shrimp & Seafood Co. include products that range from cod, salmon, crab, scampi and shrimp. Battered and breaded butterfly shrimp are one of Richs numerous products that are recommended as an appetiser or entrée. These frozen products are either pan-fried, deep-fried or baked. The end result is a coating with a crisp texture contrasting a tender shrimp core.

Seapak is well-recognised and is ranked #1 retail brand in the frozen speciality seafood category. Thus, demonstrating how Rich and Kerry have developed a superior quality product versus major competitors. However, a fundamental understanding of formulation and processing is lacking. By characterising and understanding the batter and breadcrumb coating, it can then be possible to manipulate the systems to control crispness. Literature has shown that consumers consider crispness as a fundamental attribute in deep-fried products (Tomasco, 2007). Therefore, as emphasised in Figure 1.0, an understanding of the microstructure will provide an in depth understanding of the main drivers of crispness. Ultimately, new ways of producing these products in the future can be explored.

1.3 Objectives

The goal of this project is to develop a fundamental understanding of the phase transitions occurring during the deep-fat frying process order to understand the development of crispness. As this research project is industrially sponsored, the interest of both sponsors must be considered. Although Seapak products are shrimp based and are used in this research, the focus of this EngD is on the deep-fried coating itself. By characterising the microstructure of deep-fried coatings, it can then be possible to relate structure to product performance. The key objectives addressed in this research project are:

To develop instrumental methods to expand understanding of the structure of deep-fried and battered and breadcrumb coatings.

To investigate the correlation between objective measurements and sensory measurements for modelling of crispness.

To determine any significant differences in structure and sensory perception when breadcrumb size is varied.

To determine consumer acceptance and liking of battered and breadcrumb coatings with varying breadcrumb size.

1.4 Thesis layout

This thesis follows the alternative format of the University of Birmingham, where results chapters (chapters 3-5) are presented in the form of a published peer-reviewed research paper. The chapters are as followed:

Chapter 2: A theoretical background of deep-fat frying and its importance in forming a crisp battered and breaded coating is explained. A comprehensive review of relevant published literature focusing on methods for measuring, understanding and predicting crispness is also discussed.

Chapter 3: This chapter is the first results chapter, published as "Characterisation of deep-fried battered and breaded coatings"(Voong et al., 2018) . This study details the physical and mechanical differences of deep-fried battered and breaded coatings when breadcrumb size is varied. A total of eight breadcrumbs sizes were characterised for their effect on the structural properties of the coating.

Chapter 4: This chapter, published as "Understanding and predicting sensory crispness of deep-fried battered and breaded coatings" (Voong et al., 2019), studies the sensory perception of eight deep-fried battered and breadcrumb coatings using a trained panel. A trained panel of eight developed a tailored lexicon for descriptive profiling of these coatings. These findings were correlated with instrumental measurements in chapter 3 to develop a statistical model to predict sensory crispness.

Chapter 5: This chapter, published as "Understanding consumer perception of deep-fried battered and breaded coatings" (Voong et al., 2020), studies the consumer perception of three deep-fried battered and breaded coatings, each with varying breadcrumb sizes. A total of 185 consumers from Buffalo, NY evaluated samples for acceptance and liking in order to provide consumer insight for potential product commercialisation. A focus is also made on the variations in microstructure, which has been used to explain the segmentation of consumer liking.

Chapter 6: This chapter is the final experimental chapter that focuses on understanding the fundamentals of crispness from a materials science perspective. The use of a high-speed camera coupled with mechanical testing has been applied with an aim to capture and understand the cracking process that defines crispness.

Chapter 7: In this final chapter, the conclusions of this research are summarised. Any future work and suggestions have also been made.

1.5 Publications and presentations

Research contained within this manuscript has been published in the following journals and presented at the conferences listed below:

1.5.1 Publications

Voong, K. Y., Norton-Welch, A., Mills, T. B. (2020) Understanding consumer perception of deep-fried battered and breaded coatings. *Journal of Texture Studies. 51, 891-901.*

Voong, K. Y., Norton-Welch, A., Mills, T. B., & Norton, I. T. (2019). Understanding and predicting sensory crispness of deep-fried battered and breaded coatings. *Journal of Texture Studies*, 50, 456-464.

Voong, K. Y., Norton, A., Mills, T., & Norton, I. (2018). Characterisation of deep-fried batter and breaded coatings. *Food Structure, 16*, 43-49.

1.5.2 Oral Presentations

Voong, K.Y., Norton, A., Mills, T., & Norton, I. Understanding and predicting sensory crispness of deep-fried battered and breaded coatings. *The 8th International Symposium on Food Rheology and Structure*. Zurich, Switzerland 2019.

Voong, K.Y., Norton, A., Mills, T., & Norton, I. Characterisation of deep-fried batter and breaded coatings. Olomouc, Czech Republic, 2018.

Voong, K.Y., Norton, A., Mills, T., & Norton, I. Characterisation of deep-fried batter and breaded coatings. *U.K. Colloids*, Manchester, 2017.

1.5.3 Poster presentations

Voong, K.Y., Norton, A., Mills, T., & Norton, I. *Bruker micro-CT User Meeting*. Brussels. 2017

1.6 References

Chang, C., Wu, G., Zhang, H., Jin, Q., & Wang, X. (2019). Deep-fried flavor: characteristics, formation mechanisms, and influencing factors. *Critical reviews in food science and nutrition*, 1-19.

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Nasiri, F. D., Mohebbi, M., Yazdi, F. T., & Khodaparast, M. H. H. (2012). Effects of soy and corn flour addition on batter rheology and quality of deep fat-fried shrimp nuggets. *Food and Bioprocess Technology, 5*(4), 1238-1245.

Norhana, M. W., Poole, S. E., Deeth, H. C., & Dykes, G. A. (2010). Prevalence, persistence and control of Salmonella and Listeria in shrimp and shrimp products: A review. *Food control, 21*(4), 343-361.

Pawar, P., Pagarkar, A., & Rathod, N. (2020). Effect of chilled storage on quality characteristics of battered and breaded snack product from large sized Catla (Catla catla). *Journal of food science and technology, 57*(1), 52-59.

Saeleaw, M., & Schleining, G. (2011). A review: Crispness in dry foods and quality measurements based on acoustic–mechanical destructive techniques. *Journal of Food Engineering, 105*(3), 387-399.

Tomasco, P. V. (2007). *Methodological developments in the assessment of the crispness as a primary quality factor in different food products.* (PhD), Polytechnic University of Valencia.

Voong, K., Norton, A., Mills, T., & Norton, I. (2018). Characterisation of deep-fried batter and breaded coatings. *Food Structure, 16*, 43-49.

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Voong, K. Y., Norton-Welch, A., Mills, T. B., & Norton, I. T. (2019). Understanding and predicting sensory crispness of deep-fried battered and breaded coatings. *Journal of Texture Studies*.

Chapter 2: Literature Review

2.1 Introduction

The aim of this chapter is to provide a comprehensive review of relevant literature. Firstly, the fundamentals of deep-fat frying are discussed to understand how a crisp structure is formed in battered and breaded coatings. This is followed by a description of the coating system used for Seapaks deep-fried battered and breaded shrimp. The fundamentals and importance of crispness are explored, this is then followed by methodologies that have been used to characterise and understand crispness. Finally, the advantages and limitations of both objective measurements and sensory measurements are discussed as crispness is a food textural property, sensory measurements should be considered. This allowed for the subsequent research in this thesis to encompass a combination of both instrumental and sensory methodologies to study crispness of deep-fried coatings.

2.2 Deep-fat frying process

In deep-fat frying, battered and breaded foods are fully submerged into hot cooking oil at a temperature between 150 ^oC - 190 ^oC (Dar & Light, 2014). The frying process has been studied extensively to show it is simultaneously a heat and mass transfer process. The interplay between heat and mass transfer influences the texture, appearance and taste of the fried product (Dana & Saguy, 2006b).

The high temperature of the cooking oil causes moisture at the surface of the coating to evaporate off immediately (Mellema, 2003), this results in surface drying, shrinkage and roughness. Subsequently, the temperature of the surrounding oil decreases but is compensated for by convection (Mellema, 2003). The moisture within the core will begin to migrate towards the surface as the pressure inside the core increases. The release of this moisture occurs via explosive evaporation, this leads to the formation of voids at the surface of the coating. The formation of these voids collectively form a porous network, which provides entry points for oil to penetrate as well as moisture to exit (Mellema, 2003). Oil and moisture exchange occurs at regions of batter where the temperature is highest i.e. near the surface. As frying time continues, the moisture content within the crust diminishes, resulting in a dry and crisp texture. The factors affecting the rate of oil and moisture exchange include: oil temperature, formulation of coating, moisture content of core, presence of and formation of pores (Mellema, 2003).

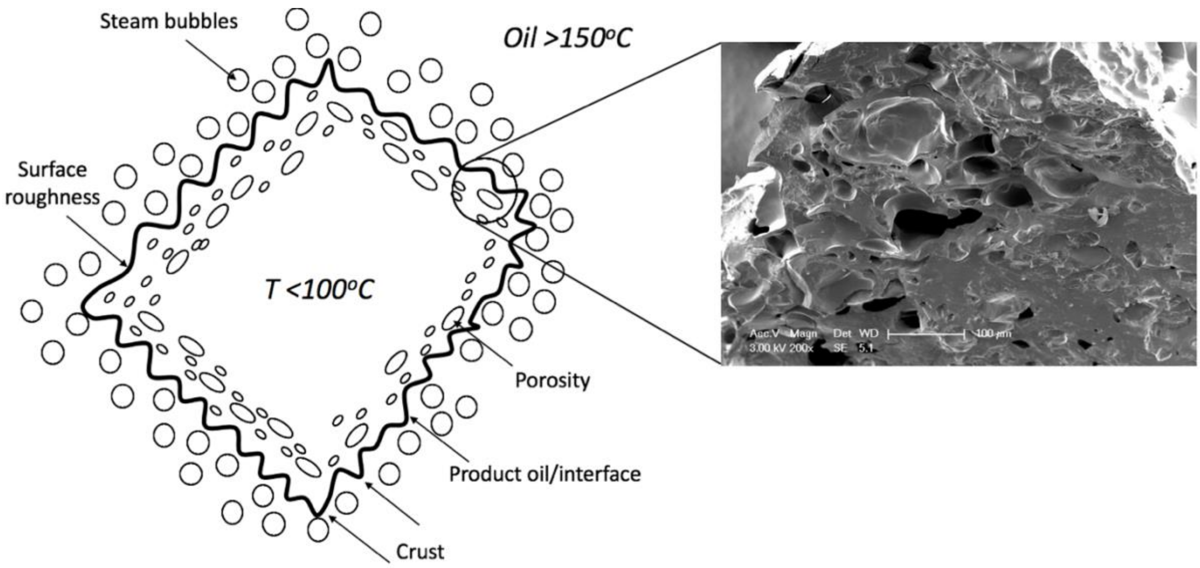

Figure 2.1 Schematic representation of battered product undergoing deep-fat frying to form the final porous and crisp crust. The focus has been made on the crust structure with Cryo-SEM image of a deep-fried batter coating. Figure adapted from (Mellema, 2003).

As well as the structural changes occurring via dehydration during frying, fried foods undergo colouring via Maillard reaction, protein denaturation and starch gelatinization (Habeebrakuman et al., 2019). The frying oil is continuously heated at high temperatures for long periods of time in the presence of food and air. Prolonged frying leads to further chemical reactions such as hydrolysis, oxidation, cyclisation and pyrolysis. All of which results in the formation of high molecular weight polar compounds and triglycerols. In addition to the flavour and colour of oil, the presence of polar compounds acts as an indicator of quality. All of which are crucial to maintaining the quality of deep-fried goods (Habeebrakuman et al., 2019).

2.2.1 Oil absorption mechanism

During and after deep-fat frying, there are several events that occur at the crust to influence oil penetration. If pores are filled with water after frying, the oil will not be able to penetrate as the food material will be more easily wetted by water than oil. If pores are filled with water vapour, food may be wetted better by oil as water vapour can be considered to be hydrophobic (Mellema, 2003). If a pore is not filled i.e. acts as an air cavity, then oil absorption is highly likely.

A relationship between oil absorption and porosity has been extensively suggested (Moreira et al., 1999; Moreira et al., 1997; Ziaiifar et al., 2008). The mechanism by which oil is absorbed is via capillary forces. This refers to the ability of a narrow pore to draw liquid upwards and occurs when the intermolecular forces between the liquid and solid are stronger than the intermolecular forces within the liquid (Ziaiifar et al., 2008). The effect of this is a concaved meniscus forming where the oil is in contact with a vertical surface (Figure 2.2). This results in a difference in pressure between the two sides of the meniscus, which can be expressed by the Laplace law (Eq. 2.1). The capillary pressure ( ) in an ideal cylindrical pore of the radius ( ) is determined by wetting angle ( ), which is determined by a balance of interfacial tension ( ). The interfacial tension here refers to that between oil and water vapor (and between oil and solid food material (. considers the vertical component of the surface tension, the horizontal component is not considered (as this will be counteracted by the food material surface tension.

(Eq. 2.1)

(Eq. 2.2)

Equation 2.1 shows that wider pores and contact angles above 90° result in low capillary pressures (Mellema, 2003; Saguy & Pinthus, 1995). Alternatively, narrower pores with low contact angle between oil and food material result in higher adhesion force for oil uptake. Finally, a high surface tension (will also result in high oil uptake (Moreira et al., 1997).

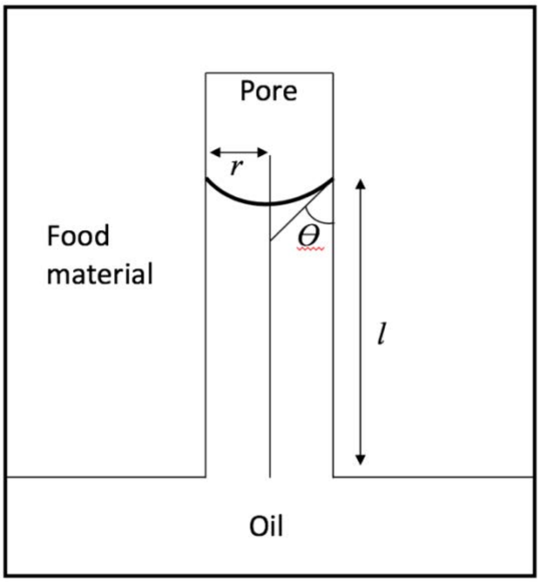

Figure 2.2 Schematic representation of oil flowing into a cylindrical pore. r = radius, = wetting angle, = length of pore. Figure adapted from (Ziaiifar et al., 2008)

2.2.2 Oil

Frying oil becomes a final ingredient in the product and can represent up to 40 % of the total mass in deep-fried products (Ziaiifar et al., 2008). The mean oil content in deep-fried breaded shrimp has been quoted to be typically 15.2 g/100 g (Dana & Saguy, 2006b).

The type of frying oil used can range from non-hydrogenated fully refined fats and oils to hydrogenated fats designed for frying. The selection criteria will depend on any contribution of off-flavours, ease of handling, availability and cost. Soybean oil is extracted from the seed of soybean (*glycine max*). Soybean oil is highly recommended for deep-fat frying as it as a smoke point of 210 ^{o}C (460^{o}F), which is higher than any other vegetable oil (Goyary et al., 2015). This is favoured to prevent the formation of toxic fumes, oil decomposition and maintain product quality. Soybean oil also contains a high amount of mono-saturated fatty acids, which is favoured for health benefits (Goyary et al., 2015). This explains the use of soybean oil in the commercial production of deep-fried battered and breaded goods.

2.4 Coating system

The consumption of battered and breaded goods has been popularised over the years, especially poultry, cheeses, vegetables and seafood (Dogan et al., 2005). Studies from equipment manufacturers have shown that 50 % of purchases are related to poultry, making poultry the leading segment in batter and breaded products. This is followed by seafood at 30 % (Barbut, 2013). Shrimp is one of the most popular deep-fried seafood products with an increase of consumption per capita from an average of 1.0 kg/year in 1989 to 1.8 kg/year in 2005 (Norhana et al., 2010). Shrimps are a source of protein, minerals, vitamins and polyunsaturated fatty acids (Nasiri et al., 2012). However, they are a perishable product and water loss occurs during cooking. Therefore, a coating system acts as a preservation method to prolong shelf life by acting as a barrier to retain the natural juices of the core (Yerlikaya et al., 2010). Other advantages of a coating system provide palatable taste, enhanced texture, appealing aromas and attractive appearance.

The appearance of coated fried foods can be altered by varying the cooking procedure, frying medium, composition of ingredients, addition of hydrocolloids in the batter and selection of breading type. The coating system for Seapak butterfly shrimp is comprised of three layers: predust flour, liquid batter and finally panko breadcrumbs, as shown in Figure 2.3. The significance and function of each layer will be discussed further.

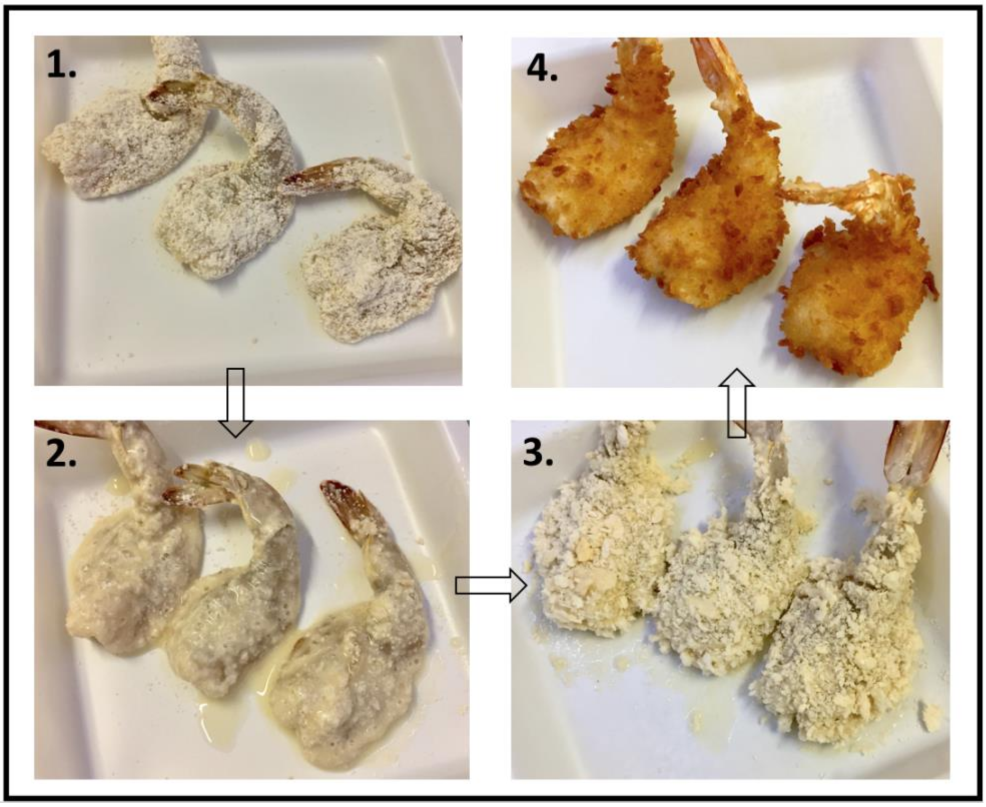

Figure 2.3 Example of the coating steps involved in Seapaks battered and breaded shrimp product. All shrimp are butterflied, then coated in predust flour, liquid batter and panko breadcrumbs.

2.4.1 Predust flour

Predust flour is typically a combination or separately wheat flour, cracker meal, fine breadcrumbs, seasonings, gums, modified starches and seasonings. (Perera & Embuscado, 2014). The purpose of a predust layer is to act as an adhesive surface between the substrate and the batter layer. It improves adhesion by absorbing a part of the moisture from the substrate, thereby preventing the batter from slipping and leaving areas uncovered. The use of a predust layer also allows an increase of pickup (Fiszman & Salvador, 2003).

2.4.2 Batter layer

Batters are essentially a corn flour and wheat flour mixture, with the addition of modified starches, thickeners and seasonings. This liquid mixture is used to coat a food product before breading and/or frying. The rapid formation of a hard crust restricts oil absorption but also acts as a barrier against moisture loss to ensure a tender final product (Albert et al., 2009).

Batters can be classified into two types; tempura/puff or adhesion/interface (Dogan et al., 2005). Tempura batter is typically wheat flour based with low protein content to reduce excess hydration and formation of a cohesive gluten matrix (Matsunaga et al., 2003). Unlike adhesion batters, it is essential that tempura batters are mixed with cold water before frying (Matsunaga et al., 2003).

The batter used in these studies are adhesion batters, meaning the layer is an adhesive surface between core and breadcrumbs (Perera & Embuscado, 2014). This layer also provides flavour, texture and appearance to the food, whilst acting as a barrier to retain moisture. This ensures a tender and juicy core contrasting a crisp outer crust (Mellema, 2003). Batters are typically wheat flour-based but can also contain modified starches to increase viscosity and adhesive properties.

Batter viscosity affects pickup, appearance, texture and final handling of the product (Mukprasirt et al., 2000). The viscosity of batters must be controlled to ensure the correct amount is picked up onto the product. If the viscosity is too low, the batter layer will be too thin and when fried will not impart a desired crisp structure. A thin layer of batter is also less efficient at retaining moisture, this could result in an overly dry substrate but will also reduce freshness and crispness (Mallikarjunan, 2004). If the viscosity is too high, a thick batter layer can be cooked incompletely and there is a risk of developing an inhomogeneous mixture (Fiszman & Salvador, 2003).

Additional ingredients can be added to the predust and batter layer to enhance its properties. Such include salts, flavourings, flours, gums, modified starches and maltodextrin. Modifications to the batter may be made to alter viscosity, improve adhesion, leavening or crispness.

2.4.3 Breadcrumb layer (Japanese style breadcrumbs)

Japanese style breadcrumbs or Panko breadcrumbs are made from a wheat flour based bread. They typically adhere to the batter layer and act as the outer coating to provide a crisp texture. Japanese style breadcrumbs are produced using ohmic heating, a process that bakes bread by passing an electric current through the material, thereby acting as electrical resistance. The advantages of this method is uniform heating, minimal heat transfer after shut off and the formation of crustless bread without a golden brown colour (Perera & Embuscado, 2014). After baking, the bread loaf is ground down and dried to the desired particle size range. The resulting crumb is porous, light and elongated and provides a crisp texture upon frying.

A loss of breadcrumb coating may occur during processing, transportation or handling to consumers. Subsequently, this results in product wastage and affects product appearance (Suderman & Cunningham, 1983).

2.4.4 Food core (Shrimp)

Whiteleg shrimps or king prawns (*Penaeus Vannamei*) are the core of the coating system in this research and are sourced from Indonesia, India and Guatemala. Shrimps are favoured for their unique flavour, texture and are a source of protein, minerals, vitamins and polyunsaturated fats (Nasiri et al., 2012). They are considered to have a mild but distinctive flavour with a tender and delicate texture (Erickson et al., 2007).

As shrimps can be imported from a wide geographical range, a multitude of species can enter the market. These include black tiger (*Penaeus monodo),* white shrimp (*P. setiferus*), pink (*Penaeus duorarum*) and brown (*Penaeus aztecus*). This does allow for a diversity of flavours and textures to exist in commercial shrimps. However, studies have shown that no single flavour or texture attribute could be used to distinguish one species from another (Erickson et al., 2007). It was only possible to distinguish species based on appearance attributes (Erickson et al., 2007).

It should also be noted that although the term shrimp and prawn are commonly used interchangeably, they differ in zoological classification and anatomy.

2.5 Crispness

Crispness is a texture attribute that is assessed to an extent visually and manually, but the main evaluation occurs when placed in the oral cavity. Texture perception is a manifestation of structural, mechanical and surface properties. These different interrelations for crispness perception are shown schematically in Figure 2.4 It should be noted that the definition of crispy and crunchy is not the same but are closely related, how they are distinguished will be further discussed.

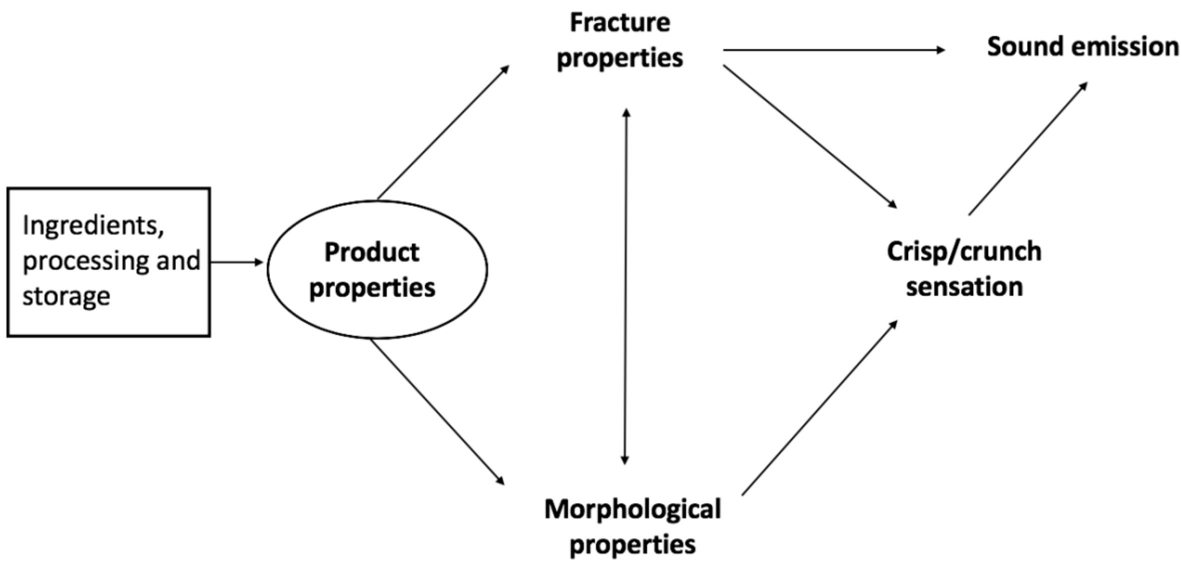

Figure 2.4 Schematic representation of the different stimuli affecting the sensation of crispness. Image adapted from (Luyten & Van Vliet, 2004).

Products with contrasts in texture have been shown to act as a connotation of quality and therefore increases product enjoyment (Tomasco, 2007). This is relevant to Seapak as consumers expect a dry crisp texture contrasting a moist tender core. Crispness is known to be one of the most important quality parameters in consumer acceptance of fried goods (Gouyo et al., 2020). Therefore, it's influence and importance will be explored further in this research. The definition of crispness varies depending on the product e.g. the crispness of an apple differs to the crispness of French fries. Historically, crispness can be defined as the fracturing of material under compressive pressure into small pieces, this is associated with brittleness (Tomasco, 2007). However, it was concluded that this definition is not sufficient to explain crispness in all products (Vickers & Bourne, 1976). This is due to crispness being classified into different types: wet, dry and crusted.

2.5.1 Dry crispness

Cellular foods that contain only air within their cells are classified as dry crisp, these include biscuits or potato chips (Labuza et al., 2004). These cellular foods have a foam like structure, with empty cavities and a structural phase that is brittle in nature (Figure 2.5). It's mechanical behaviour is dependent on the volume of air, the structure of the solid matrix and whether the cells are open or closed (Van Vliet & Primo-Martin, 2011).

The breakage around a brittle cavity produces a snap, which generates subsequent vibrations to cause a sound pressure wave (Duizer, 2001). A louder crispness perception will be due to a stiffer matrix that will require a higher force to fracture. Subsequently, a loss in crispness is due to hydration of the brittle matrix. The morphology of the structure and molecular mobility of plasticisers will affect crispness. Heterogeneities in the structure can be expected, this allows for fracture of the material to begin at inhomogeneities because stress will be concentrated at these weak points. This results in an uneven breakdown pathway (Tomasco, 2007). Therefore, material heterogeneities are important for its brittle nature and generating a crisp texture. There are very few dry crisp foods that are homogeneous at a mesoscopic (0.1-1000 m) and macroscopic scale (Van Vliet & Primo-Martin, 2011).

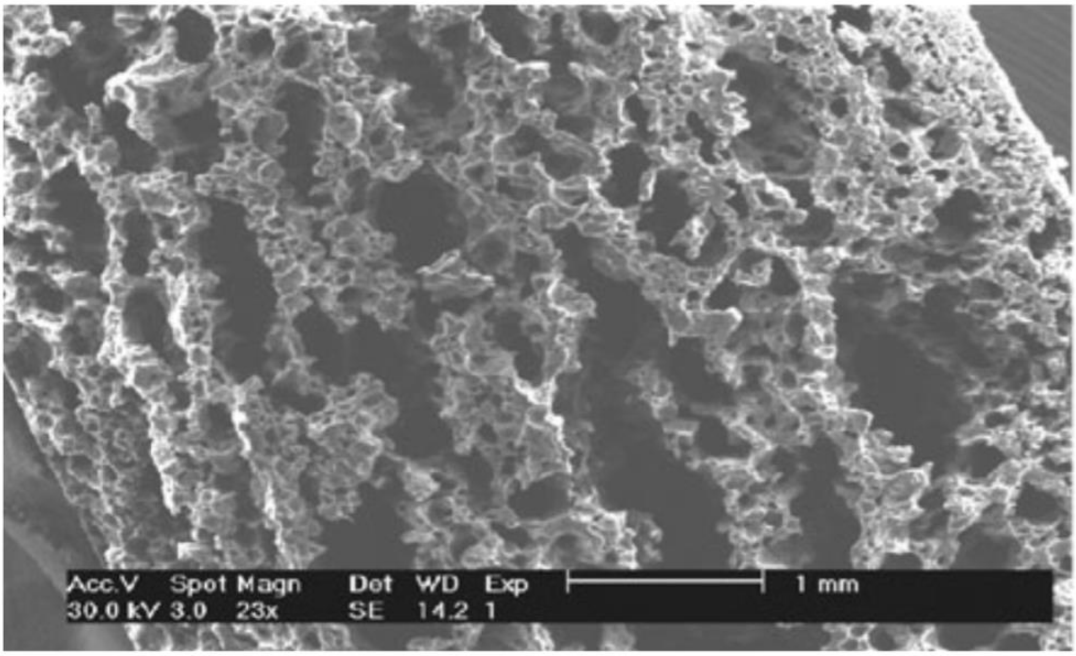

Figure 2.5 SEM image of crisp biscuit, highlighting pores of different sizes within the cellular structure. Image from (Luyten & Vliet, 2006).

2.5.2 Wet crispness

Cellular foods that retain fluid within their cells are termed as wet crisp, such include fruit and vegetables (Chauvin et al., 2008). Cells are often anisotropic e.g. apples are elongated in the radial direction, but some are isotropic e.g. potato tubers (Van Vliet & Primo-Martin, 2011).

The texture in wet crisp products is derived from the stiffness and strength of the cell walls. The lamella layer, the fibrous tissue and the turgor pressure contribute to the rigidity of these cells. Turgor describes the intercellular pressure due to water content, the outward force is balanced by the elasticity and strength of the cell walls. When a turgid cell in a fruit or vegetable is bitten into, the cell wall skeleton ruptures and deforms (Figure 2.6). This rupture expands at an outward momentum, it is transferred from molecule to molecule, causing an oscillation and forming a soundwave (Tomasco, 2007). This describes how wet crispness is perceived, and it is changes in turgor pressure that will affect crispness. This explains why crispness is lost during cooking, freezing, or drying because there is an alteration of the structure by chemical or physical processing.

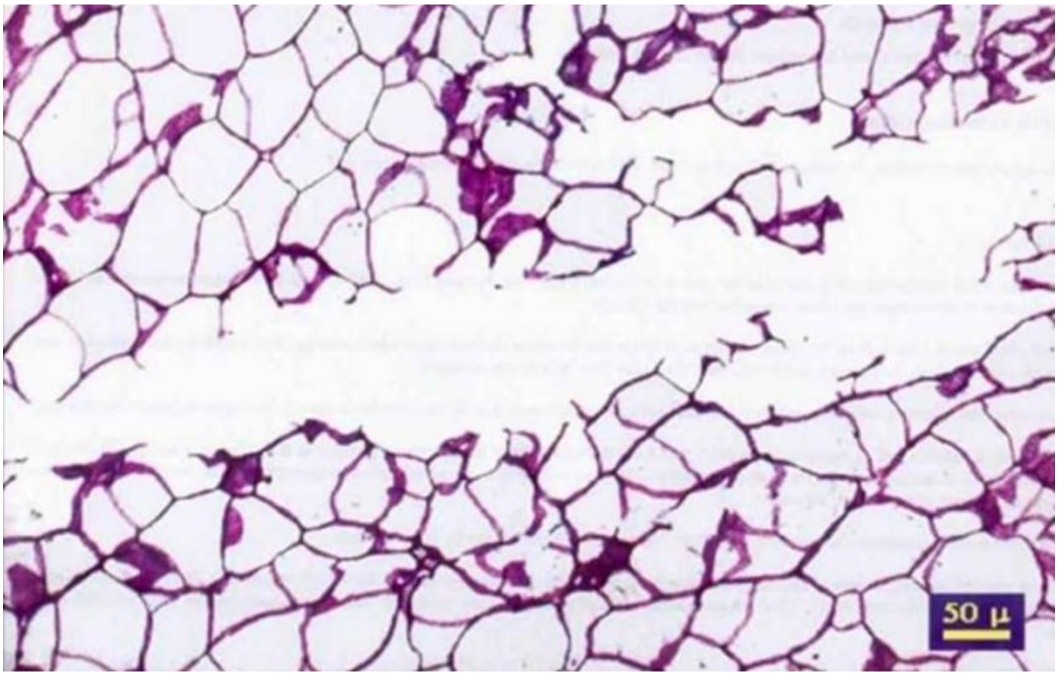

Figure 2.6 SEM image of fracture through a fresh carrot. Note the rupture pathway is through the cell, not along the cell walls. Image from (Lillford, 2000).

2.5.3 Crusted crispness

Crusted crisp products have a distinguishable morphological structure in comparison to dry and wet crisp. A crusted crisp refers to a dry crust, which is built of several layers. These layers collectively have a distribution of pore sizes and shape. The surrounding solid material around the pores consist of protein and starch acting as beams and columns. The distribution of plasticizers and soluble components within the crust determine its crisp behaviour (Luyten & Van Vliet, 2004). The contrasting material is a high moisture centre with high water activity.

Examples of products include crusty breads, filled baked goods or deep-fried goods. The final structure is dependent on the composition of the core and the coating after processing. Variables will include water content, size of food pieces, the composition of the coating, availability of starches and proteins, and finally cooking procedure. A loss of crispness will be due to absorption of moisture from the environment, as well as moisture from the core which has high water activity (Luyten & Van Vliet, 2004).

The perception of crusted crispness is not as easy to evaluate as wet or dry crisp because of its layered sandwich-like structure. It is therefore difficult to distinguish the contribution of each layer. However, the mechanics of both together are essential to understand texture perception as a whole. Similar to dry crisp, structural heterogeneities are expected in crusted crisp. However, these heterogeneities in crusted crisp have been considered to be problematic for measuring physical properties. This is because the heterogeneities in crusted crisp are large in comparison to the thickness of the entire coating (Tomasco, 2007). There are numerous structural elements to be considered, such as breadcrumb size, cracks, pores, air pockets and oil droplets. These are large when compared to a fruit or a biscuit, where the food piece is large in comparison to its inhomogeneities (Luyten & Van Vliet, 2004). This has been considered to make the evaluation of crusted crisp difficult. As studies on the evaluation of crusted crisp are inconclusive, this research focuses on developing methodologies to understand texture perception in crusted crisp products.

2.6 Characterising crispness

Crispness is synonymous of freshness and quality in food products. Therefore, it is in the best interest of the food industry to understand the drivers of crispness. This allows for control and maintenance of product quality. As crispness is a combination of mechanical, tactile, kinaesthetic and auditory properties (Vickers, 1988), a combined instrumental and sensory research approach can be recommended to understand crispness perception.

The structure of a crisp coating should resist the initial first bite, this is then completely destroyed during mastication (Loewe, 1993). This is because coatings behave as a brittle material, i.e. will fracture under a low strain. Complete mechanical failure is expected during biting and grinding between molars. The loss of crispness is also due to moisture uptake to the surface of the crust, this can come from the core, the surrounding environment or saliva.

2.7 Instrumental characterisation of crispness

The advantages of instrumental testing provide objective measurements to quantify crispness via physical and mechanical properties. An understanding of the material properties allow for a clearer understanding of structural performance. Literature has reported the following techniques as reliable and efficient methods to explore and characterise crispness, the merits and limitations of each technique will be discussed.

2.7.1 Microscopy

An understanding of a structure on a microscopic scale forms the basis for optimizing the processes that lead to their formation. It also lays the foundation for developing new or higher quality products. A number of microscopy techniques have been applied to study the surface and internal morphological detail of deep-fried goods.

Confocal laser scanning microscopy (CSLM) is an improvement from the traditional light microscopy as it is capable of scanning different depths, whilst reducing artefacts and rendering images in three dimension. This has been successfully applied when highlighting the structural composition in French fries (van Loon et al., 2007). Samples are stained with a fluorescent dye that fluoresces under a known wavelength, thereby illuminating and differentiating components of the structure (Dürrenberger et al., 2001). However, the dye preparation can be laborious and destruction of the sample may be required.

Scanning electron microscopy (SEM) has been shown to be useful for studying the porosity of crusts and has been demonstrated with bread crust (Primo-Martin et al., 2006). However, SEM is limited in that samples must be solid and vacuum-compatible, therefore moisture and oil must be removed or frozen in crusted crisp products. A more appropriate technique would include Cryo-SEM, which has been successfully used to capture the changes in a wheat batter as it transitions from liquid, to fried and then frozen (Llorca et al., 2001).

Recent studies have demonstrated the use of X-ray Micro-computed tomography (MicroCT) as a far more superior technique to capture the microstructure. As an imaging tool, MicroCT is a non-invasive technique that is able to reconstruct 3D images at a high resolution without destroying the sample. Studies have related the microstructure to crispness for potato crisps (Renshaw et al., 2016), French fries (Miri et al., 2006) and breaded coatings (Adedeji & Ngadi, 2009). It can be noted that the disadvantages of MicroCT include the presence of potential image artefacts, it is an expensive instrument and the use of radiation can be harmful when testing biological samples.

2.7.2 Texture analysis

Measuring the resistance to compression from a probe or a tensile fixture has been shown to provide information about structural properties of a material. Therefore, texture analysis has been commonly used to simulate a texture profile that resembles biting or chewing. The mechanical variables are extracted from a force-deformation of a stress-strain curve, force is used to describe brittleness or hardness (Szczesniak, 1963). The area under the curve can then be used to determine the amount of energy required to fracture the material, which can be translated to the energy required to bite or chew the material (Seymour & Ann, 1988).

The test probes used can vary and range from a cylindrical probe, Volodkevich tooth, a wedge-shaped probe or to a more complex attachment such as a Kramer shear cell. The type of test methods can also range from a three-point bend, compression, puncture, tensile or cutting/shearing test.

The use of mechanical tests for crisp foods has been arguably discouraged. This is due to the irregularities in shape, size and presence of non-crisp parts. However, studies have shown that much can be extracted from an irregular force profile. Typically, deformation of crisp foods is measured as a function of time and at a low strain in order to study individual fracture events. The deformation speed can be altered to mimic mastication speed, which can range between 10-40 mm s^{-1}. A deformation speed up to 22 mm s^{-1} has been shown to successfully profile the mechanical breakdown of potato chips (Taniwaki & Kohyama, 2012). However, reducing deformation speed increases sensitivity to allow for the identification of individual fracture events (Prada et al., 2006). Dry crisp products are predominantly elastic in nature, therefore time-independent fracture behaviour can be expected. This will not be applicable for crusted crisp as there is a more viscoelastic material beneath, meaning that the fracture behaviour of the crust is affected by the material properties of the adhering layer, which will depend on deformation speed (Luyten & Van Vliet, 2004).

This supports the argument that mechanical testing does not need to mimic the oral processing speed entirely. An ideal circumstance may be enough to understand a materials mechanical properties.

A schematic example of a crisp deformation curve is shown in Figure 2.7. As a compression force is applied, the material composition and structure will dictate its stiffness and resistance to fracture. A fracture occurs because critical stress energy, fracture stress and fracture energy have been reached (Van Vliet & Luyten, 1995). As crack propagation begins, the crack speed will accelerate at a speed depending on the stress applied. Once past a certain velocity, the growth of the crack is unstable, which results in the fractured surface no longer being smooth (Luyten & Vliet, 2006). The fracture speed and pathway will be dependent on the energy available versus the fracture energy (Luyten & Van Vliet, 2004). As shown in Figure 2.7, a single fracture event is recognised by a drop in force and an accompanying acoustic signal.

A single crack pathway can splinter into multiple cracks. The crack speed is regulated by defects and weak points such as cavities, pores or thinner material. These defects will temporarily slow down the crack pathway or stop it by energy dissipation. This explains the jagged force profile seen in Figure 2.7.

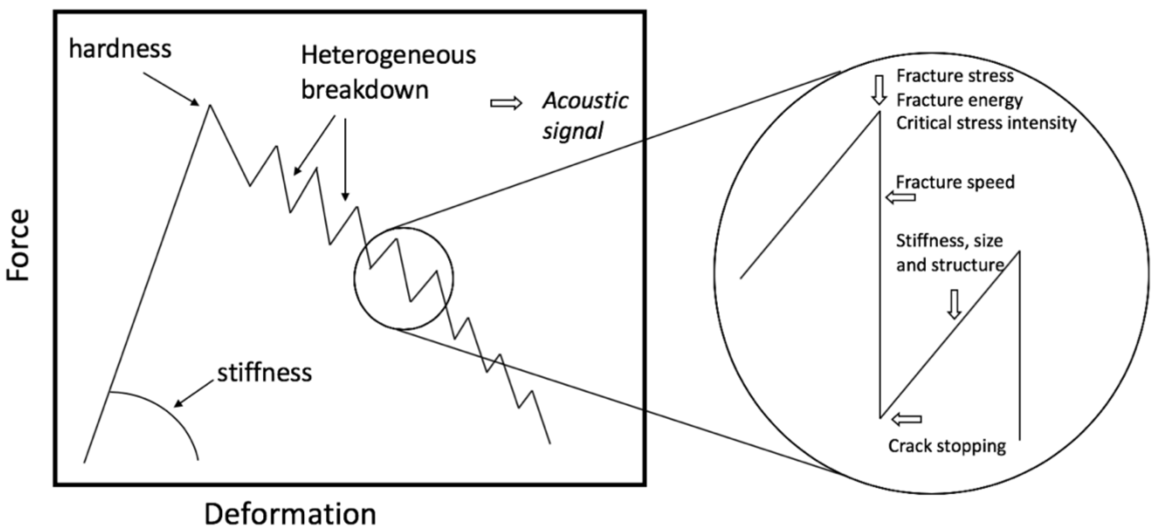

Figure 2.7 Schematic example of a force-deformation curve of crisp material. A single fracture event has been highlighted to show the properties that can be extracted. Image adapted from (Luyten & Van Vliet, 2004)

Further compression after the first fracture event will increase the force again, the slope of this curve will then depend on the stiffness and size of structural elements. As deformation continues, fragments of brittle material shatter and become smaller, therefore the slope of the curve will decrease.

The relationship between fracture parameters and microstructure have been studied qualitatively for crisp fruits and vegetables (Alvarez et al., 2000). The irregularity of a fracture pathway for dry crisp products has also been studied extensively (Norton et al., 1998; Peleg, 2003; Peleg & McClements, 1997), but literature on the relationship between microstructure of crusted crisp and fractures is limited.

2.7.3 Fracture mechanics

As stated in section 2.7.2, the mechanical properties of a crisp material and the presence of inhomogeneities determine its fracture behaviour. Inhomogeneities can be considered as small cracks, cell wall thickness or presence of plasticizer. When a stress is applied, it will be concentrated at the tip of these cracks as shown in Figure 2.8.

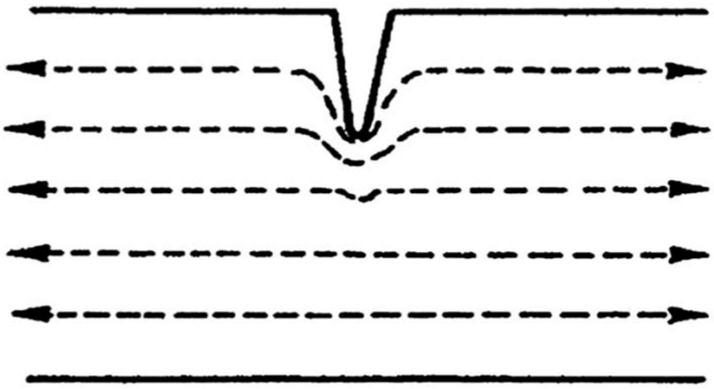

Figure 2.8 Schematic representation of how stress is concentrated at the tip of a crack in crisp material whilst subjected to tensile stress. This is represented by the arrows perpendicular to the crack. Image from (Van Vliet & Primo-Martin, 2011).

Stress will be concentrated at the tip of these cracks and the extent of stress concentration will depend on the shape and size. Most dry crisp products have a crack speed within the range of 300-500 m/s (Luyten & Vliet, 2006). In biscuits, a speed of at least 100 m/s was measured using a high speed camera, however, this was most likely higher in reality (Luyten & Van Vliet, 2004).

The crack speed can be understood by considering the fracture process as an energy balance as shown below (Luyten & Vliet, 2006; Van Vliet & Primo-Martin, 2011):

(Eq. 2.3)

W = energy supplied to the material during deformation

W' = elastically stored energy

W'' = dissipated energy

W_f = fracture energy

The elastically stored energy is available for crack growth as the stress in the material surrounding the newly formed crack can relax. Crack growth will continue spontaneously if the differential energy that is released during crack growth is greater than the differential energy required (Van Vliet et al., 1991). The crack speed is regulated by local differences in the meso-structure, the presence of cavities, localisation of fat, protein or water-rich regions, all of which will cause the crack to stop or slow down. Energy dissipation (*W*") will also slow down crack speed as less energy becomes available for the fracture process (Luyten & Vliet, 2006). A high critical velocity is needed to be able to release an acoustic emission. This explains how acoustic emission is dependent on the material properties and the structure but also how products are perceived as less crispy (Luyten & Vliet, 2006).

2.7.4 Acoustic emission coupled with force-deformation

A combination of acoustic and force-deformation measurements have been shown to be useful for measuring oral crispness (Vickers, 1988; Vickers & Bourne, 1976). This has led to the use of acoustic envelope detectors (AED) coupled with texture analysers to simultaneously measure sound pressure changes generated from a fracture (Castro-prada et al., 2007; Chen et al., 2005; Saeleaw & Schleining, 2011). Alternatively, acoustic emissions can be recorded as a product is being chewed, this allows for an understanding of changes in acoustic signals during oral processing. This method has been carried out for apples, (De Belie et al., 2000) potato chips and crackers (De Belie et al., 2003).

In force-deformation curves using a texture analyser and an AED, a force drop will typically be accompanied by an acoustic event, this is demonstrated in Figure 2.9. As shown in Figure 2.9, more acoustic events can be expected than force fracture events due to a single fracture event splintering into many (Taniwaki & Kohyama, 2012). The sound peaks are a result of released stored strain energy whilst the force curve reflects the amount of energy applied to the material.

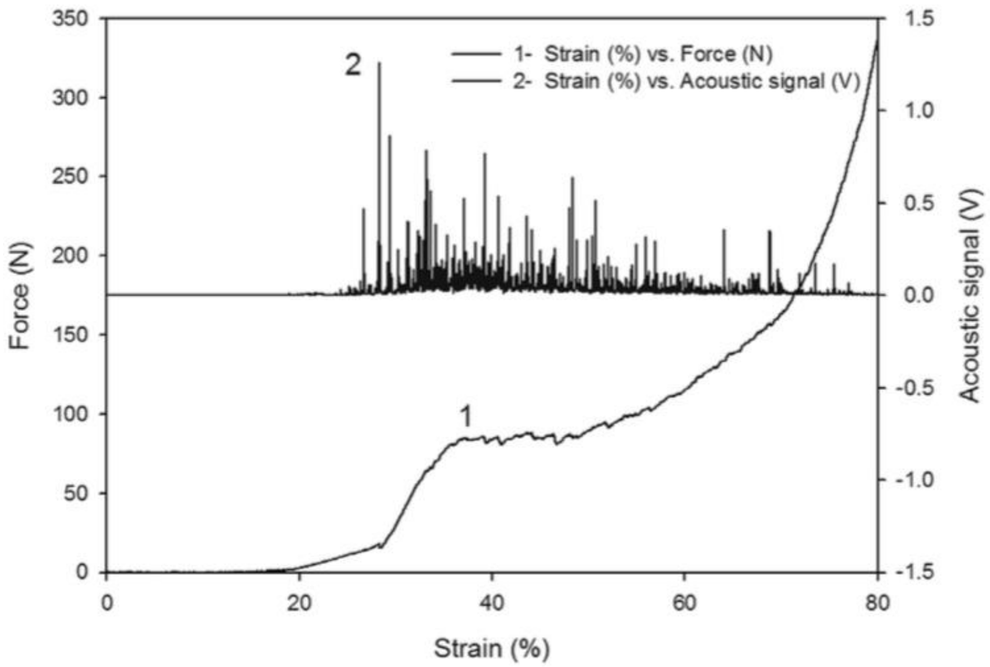

Figure 2.9 Relationship between force, strain and acoustic signal during compression of crisp bread sample. Note that at the initial phase of penetration, acoustic emission is negligible, the structure is deforming but not fracturing until 30 % strain. Image from (Gondek et al., 2013)

In a dry cellular crisp product, the sound produced is due to the rupture of a cell. In a non-cellular product such as potato crisps, the sound is produced from the repeated fracture of the thin cell walls (Duizer, 2001). A study using crackers to represent dry crisp have shown that an acoustic emission can only be detected for force drops that are larger than 0.3 N (Luyten & Vliet, 2006).

2.7.5 Sound analysis

The use of a texture analyser coupled with an AED allows for the following parameters to be extracted; the number of sound peaks, area under force curve, maximum sound peak and sound pressure level. When studying further into spectral acoustic analysis, frequency, also referred to as pitch, is a parameter that refers to the number of times per second that a sound wave is repeating itself. Humans can hear at a frequency range of 20 to 20,000 Hz (Chaunier et al., 2005). Above this range is ultrasound, below this range in infrasound. Non-crispy products can produce frequencies ranges lower than 3 kHz, these are commonly recognised as crunchy as opposed to crispy (Chaunier et al., 2005). Whereas crispy foods can produce frequencies between 5 – 12.8 kHz (Vickers, 1987). Analysis of the acoustic properties of food has shown that crispy foods have a typically higher frequency in comparison to crunchy foods (Zampini & Spence, 2004). Although crispy and crunchy are positively related, a difference in frequency means they can be analytically distinguished (Zampini & Spence, 2004).

However, texture analysers have a limited sampling rate (500 pps), this is also the case for the accompanying AED. This is problematic when trying to depict the frequency emitted during the deformation process because the acquisition of the acoustic emission must have a significantly high sampling frequency. A high sampling rate has been emphasised by authors studying acoustic emissions from biscuits and potato chips (Castro-prada et al., 2009; Taniwaki & Kohyama, 2012).

As crisp material fractures, a sound wave propagation is caused by simultaneous compression and rarefaction of molecules in the air (Speaks, 2017). Amplitude refers to the magnitude of air molecules displaced, this displacement is proportional to the fracture force that was applied to the crisp material (Speaks, 2017). This means a greater fracture force will result in greater displacement of molecules from equilibrium, therefore a louder sound produced and a high crispness perception. The molecular displacement can be graphically represented using an amplitude-time plot (Figure 2.10). The acoustic parameters that can be extracted from an amplitude-time plot include maximum amplitude, number of peaks, the height of peaks and duration of a sound. All of which has been used when studying crisp products during mastication (Duizer, 2001)

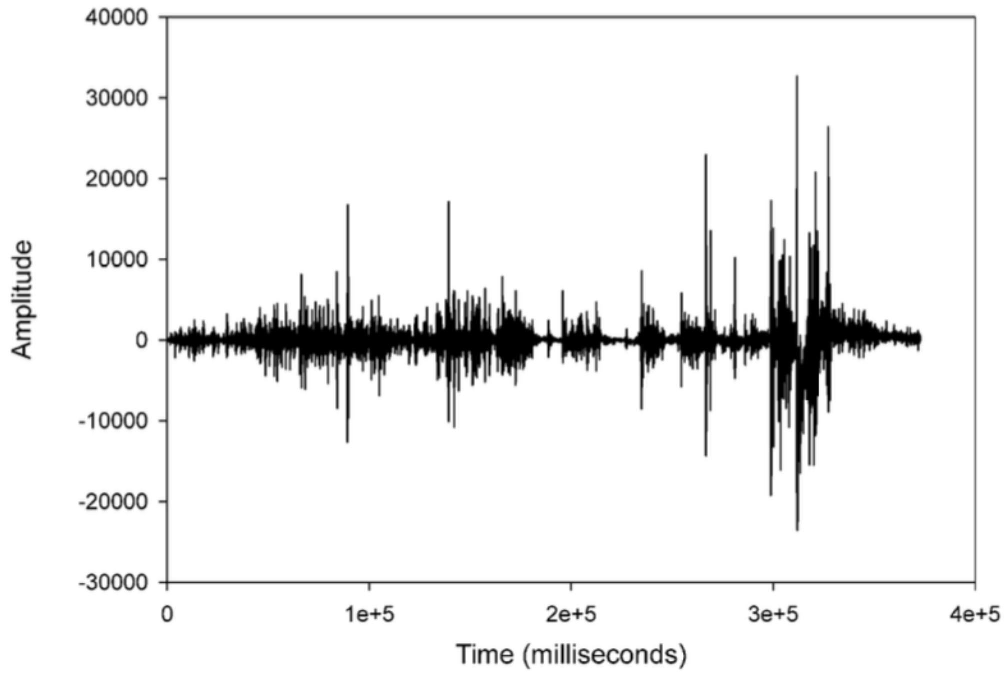

Figure 2.10 Example of an amplitude-time plot of a crisp product. Image from (Duizer, 2001).

A study using toast have inferred that high amplitude translates to crispier toast (Drake, 1963). The number of peaks has been discussed as a good predictor of potato chip crispness.

However, the mean height of peaks has been found to not correlate well with crispness in potato chips (Vickers, 1987). It should be noted that correlating crispness to acoustics during mastication is difficult due to differences in biting distances, teeth arrangement and biting forces. Therefore, using an instrument to deform a sample for acoustic analysis is recommended for objective recordings of sound (Duizer, 2001)

Acoustic studies have analysed either the amplitude-time plot or the amplitude-frequency using Fast Fourier Transform. This aims to extract amplitude, the height of sound peaks or sound pressure level. Limitations of acoustic testing have been found, as (Tesch et al., 1996) described that it was not possible to establish a relationship between mechanical and acoustic signature by compression testing. This was possibly due to the AED not having a high enough sampling frequency, a common limitation of using TA-AED.

However, as technology has progressed, the use of acoustics coupled with force deformation experiments have shown acoustic patterns can be identified and related back to textural properties. This has been shown in foods ranging from almonds (Varela et al., 2006), apples (Costa et al., 2011) and potato snacks (Salvador et al., 2009)

2.7.6 Sound perception of crispness

A sound wave is propagated when one air molecule is displaced from its equilibrium, this then displaces adjacent molecules and causes surrounding molecules to vibrate (Duizer, 2001). Humans perceive sound waves through air conduction to the ear and bone conduction via the mandible, cheeks and tongue (Duizer, 2001). A sound wave travels through the auditory canal to trigger vibrations within the eardrum. The ossicles are activated to transfer the wave to the inner ear. It is within the inner ear that sound waves are divided into components of frequencies. It is the composition of these frequencies that allow textural properties to be perceived as a sound.

Sound waves transmitted through the mandible and soft tissue to the inner ear are typically of low frequencies due to majority of the sound being absorbed by the soft tissue around the mouth and jaw (Duizer, 2001).

The sound sensations of crispness and crunchiness have been reported to be distinguishable by consumers: crisp is a short sound i.e. high frequency (walking on snow), whilst crunch has a longer duration i.e. low frequency (walking on gravel) (Fillion & Kilcast, 2002).

When sound has been artificially modified, the sensory evaluation of crispness varies significantly (Zampini & Spence, 2004). Without a sound emission, the food product will still behave in a brittle manner, but the crisp characteristic will be perceived as less or absent (Luyten & Vliet, 2006). As mastication continues, sound emission changes as sample dimension changes, in addition to the presence of saliva (Duizer, 2001). Thus explaining why maximum crispness is perceived during the first bite.

2.8 Measuring sensory crispness

The importance of crispness as a sensory attribute has been shown in food texture studies as early as the 1970s (Szczesniak, 1971). The results from Szczesniaks' word association tests found that the term 'crisp' was mentioned more often than any other attribute. Consumers were also ranking products according to crispness as well as preference. These results were replicated in the 1980s to emphasize the influence of crispness on consumer acceptability (Katz & Labuza, 1981). Thus, crispness became considered a necessity to control during processing and storage.

It is widely accepted that crispness depends on *ad hoc* rheological and mechanical characteristics but it also relies on sensory perception. The challenge then becomes developing methodologies to measure sensory crispness. Szczesniak (1988) conducted a study with two hundred consumers to define crispness. The results of this study concluded three types of sensory crispness 1) raw fruits and vegetables, 2) porous dry foods, and 3) fried products (Antonova et al., 2003). There are essentially five aspects of any definition of crispness, these have been quoted as an intact structure, the sound emitted upon fracture, the force required for fracture, how the structure deforms and finally the fragments formed after fracture (Antonova et al., 2003).

Sensory crispness is strongly associated with sensory hardness, brittleness, crackliness and crunchiness (Mallikarjunan, 2004). As shown in Table 2.1, generalised concepts of crispness have been established, emphasizing that there is no clear singular definition of crisp. In fact, crispness, crunchiness and crackliness are often closely correlated and interchangeable (Chauvin et al., 2008). Crispness and how to evaluate it will vary from country to country (Table 2.1), this of course depends on the sample being evaluated.

Table 2.1. Example of how definitions of sensory crispness vary from country to country

Location	Crispness definition	Reference
USA	The perceived horizontal force with which the product separates into two or more distinct pieces during a single bite with the incisors. An abrupt and complete failure of the product is required.	(Barrett et al., 1994)
UK	Place a small piece between the molars and bite down slowly and evenly until a sudden and continuous breakdown of the biscuit structure occurs. Assess the rate at which this breakdown into small fragments occurs using as near as possible the same biting rate.	(Brennan et al., 1974)
New Zealand	A combination of the noise produced and the breakdown of the product as it is bitten entirely through with the back molars.	(Duizer et al., 1998)
France	Noisy at biting, aerated, light and that crumble. The fracture is progressive during biting (translation from French).	(Dacremont, 1992)

As mentioned in section 2.5.3. crusted crispness is a combination of wet and dry properties. Table 2.2 highlights similarities in the definition of crusted crispness, it can be noted that the emphasis is made on the mechanical and auditory

Table 2.2 Description of sensory evaluation techniques for crusted crispness.

Sample	Crispness definition	Reference
Coated shrimp	The ease of fracture in the mouth combined with loudness of the sound produced	(Tahnpoonsuk, 1999)
Coated chicken	The force and noise with which a product breaks or fractures (rather than deforms) when chewed with the molar teeth (first and second chew).	(Antonova et al., 2004)
Coated turkey	The force and noise level, at which a product breaks or fracture (rather than deforms) when chewed with the molar teeth during first and second chew	(Iliassafov & Shimoni, 2007)
French fries	Multiple, high-pitched sounds produced when the sample is crushed with back molars	(Li et al., 2020)

2.8.1 Sensory test methods

The types of sensory evaluations including possible test methods are summarised in Figure 2.11. The objective of the sensory evaluation dictates which test method is the most appropriate. There are four types of data that can be produced; nominal, ordinal (both qualitative data), interval and ratio (both quantitative data). Each type will dictate the appropriate statistical analysis.

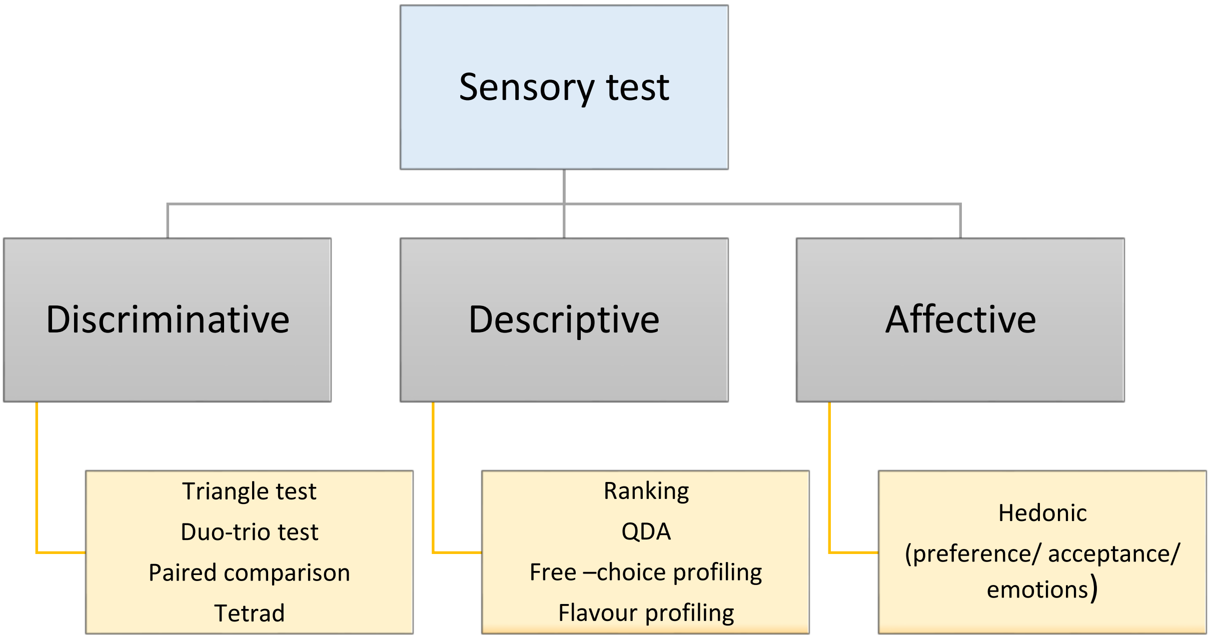

Figure 2.11 A summary of the types of sensory evaluations with examples of possible tests used for assessing samples.

2.8.2 Descriptive testing

Descriptive testing is favoured as the results generated can be used to support product market decisions. In descriptive methodologies, quantitative word descriptions are produced based on the perception of a group of trained panellists. The descriptions can take into account of all sensations perceived via visual, auditory, gustatory, olfactory and kinesthetic (Kemp, 2009). Alternatively, the evaluation could focus on a single modality such as texture or flavour. The product handling and usage at home could also be explored, thus providing a more realistic experience (Caballero et al., 2003).

As a method, descriptive tests can be expensive and time-consuming due to the necessity of training and profiling individuals over a period of time. However, the individuals are trained to become experts and carry out assessments at a level that is arguably more sensitive than instruments. Companies value the use of descriptive testing because it can be applied to bench-mark testing, shelf-life testing, quality assurance, monitoring panel performance and identifying drivers of consumer response (Kemp, 2009). The use of descriptive analysis became popularised during the 1980s and was acknowledged as a reliable method to measure sensory attributes, including crispness.

The use of a standard sensory rating scales was first introduced by Szczesniak et al., who scaled attributes including hardness, brittleness, chewiness, gumminess, adhesiveness and viscosity. Commercial products could then be included as anchors in the scales and used for comparisons when evaluating actual test samples (Szczesniak, 1987). The advantage of this method allows for a clear indication of intensities and calibrating panellists, in a manner that is similar to calibrating a pH meter with buffer solutions (Xiong et al., 2010).
Recent studies focusing on descriptive testing of crispness show that the use of a trained panel is favourable (Kwak et al., 2019). As shown in Table 2.1, the definition of crispness is not unanimous. Therefore, the use of a trained panel can bring consensus.

2.8.3 Affective testing

Affective testing, also known as consumer testing involves the use of untrained panellists. The aim of affective testing is to assess the preference or liking of a product. The main disadvantage of this type of testing is the lack of information on the magnitude of liking or disliking (Lawless & Heymann, 2013). The most well tried and tested scale to measure liking data is the 9-point hedonic scale (Kemp, 2009). The hedonic scales were developed at the U.S. Army Food and Container Institute in the 1940s. A balanced 9-point scale was produced with each category being associated with a verbal descriptor from 1 = extreme dislike to 9 = like extremely (Lawless & Heymann, 2013).

Although the hedonic scales are still heavily used, there are limitations to be considered. A large panel size is required to account for the high variability of individual preference, thereby ensuring a high statistical power (Lawless & Heymann, 2013). The use of a large panel allows for opportunities to look for segments of consumers that have a specific behaviour or preference. However, hedonic scales are vulnerable to ceiling effects (Schutz & Cardello, 2001) because of the small number of categories and the tendency of consumers to avoid the extremes of the scale (Moskowitz, 1982). Finally, there is arguably a lack of equal hedonic interval between the categories. However, hedonic scales are favoured by sensory professionals for its simplicity, accuracy and ability to infer consumer liking (Muellenet, 2004).

When considering the acceptance of a food product, an understanding of the attributes that affect overall liking is beneficial. Therefore, the use of a just-about-right (JAR) scale identifies where a product may fall short or can be improved. JAR uses a 5-point category scale with the midpoint being JAR, and the two ends semantic opposites, “much too weak” or “much too strong” (ASTM, 2009).

There is debate over the application of a JAR scale as a diagnostic tool. As JAR combines preference and intensity, it is deemed more appropriate for consumer testing as opposed to a trained panel. There is also a risk of interpretative errors if inappropriate attributes are chosen. However, several publications report the successful use of JAR to further develop products. Such have included dairy products, fruit fillings and juices (Gere et al., 2017).

2.9 Combination of sensory and instrumental measurements

The use of both instrumental and sensory testing to evaluate a texture attribute is well documented in literature. Studies have been carried out to measure textural properties for fish muscle (Hyldig & Nielsen, 2001), dairy products (Skarlatos et al., 2020), breads (Marinopoulou et al., 2019) and fruits (Aaby et al., 2019). The same principles have been applied to deep-fried foods such as French fries(Li et al., 2020), fried doughs (Ndlala et al., 2019) and potato chips (Kwak et al., 2019).

Attempts have been made to establish the relationship or develop a predictive model between sensory and instrumental parameters. This is a common practice to incorporate both instrumental and sensory parameters. The advantages of this include finding instrumental parameters to monitor any changes in product quality, predict consumer response, understand the sensory perception and utilising instrumental test methods (Li et al., 2020). If a strong correlation (r = ±0.8 ~±0.9) is calculated, then a predictive model between variables can be established (Kwak et al., 2019).

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Chapter 3: Characterisation of deep-fried batter and breaded coatings

Based on work published as: Voong, K., Norton, A., Mills, T., & Norton, I. (2018). Characterisation of deep-fried batter and breaded coatings. *Food Structure, 16*, 43-49.

Additional data has been added to this chapter to further support the results and discussion section. This data will have been acquired after the publication was cleared.

3.1 Background

The aim of this chapter was to first characterise a standard deep-fried battered and breaded coating from a shrimp product, with an ultimate goal to quantify the link between microstructure and crisp texture. Shrimps are coated with a wheat flour predust layer, followed by a liquid wheat flour based batter, finally a panko breadcrumb layer is added before deep-fat frying. The coating is of interest due to its palatable taste and unique crisp texture. Crispness is a sensory and textural attribute that is used by consumers to determine quality and freshness (Chauvin et al., 2008). Therefore, visualising the structural composition and quantifying physical properties were necessary in order to understand how crispness perception occurs. The internal morphology of the deep-fried coatings were investigated using X-ray MicroCT. An evaluation of the physical and mechanical properties were studied using texture analysis and acoustics. In addition, microscopy was applied to highlight differences in structural composition and identify where oil and moisture accumulates. Panko breadcrumbs are the final step of the coating process, they are also the first part of the structure that will be compressed during mastication. Therefore, the effect of panko breadcrumb size on the physical and mechanical properties of the deep-fried coating were investigated.

3.2 Materials and Method

3.2.1 Materials

White shrimps were obtained from Hyperama Plc, UK, at a specification size of 50-60 (average count per kg). Soya bean oil was also obtained from Hyperama Plc, UK. Sodium phosphate, predust flour, dry batter mixture and panko breadcrumbs were kindly supplied by Kerry Ingredients, and were shipped from Beloit, WI. Nile red dye used for confocal microscopy was obtained from Sigma Aldrich 72485, UK.

3.2.2 Preparation of samples for deep-fat frying

Frozen white shrimp were defrosted at 4 ^{o}C overnight prior to use. Each shrimp was butterflied and deveined, then soaked in a sodium phosphate solution for 1 hour before coating. The sodium phosphate solution was made up to a concentration of 10 wt %.

After draining the samples from the phosphate buffer solution, each shrimp was weighed to calculate the correct percentage required for the coating step. The amount of coating adhering to the sample prior to frying was calculated by the weight of coated sample divided by weight of sample before coating multiplied by 100. The total pick-up percentage was expected to be 50 % ± 2 %.

The first layer consisted of powdered predust flour (pick-up 12 %), then a liquid batter layer (pick-up 18-20 %). In order to avoid batter dripping from the sample affecting the measurement of pick up, samples were allowed to drip for 30 s before weighing. The final layer was a coating of panko breadcrumbs (pick-up 18 %). To investigate the effect of breadcrumb size, panko breadcrumbs were separated using the following sieve apertures: 4.0 mm, 2.8 mm, 2.0 mm, 1.4 mm, 1.0 mm, 710 µm, 500 µm, 355 µm (Endecotts Ltd. London, England). Therefore, all coatings had the same level of predust flour and batter layer, but a different breadcrumb size. A size range of 4.0 mm – 355 µm was chosen based on the sequence 2, a conventional approach in particle size distribution as particle size distribution is typically log-normal.

All samples were fried at 195 °C for 42 seconds in soya bean oil (Fryer model NPDF3, Parry Catering Ltd UK). The fryer was preheated for a minimum of 1 hour before use. Each coating was then evaluated by removing from the shrimp core post-frying.

3.2.3 Moisture and oil content

Moisture and oil content were calculated for the coating post-fried to assess changes in moisture and oil content with breadcrumb size. Moisture content was determined by calculating the difference in weight before and after vacuum oven-drying for 24 h at 70 ^{o}C. Oil content was determined by Soxhlet solvent extraction for 5-6 hours, followed by rotary evaporation to extract the amount of oil inside the fried coatings. Samples were carried out in three replicates.

3.2.4 Confocal microscopy

Confocal microscopy was used in order to visualise the accumulation of oil in the coating. Batter and breadcrumb coating cross-sections were cut and stained after frying with a Nile red in ethanol solution (Sigma Aldrich 72485, UK) (0.01 % w/v). This allowed for observation of the depth of oil penetration. Approximately 100 l of dye was used to stain a sample size of 0.5 x 1 cm. The staining procedure was carried out in minimal light conditions as Nile red is photosensitive. All samples were placed under the confocal microscope immediately for scanning.

A confocal microscope (Leica TCS SP5, Germany) was used to acquire images after exciting at 543 nm with a He/Ne laser. Image acquisition was performed at a pinhole size of 100 µm with 10 x magnification objective lens.

3.2.5 Cryo scanning electron microscopy (Cryo-SEM)

As deep-fried coatings contained a mixture of oil and moisture, cryo-SEM was deemed appropriate to visualise the structure. Samples of deep-fried batter coating were cut and fixed to platforms (50 mm in diameter) with colloidal graphite (Agar scientific UK). These were then rapidly frozen in semi-solid nitrogen, inside the quorum cryo chamber. Model used was X130 ESEM-FEG (Philips, Holland) fitted with a PolarPrep 200 Cryo-Stage (Quorum Technologies, UK). Samples were being scanned at 5 kV. Images were acquired using FEI operating software (Thermo Fishers Scientific), at magnifications up to x10000.

3.2.6 X-ray Micro computed tomography (MicroCT)

Samples of deep-fried coating were cut to fit inside a 6 mm plastic straw before being covered in parafilm to prevent moisture lost. Samples were scanned using a voltage of 59 kV, current of 100 µA and no filter (Skyscan 1172, Bruker, Belgium). Software NRecon, CTAn and CTVox was used to reconstruct images and carry out 3D analysis. Experiments were carried out in three replicates.

3.2.7 Texture and sound emission analysis

Compression testing was carried out using a TA XT plus Texture Analyser (Stable Micro Systems Ltd. UK) with 5 kg load cell, 3 g trigger force, P/40 cylindrical aluminium probe at a constant speed of 0.5 mm/s. Deep-fried battered and breaded coating were peeled from the core substrate, cut into 20 mm diameter shapes and subjected to 60 % compression ratio with top surface of the coating facing upwards. Ten replicates were performed for each sample.

Acoustic envelope detector (AED) (TA-XT Plus, Stable Micro Systems Ltd., UK) was used for force-displacement acoustic measurements and recorded using Texture Exponent (Version 6.1.10.0). A Microphone (12 mm diameter) was positioned 7 cm horizontally from centre of platform. Although a 45^{o} angle is recommended by the manufacturer, the angle of the microphone has been shown to have a small effect on acoustic signal (Chen et al., 2005). Calibrated using a sound calibrator at 94 dB and 114 dB at 1000 Hz. Any background noise was filtered using 3.125 kHz corner frequency. A gain of AED was set at 3 with data acquisition rate set to 500 pps for force and sound measurements. Ten replications were performed for each sample. Parameters extracted included: Maximum force, area under force curve, force peaks (drops in force above 0.049 N), maximum sound pressure level and number of sound peaks (drop in sound pressure level above 10 dB). All measurements were carried out 2 minutes after frying to allow equal cooling time.

3.2.8 Statistical Analysis

One-way ANOVA and post-hoc Tukey test was performed to evaluate any significant differences between samples (XLSTAT software 2018.3 Addinsoft, Paris, France.).

3.3 Results and discussion

3.3.1 Microstructure of fried batter and breadcrumb coatings

The microstructure of batter coatings has been previously explored with microscopy techniques (Llorca et al., 2001; Moreno & Bouchon, 2013). The use of microscopy to study internal morphology of deep-fat fried batter is demonstrated in Figure 3.1, which shows a decrease in fluorescence deeper within the coating, highlighting the differences in structure throughout the sample. Regions of high fluorescence are clustered at the surface of the coating, suggesting oil accumulates within breadcrumb pieces. This is in contrast to low fluorescence deeper within the coating, where moisture content is higher than at the surface and oil content is lower. The depth of oil penetration can also be observed; a longer frying time is required for deeper oil penetration. Figure 3.2 shows cross-section images of a deep-fried batter coating without breadcrumbs, captured using cryo-SEM. The images highlight the change in structural composition upon frying. Figure 3.2a shows clear distinction in structural change where oil penetration has ceased. This has been highlighted further at a higher magnification in Figure 3.2b, to show where oil and moisture exchange has occurred, a porous network has formed around starch granules. Starch granules also show surface disruptions resembling a porous open structure. This damage to the structure could be sign a of starch gelatinisation, as prolonged frying time has been shown to lead to a higher degree of gelatinisation (Ding et al., 2018). The contrasting structure has moisture retained, low porosity and swollen starch granules. This shows the formation of a crisp crust contrasting a high moisture core.

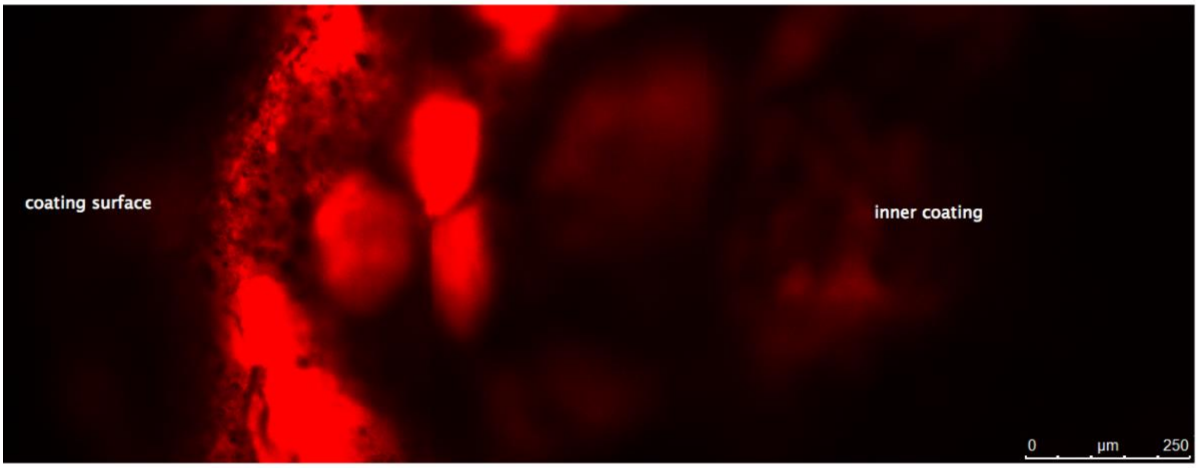
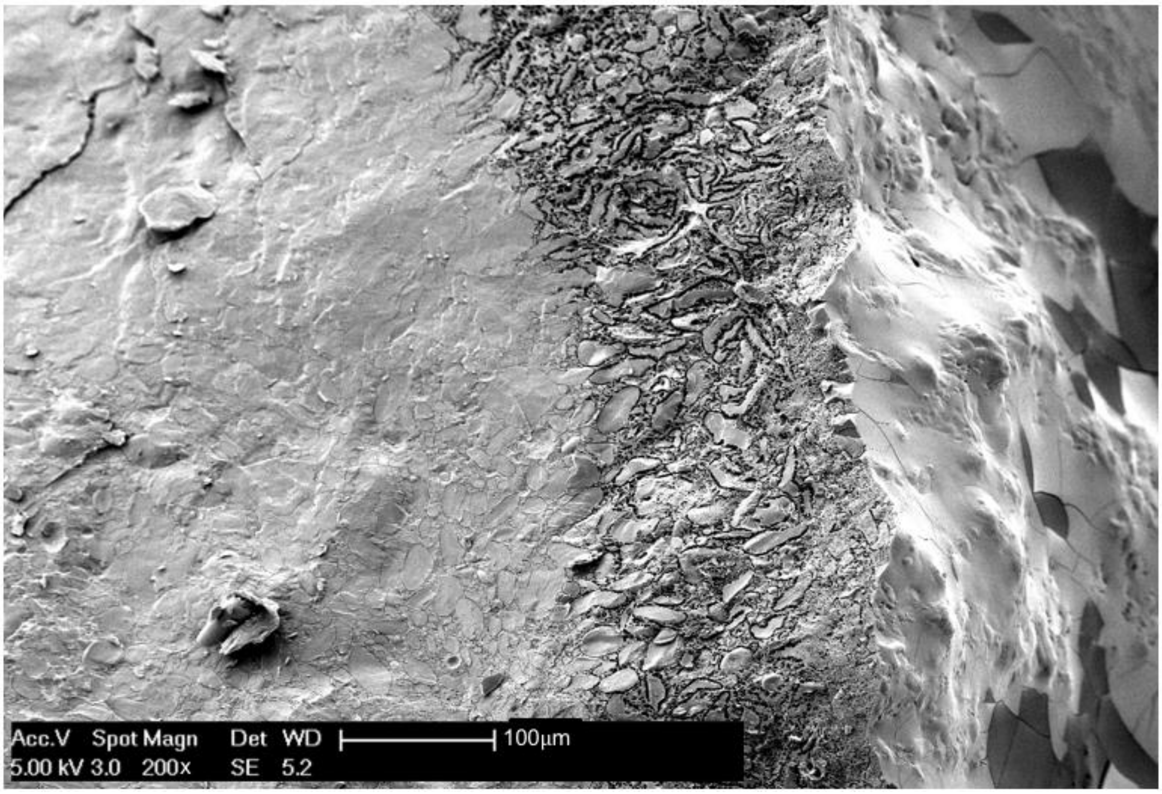


Figure 3.1 CLSM image shows cross-section of fried batter and breadcrumb (not sieved) coating stained with Nile red to observe depth of oil penetration. Nile red highlights differences in morphology at layers of the crust

a)



b)

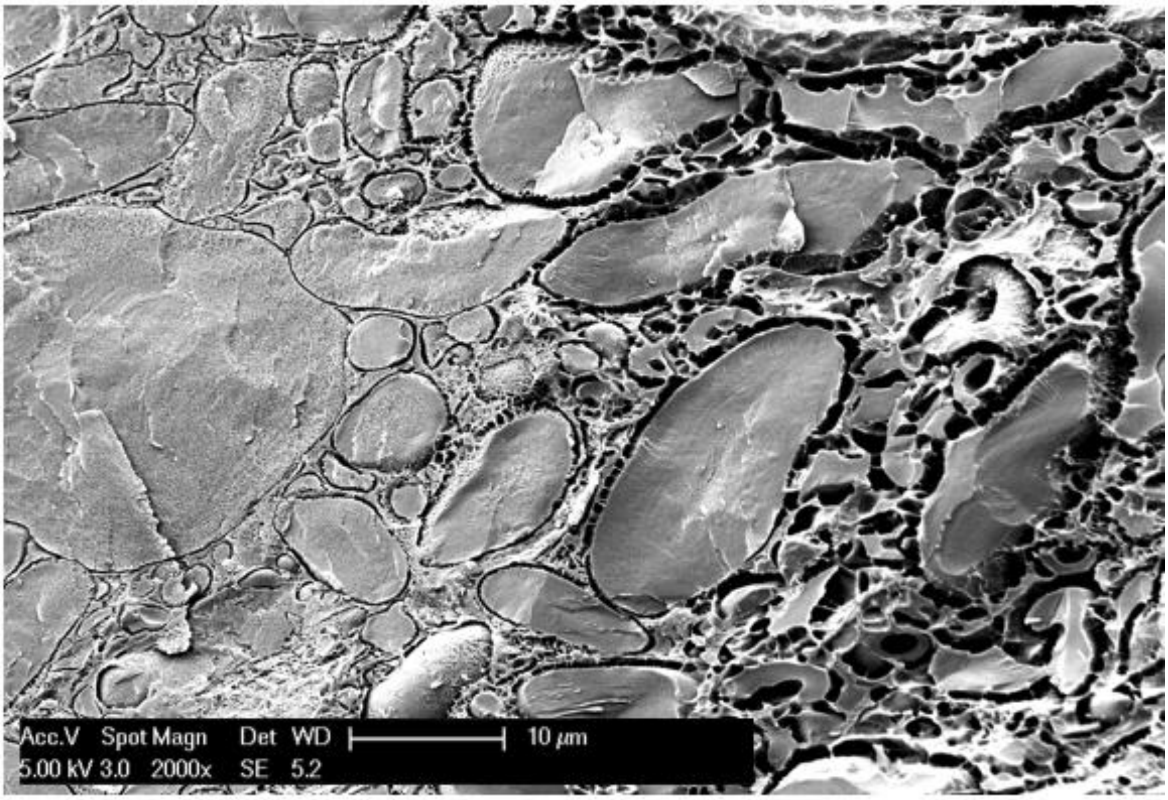


Figure 3.2 Cryo-SEM image of deep-fried batter coating a) entire cross-section visible from top surface of coating to inner surface. b) 2000x magnification highlighting where oil penetration ceased.

Microscopy techniques are limited in terms of resolution and require laborious sample preparation. As a result, MicroCT has been employed in this study for its non-invasive and high resolution ability to quantify structural parameters; total porosity, pore size distribution and structural thickness. These physical parameters are structural modifications caused by heat and mass transfer during deep fat frying, the degree of these structural changes will affect mass migration (Adedeji & Ngadi, 2011).

Surface topography influences batter oil drainage during cooling but an understanding of the internal morphology provides an indication of permeability and space for oil absorption (Moreno & Bouchon, 2013). Prior to scanning, the surface of coatings was observed to be more uniform and with a smoother surface with decreasing breadcrumb size. 2D greyscale slices shown in Figure 3.3 demonstrate that with decreasing breadcrumb size, coatings appear to be visibly thinner, large pores are clustered towards the top of the coating whilst the majority of small pores are seen towards the core. Pores shaded grey appear to have an attenuation for X-ray, suggesting they are filled with oil as opposed to air. A prominent batter layer can also be seen with decreasing breadcrumb size suggesting higher moisture content, which is supported by Table 3.1 Moisture content increases whilst oil content decreases with breadcrumb size, a high moisture layer suggests a soft and pliant core (Luyten & Van Vliet, 2004).

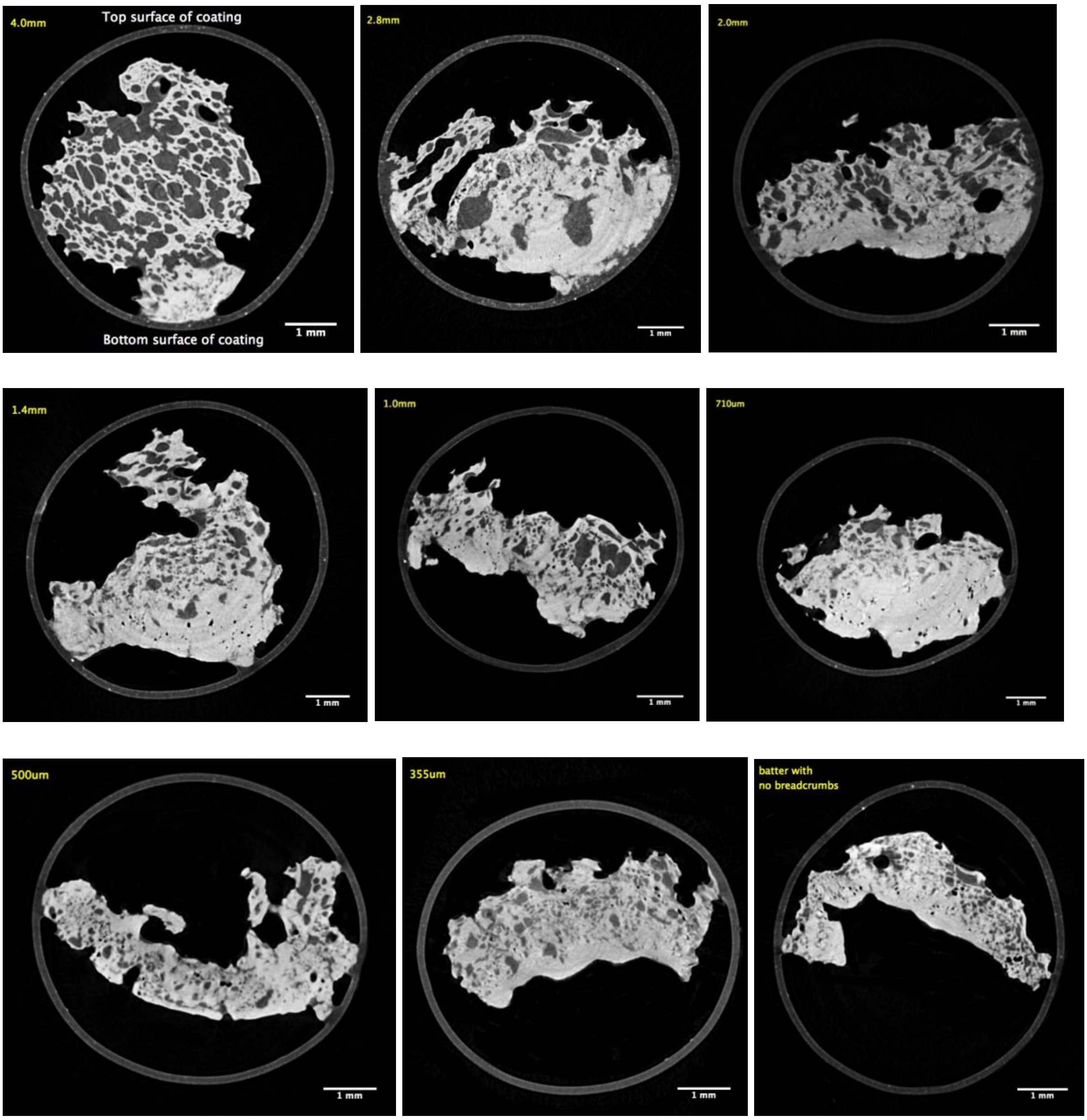


Figure 3.3 MicroCT 2D-slice image of batter and breadcrumb coatings peeled away from the substrate post-frying. 2D-slice grey scale image displays differences in morphology from top surface (top of each image) to bottom surface (bottom of each image) of coating. Each image is labelled with size of aperture used to separate breadcrumb size.

Table 3.1 Moisture content percentage (wt/wt) and oil content percentage (wt/wt) of deep-fried battered and breadcrumb coatings with variable breadcrumb sizes. Results for largest (4.0mm), intermediate (2.0mm, 1.4mm, 1.0mm) and smallest (500um, 355um) breadcrumb sizes have been stated for oil content percentage. Decreasing breadcrumb coating size show a general increase in moisture content and decrease in oil content. Standard coating refers to standard Seapak coating.

	Standard coating	**4.0mm**	**2.8mm**	**2.0mm**	**1.4mm**	**1.0mm**	**710um**	**500um**	**355um**	**Batter only**
Moisture content % (wt/wt)	23.8 (±1.8)	26.3 (±1.4)	26.3 (±3.3)	27.0 (±2.8)	29.8 (±0.1)	31.8 (±1.6)	32.0 (±1.9)	33.9 (±3.0)	35.3 (± 1.1)	50.6 (±2.6)
Oil content % (wt/wt)	49.1 (±4.3)	42.8 (±1.3)	-	41.6 (±0.9)	41.6 (±1.0)	41.1 (±1.8)	-	40.0 (±1.2)	33.8 (±0.6)	-

As fried batter is a cellular structure, porosity is a structural property of interest and can be defined as the volume of pores relative to the volume of the entire matrix (Dogan et al., 2005). Total porosity is highest for coatings with the largest breadcrumb size (Figure 3.4), a higher porosity has been shown to result in a higher perception of crispness (Van Koerten et al., 2015).

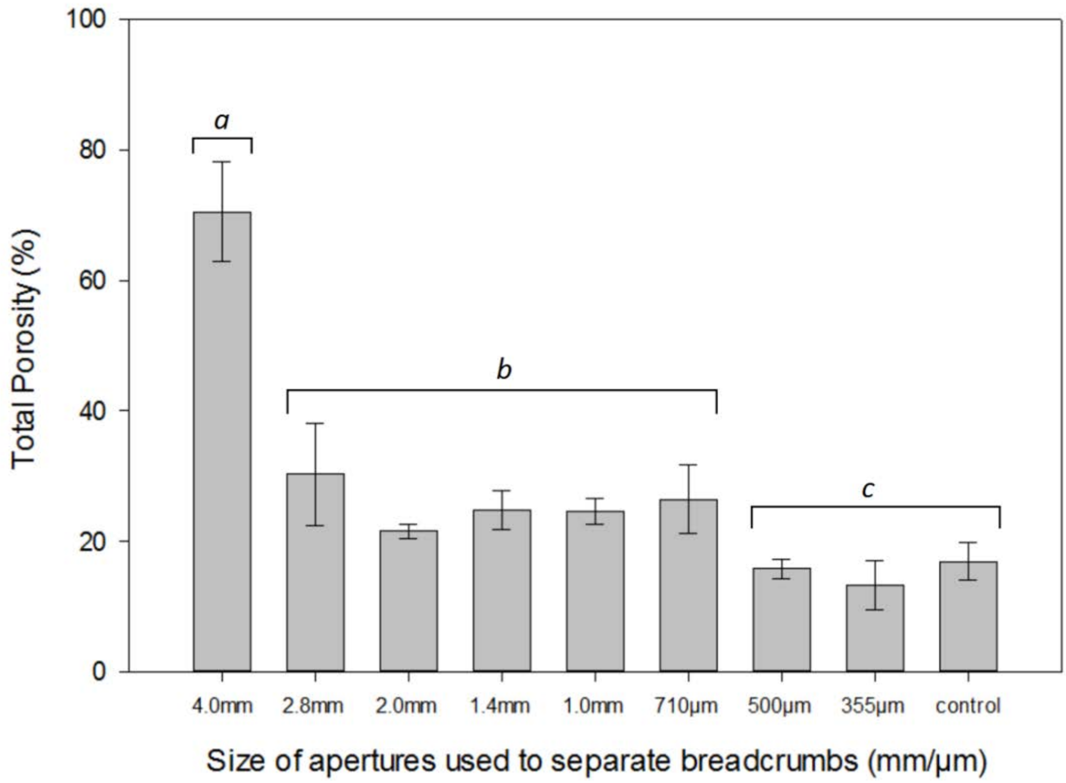


Figure 3.4 Summary of total porosity of batter and breadcrumb coatings from MicroCT analysis. Eight sizes of breadcrumb coating used with apertures listed. Identical letters indicate no significant difference at p>0.05 according to Tukeys HSD.

From Figure 3.4, total porosity of breadcrumb coatings from apertures 4.0 mm are significantly different to those from 2.8 mm to 710 µm and 500 µm to 'control' (batter without any breadcrumb), suggesting that total porosity decreases with breadcrumb size. This is evident from the 2D greyscale images (Figure 3.3) that show the structure becoming thinner with decreasing breadcrumb size whilst a high moisture batter layer is more prominent. This can be explained as breadcrumb size decreases, breadcrumbs are able to provide an even distribution of coverage across the surface, as some batter loses adhesion during the frying process, a full coverage of breadcrumbs provides a sealed barrier to prevent batter being lost (Van Koerten et al., 2015). Subsequently, a longer fry time may be required for oil to penetrate the coating to create a porous structure. Evaporation of moisture at the surface is also quicker than moisture migration deeper within the product, therefore a crisp crust is able to form (Van Koerten et al., 2015).

Studying the range of pore size within batter coatings were of interest because the presence of micropores is suggested to influence mass transfer during frying (Mellema, 2003). In fact, the smaller the pores the higher the amount of fat absorbed via capillary forces during cooling (Moreira et al., 1997).

MicroCT analysis of pore size distribution shows that coatings with the largest breadcrumb size (4.0 mm aperture) has the widest distribution of pore sizes and the largest pore sizes (Figure 3.5). Whilst decreasing breadcrumb size shows a narrowing range in pore size distribution. In fact, breadcrumbs from less than 2.8 mm aperture shows the majority of pore sizes to be <201 µm. This suggests that pore size is batter dependent for coatings with breadcrumbs <2.8 mm aperture. This is in agreement with previous studies that showed pore size distribution for deep-fried breaded coatings to range between 9-206 µm (Adedeji & Ngadi, 2009). However, the effect of breadcrumb size on pore size was not investigated in that study. A wide range of pore sizes creates heterogeneities within a structure with varying structural strength and fracture mechanics, this translates to a desirable crisp texture.

Figure 3.5 shows that coatings with breadcrumb sizes greater than 2.8 mm suggest that pore size is breadcrumb dependent, therefore a wider distribution is seen. Total porosity and pore size co-determine the amount of oil that is absorbed into the structure and has been found to increase with frying time (Van Koerten et al., 2015). Therefore, the findings in this study demonstrate the importance of breadcrumb size in fried foods formulation.

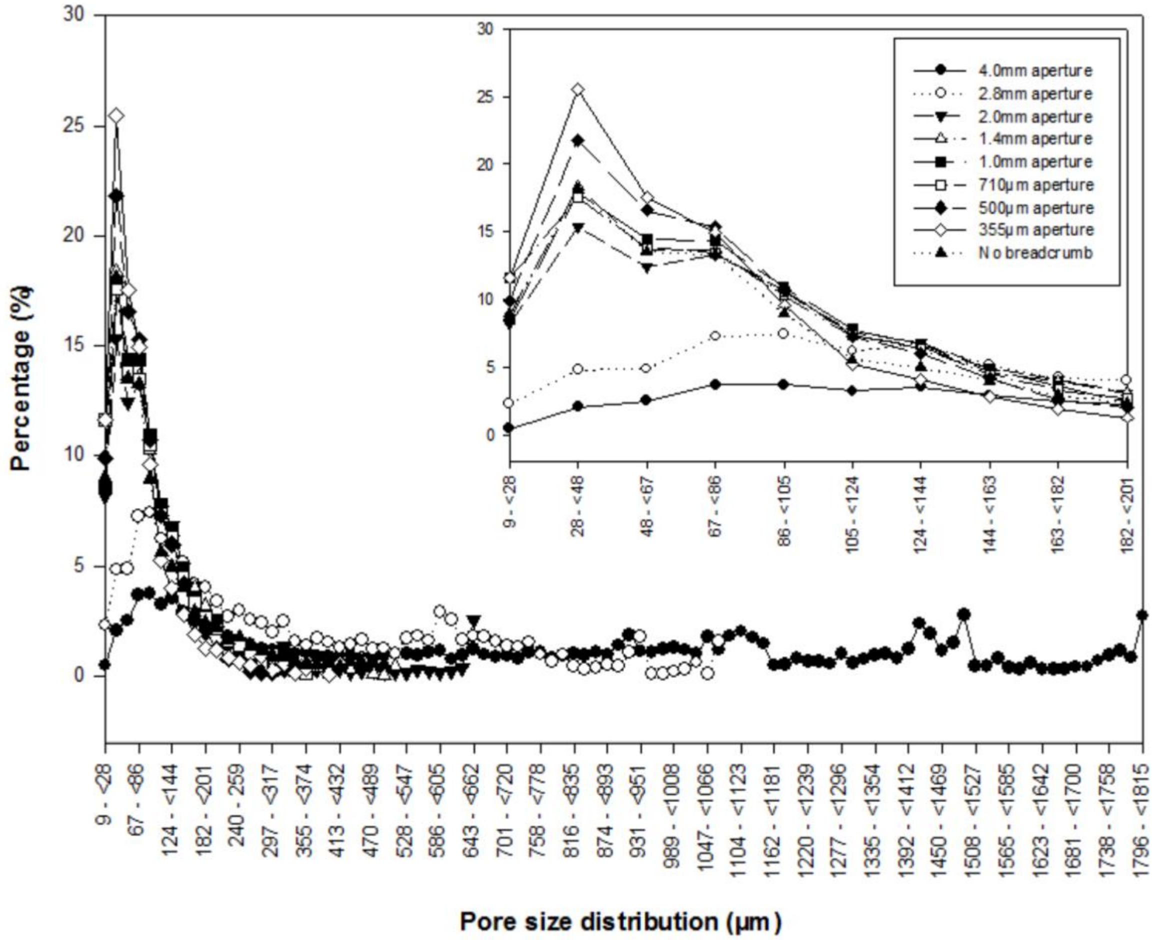


Figure 3.5 MicoCT analysis of pore size distribution of batter and breadcrumb coatings. Distribution between 9-201 µm has been highlighted as shown in graph in right hand corner.

As oil absorption is influenced by porosity and pore size, visualising the internal structure allows a clear understanding of the arrangement of pores and the degree of open and closed porosity (Figure 3.6). Colour-coding analysis shows large breadcrumb coatings (Figure 3.6A) to have a wide range and large pore sizes (>1000 µm), this explains the presence of the large yellow spots, which represent pores exceeding 1000 µm. Figure 3.6B shows a

smaller breadcrumb coatings, which highlights a narrower range and smaller pore sizes (~500 µm). The presence of blue spots is more prominent here, representing pores <100 µm. Figure

3.6A shows pores to be more clustered in comparison to Figure 3.6B, suggesting differences in structural thickness between breadcrumb coatings.

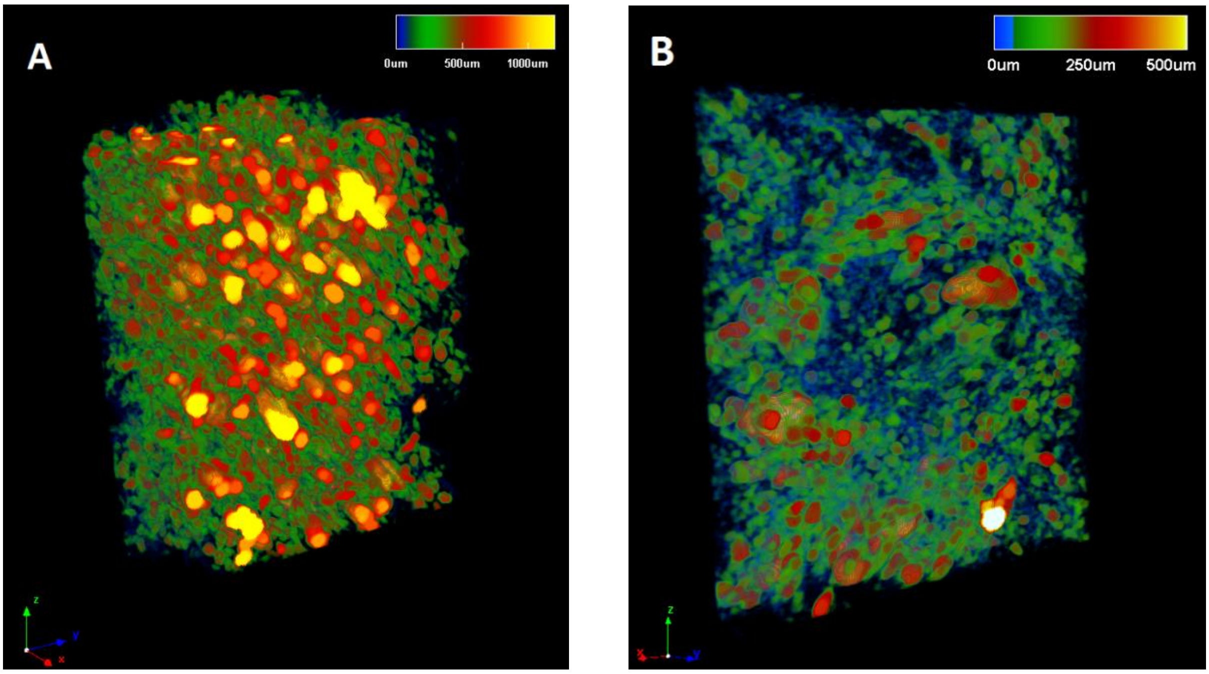


Figure 3.6 MicroCT analysis of pore size distribution processed by CTVox into colour coded 3D model of A) Breadcrumb coating form 4.0mm aperture B) Breadcrumb coating from 1.4mm aperture. Key represents the size range of pores within each coating. It should be noted the ranges differ (0-1000 µm and 0-500 µm)

The matrix between the pores acts as a scaffolding for the structure, this structural thickness could provide an indication of mechanical strength and therefore affect compression force. Compression force would translate to the amount of biting force required to fracture the structure, therefore an indication of crispness perception. MicroCT analysis has shown that the percentage volume for structural thickness for batter coatings varies with breadcrumb sizes (Figure 3.7). Structural thickness range for large breadcrumb coatings (4.0 mm) is narrow (9-220 µm) but as breadcrumb size decreases, a wider range in structure thickness is seen (9-797 µm). As expected, structural thickness appears to be inversely proportional to pore size distribution and total porosity. All coatings also show porosity to be dominated by open pores as opposed to closed pores, meaning that the majority of pores are interconnected. A higher proportion of open porosity allows space for oil to be deposited.

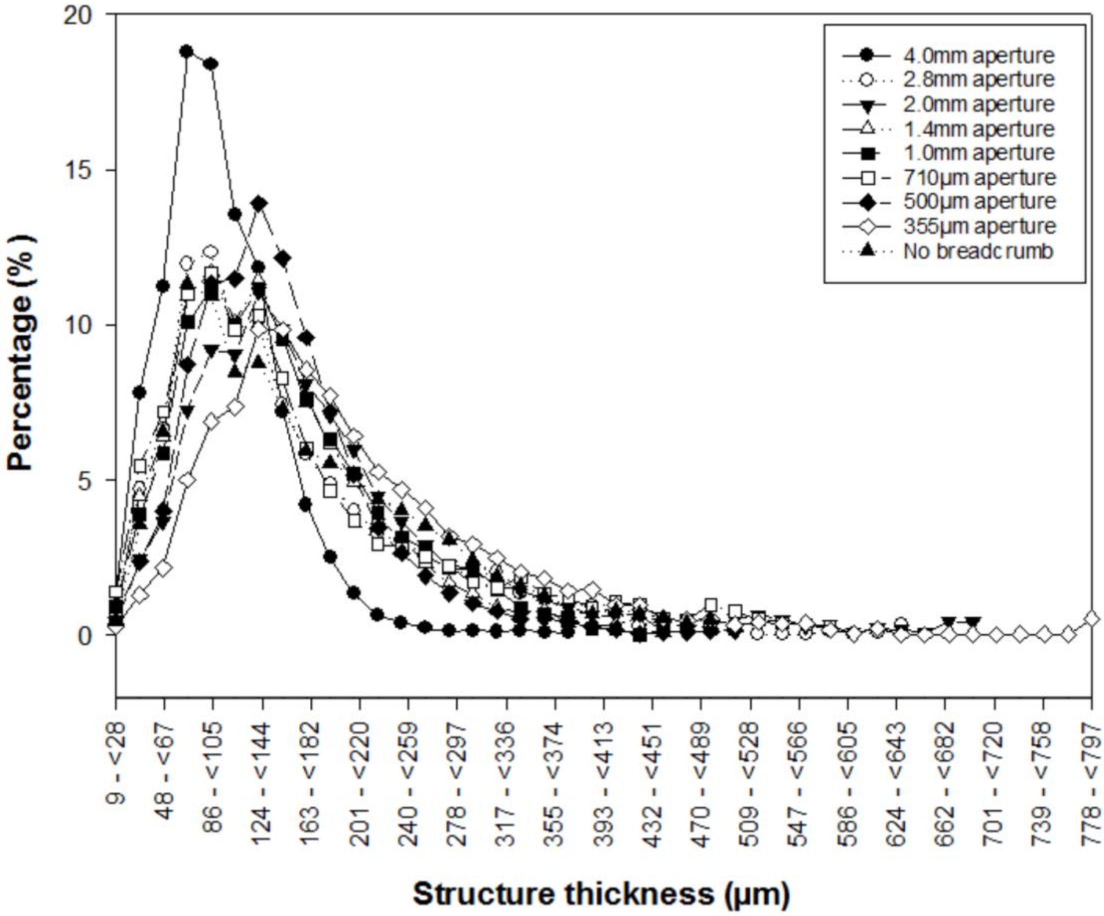


Figure 3.7 MicroCT analysis of structure thickness distribution for batter and breadcrumb coatings.

The strength of the matrix will also depend on material properties, moisture is lost during frying which enables a crisp crust to form. Moisture is a common plasticiser which enables mobility of polymers, the composition of moisture within the matrix will change during frying (Luyten & Van Vliet, 2004). Therefore the concentration will affect the mechanics of the protein and starch matrix and subsequently affect fracture propagation (Luyten & Van Vliet, 2004). The loss of crispness by moisture plasticiser is also governed by the glass transition phenomenon (Slade & Levine, 1995). Therefore, an understanding of components such as starch matrix and protein-rich phases is necessary to understand the crisp texture. Thermal and rheological properties will also assist in understanding the phase transitions during the frying and aging process.

3.3.2 Texture and acoustic emission analysis of crispness

The effect of breadcrumb size on acoustic emission has been previously investigated and no significant differences found (Maskat & Kerr, 2002). However, the size of breadcrumbs investigated were separated using a mesh size ranging 250-850 µm (Maskat & Kerr, 2002), this study focuses on a wider range of apertures and therefore a wider range of breadcrumb sizes.

In terms of texture analysis, battered and breaded coatings have been previously analysed by separating these from the core before and after frying (Fan et al., 1997; Maskat & Kerr, 2002). This study focuses on the deformation of the coating alone, however, during mastication the deformation of the coating will also depend on the mechanics of the high moisture core, where a combination of compression and shear are involved. (Luyten & Van Vliet, 2004).

As expected with crisp foods, the force-deformation profiles show multiple fracture events (Figure 3.8), which is indicative of fracture events occurring simultaneously and is perceived as crispness (Maskat & Kerr, 2002). Once fracture stress, fracture energy and critical stress intensity have been reached, fracture will begin again at the top of the curve (Luyten & Vliet, 1995). The force that is required for subsequent fractures will depend on the composition of material and size of previous fractures (Luyten & Van Vliet, 2004). This jagged behaviour is particularly prominent of large breadcrumb coatings (4.0 mm and 2.8 mm aperture), this can be explained as battered and breaded coatings consist of a high moisture core and a rough uneven surface. A highly rough surface is due to breadcrumbs lack of ability to merge with the batter. Smaller breadcrumbs are able to merge and be contained within the batter to form a smooth and uniform layer which is able to retain more moisture than large breading size coatings (Maskat & Kerr, 2002). A higher retained moisture content explains why a lower compression force is required to compress 60 % strain of smaller breadcrumb coatings and reduced jagged behaviour is seen (Figure 3.8).

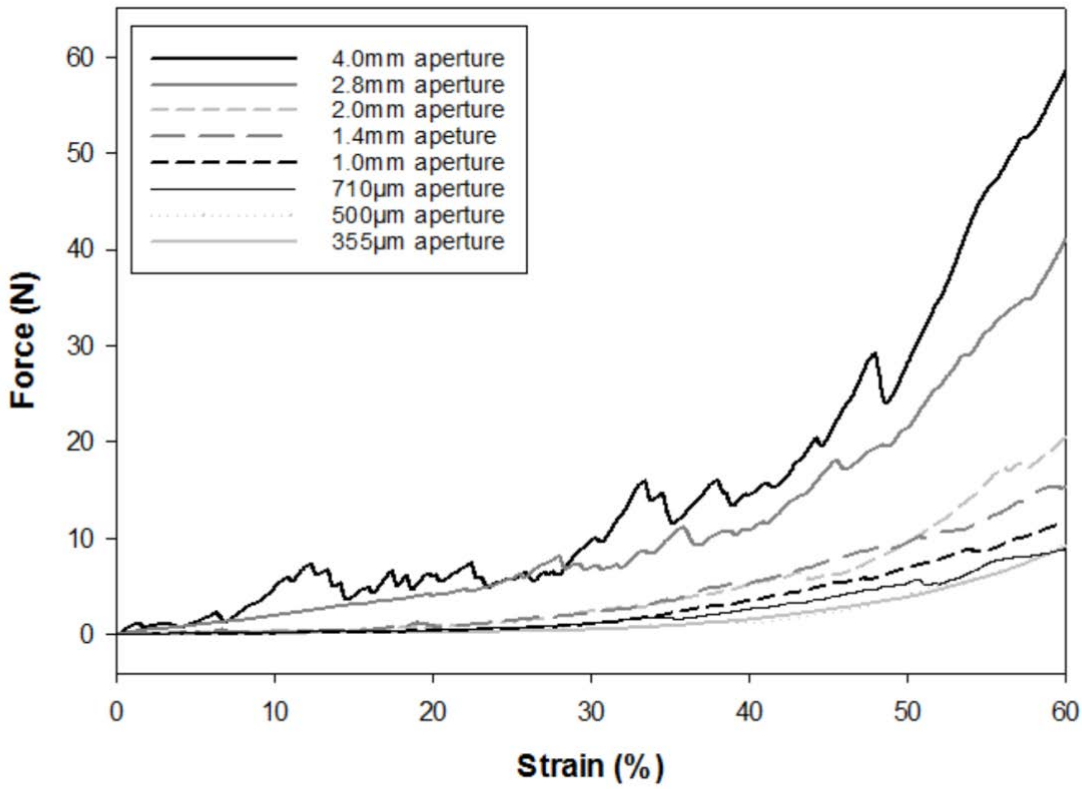


Figure 3.8 Texture analysis force profile of batter and breadcrumb coatings with variable breadcrumb sizes

Breadcrumb structure contains regions of defects that are weaker in strength, this could be due to differences in meso-structure e.g. ingredients have phase separated (Scanlon & Zghal, 2001). This results in stress being concentrated and a fracture point is created (Luyten & Vliet, 1995; Vincent et al., 1991). Once crack propagation has begun, the surrounding material around the crack relaxes and any stored elastic energy becomes available for acoustic emission or reshaping the deformed structure (Luyten & Van Vliet, 2004).

The relationship between force drops and sound pressure level (SPL) can be in one-to-one correspondence (Chen et al., 2005), indicating large structural breakdown to be accompanied by high SPL. However, as shown by (Chen et al., 2005) this is also dependent on the geometry used. The use of a three point bend for example will allow for localised fracture but as shown in Figure 3.9, the relationship between SPL and force drops is not always in one-to-one correspondence.

Figure 3.9 shows multiple acoustic peaks, which is due to the use of a cylindrical probe but also due to heterogeneities in the microstructure (porosity, pore size, structural thickness, high moisture core). Therefore, there are multiple crack and fracture events occurring simultaneously. Sound peaks occur as the sample begins to deform and last for the entire duration of testing.

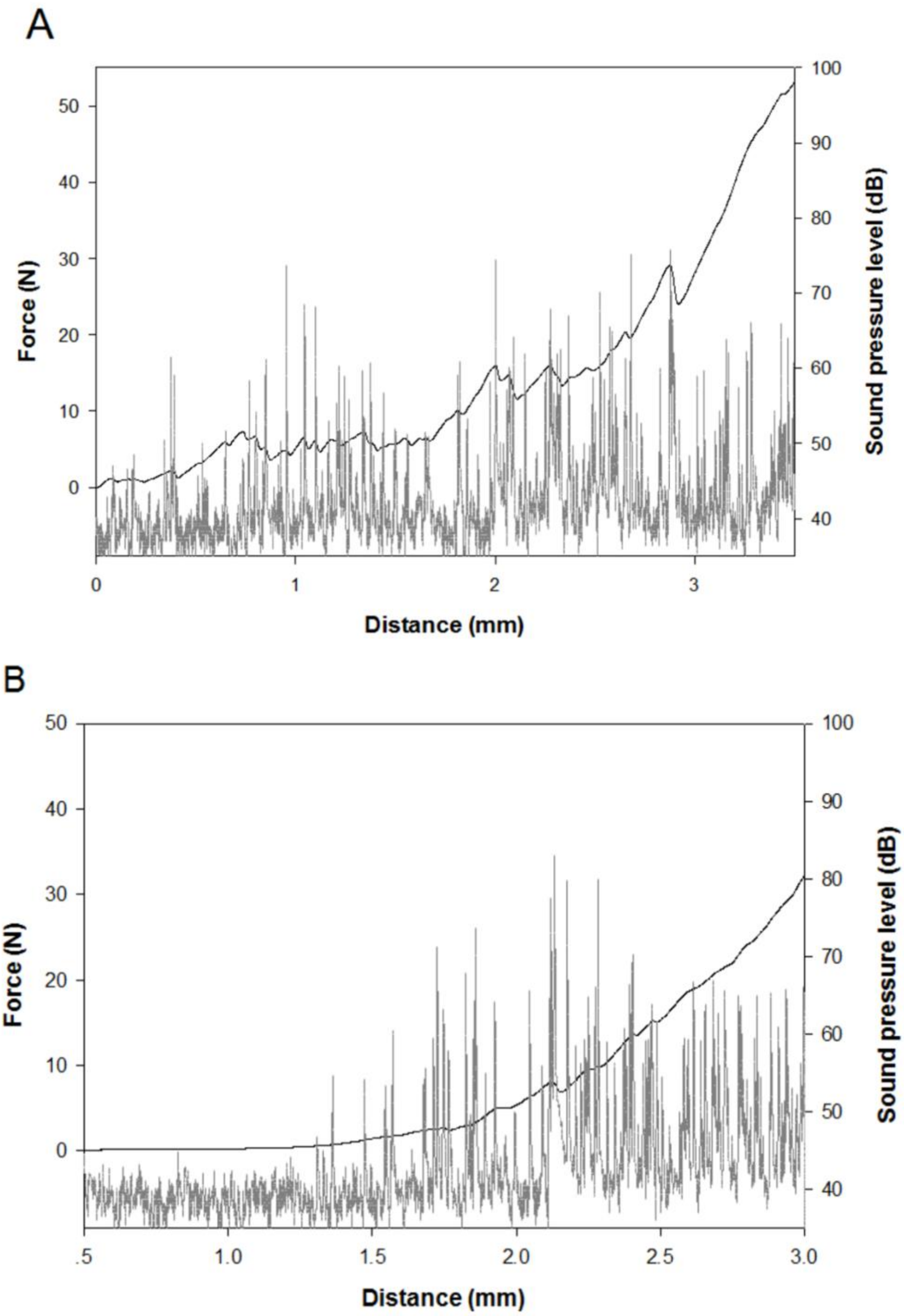


Figure 3.9 Force-displacement of sound pressure level (db) (spiked curve), force (N) (continuous curve) versus Distance (mm) for A) breadcrumb coating from 4.0 mm aperture B) breadcrumb coating from 1.4 mm aperture.

Table 3.2 Mean values of mechanical and acoustic parameters from texture analyser and AED for batter and breadcrumb coatings with varying breadcrumb size. ^{abcde} *Different letters for the same row refer to a significant difference (p<0.05) according to Tukey's Test.*

Parameter	4.0 mm	2.8 mm	2.0 mm	1.4 mm	1.0 mm	710 m	500 m	355 m
Max Force (N)	45.5 ± 8.6^{a}	29.82 ± 5.6^{b}	21.4 ± 2.8^{c}	12.5 ± 2.7^{d}	13.3 ± 4.9^{d}	9.33 ± 3.6^{de}	7.48 ± 2.7^{de}	4.95 ± 2.0^{e}
Area (N.sec)	84.5 ± 24.5^{a}	49.0 ± 8.5^{b}	34.6 ± 5.9^{b}	16.2 ± 5.4^{c}	18.9 ± 10.6^{c}	8.94 ± 4.5^{c}	7.64 ± 2.1^{c}	4.5 ± 1.0^{c}
Force peaks (drops in force more than 0.049 N)	0.88 ± 0.3^{a}	0.881 ± 0.8^{a}	0.36 ± 0.1^{b}	0.28 ± 0.2^{b}	0.35 ± 0.3^{b}	0.16 ± 0.1^{b}	0.17 ± 0.1^{b}	0.13 ± 0.1^{b}
Max SPL (dB)	75.1 ± 4.6^{a}	74.3 ± 3.6^{ab}	72.9 ± 5.9^{ab}	73.3 ± 4.4^{ab}	75.7 ± 2.3^{a}	74.7 ± 7.4^{a}	70.89 ± 5.3^{ab}	67.8 ± 3.1^{b}
Number of sound peaks	86.2 ± 29.2^{a}	62.4 ± 17.9^{b}	55.9 ± 12.2^{b}	39.6 ± 15.8^{b}	39.9 ± 11.3^{b}	33.0 ± 13.2^{b}	32.6 ± 14.0^{b}	14.4 ± 4.9^{c}

Figure 3.9 and Table 3.2 shows that both large (4.0 mm aperture) and small (1.4 mm aperture) breadcrumb coatings to have the similar peak SPL (>70 dB), however the number of sound peaks decreases significantly with smaller breadcrumbs (86.2 to 14.4) due to a smoother coverage over the battered substrate. SPL values and sound intensity has been previously found to be lower for less crisp products and high moisture (Seymour & Ann, 1988).

Table 3.2 presents the acoustic and mechanical parameters for deep-fried battered and breaded coatings with variable breadcrumb size. Maximum force, force peaks (drops in force more than 0.049 N), area, sound pressure level and number of sound peaks show significant decrease with breadcrumb size.

Maximum force is representative of hardness, whilst area under the force curve is representative of the work of compression or toughness. Both parameters decrease with decreasing breadcrumb size, this can be explained as although structural thickness increases with smaller breadcrumb size (Figure 3.7) moisture content also increases (Table 3.1) resulting in reduced structural stiffness and crispness perception.

Force peaks were calculated as a ratio between peaks and troughs, the values are indicative of jaggedness of the force profile curve (Salvador et al., 2009). As supported by Figure 3.9, a jagged curve with several fracture events is typical of a crispy products (Salvador et al., 2009). The number of force peaks is indicative of the brittleness of the food material, a peak is calculated above a threshold of 10 dB.

Table 3.2 shows that large breadcrumb coatings (4.0 mm) show high SPL and number of sound peaks, which is indicative of a loud, brittle and weak structure with many structural breakdowns (Salvador et al., 2009) and so can be expected to be perceived as more crisp than samples with low SPL and low number of sound peaks. The fracture and acoustic behaviour of cellular structures such as fried batter has been shown to depend on composition of microstructure.

3.4 Conclusion

This chapter has explored the structural composition of deep fried battered and breaded coatings. The importance of breadcrumb size on the physical and mechanical properties has been demonstrated. MicroCT has enabled structural parameters such as total porosity, pore size distribution and structural thickness to be quantified and provide an in depth understanding of the internal microstructure of batter and breadcrumb coatings. Morphological parameters such as total porosity is necessary to relate mechanics of the solid matrix to product behaviour but also for understanding the degree of mass transfer between oil and water.

As the size of breadcrumb coatings decrease from 4.0 mm aperture to 355 µm aperture, total porosity, maximum compression force, area, sound pressure level, force peaks and number of sound peaks decreases. Simultaneously, pore size distribution and moisture content increases, these parameters collectively could result in reduced crispness perception. Reduced crispness perception will also be due to changes in the solid matrix, therefore material properties and composition could be investigated. This chapter has shown that instrumental testing has potential to be used for understanding crispness. However, crispness is a sensorial attribute, therefore whether these structural differences have an impact in terms of sensory is a focus that needs to be explored.

3.5 References

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Chapter 4: Understanding and predicting sensory crispness of deep-fried battered and breaded coatings

Based on work published as: Voong, K. Y., Norton-Welch, A., Mills, T. B., & Norton, I. T. (2019). Understanding and predicting sensory crispness of deep-fried battered and breaded coatings. *Journal of Texture Studies*.

4.1 Background

The knowledge gained in Chapter 3, showed that varying size of panko breadcrumbs on the coating had a significant effect on the microstructure of the deep-fried coating. This in turn affects the physical and mechanical properties. Changes in these parameters suggest potential differences in texture and sensory perception, which laid the foundation for the research focused in Chapter 4. In this chapter, the aim was to carry forward the previous eight battered and breadcrumb coatings with varying breadcrumb size for sensory evaluation. The hypothesis being that a trained panel would also distinguish significant differences between samples, in particular crispness.

By using a trained panel, a tailored lexicon could be developed, it could then be used for descriptive profiling of each sample. A trained panel of eight spent a total of nine hours developing a tailored lexicon for a standard deep-fried battered and breaded shrimp. A total of nine attributes were carried forward for descriptive profiling. Statistical analyses including ANOVA, PCA, MFA and AHC were used to confirm significant differences, associations, similarities and correlations. Crispness was a key attribute of interest, as it was believed to be fundamental for assessing quality and enjoyment of the product. Therefore, this research aimed to develop a thorough understanding of crispness by correlating sensory parameters with instrumental parameters. By confirming a correlation between the two types of research methodologies, it provided a concise evaluation of crispness. In terms of practicality, a statistical model using only instrumental parameters was developed to predict crispness. The advantage of using a predictive model meant that it could be re-simulated for future formulation without the necessity for a trained panel

4.2 Materials and Methods

4.2.1 Materials

All deep-fried battered and breaded shrimp samples were prepared at Kerry Ingredients, Beloit, WI, for sensory evaluation. All ingredients were provided by Kerry Ingredients (white shrimp, sodium phosphate, predust flour, wheat flour batter and panko breadcrumbs).

4.2.2 Sample preparation

Frozen white shrimp were defrosted at 4°C overnight prior to use. All shrimps were deveined and butterflied before being allowed to soak in a sodium phosphate solution for 1 hour before coating. The sodium phosphate solution was made up to a concentration of 10.0 wt %.

After draining the samples from the sodium phosphate solution, shrimps were coated in predust flour, liquid batter layer and breadcrumbs prior to deep-fat frying. The pick-up percentage of the coating was expected to be 50 % ± 2 %. This was calculated by the weight of coated sample divided by weight of sample before coating multiplied by 100.

Eight breadcrumb coating sizes were investigated and were separated using the following sieve apertures: 4.0 mm, 2.8 mm, 2.0 mm, 1.4 mm, 1.0 mm, 710 m, 500 m and 355 m. Therefore, all samples had the same predust and batter layer, but a different size breadcrumb layer.

All samples were deep-fried in soyabean oil for 3 minutes at 190 °C. Samples were kept warm under a heat lamp for an additional 5 mins prior to sensory evaluation.

4.2.3 Sensory measurements

A panel of eight were recruited externally according to a set criteria (aged 24-60, six females, two males). A total of three 3-hour training sessions were held in order to familiarise panellists with the following sensory attributes in Table 4.1. A following extra 1-hour practice session took place prior to sensory evaluation. The references used for training were set according to (Meilgaard et al., 2016). Each attribute was assessed on the first bite and first chew. Spectrum training was employed for both appearance and texture modalities, references were provided according to(Kemp, 2009; Meilgaard et al., 2016). Panellists assessed nine shrimps per day (three different breadcrumb sizes, done in triplicate) plus a reference shrimp twice a day. Panellists evaluated one sample at a time at 15 min intervals using a 0-15 spectrum scale.

All samples were identified with a random 3-digit code, then presented so that each panellist received all samples three times in a random order. Deionised water and saltine crackers were provided to rinse and act as a palette cleansers. All data was collected electronically using an internal software (version unknown).

Table 4.1. Definitions for sensory attributes used for battered and breaded coatings (Meilgaard et al., 2016)

	Sensory attributes	Definition	Reference
Texture	Crispness	The force (noise) with which a product breaks or fractures, characterised by many, small breaks.	Products given to allow for comparison and discussion of attribute: Granola bar, club cracker, graham cracker, cheerios, corn flakes, melba toast.
	Cohesiveness	The amount of which sample deforms rather than crumbles, cracks or breaks.	Products given to allow for comparison and discussion of attribute: Corn muffin, hard breadsticks, cheese, pretzel.
	Denseness	The compactness of the sample cross-section.	Products given to allow for comparison and discussion of attribute: Hotdog, malted milk balls, fruit jellies.
	Hardness	The force to compress between molars.	Products given to allow for comparison and discussion of attribute: Hotdog, peanuts, almonds.
Appearance	Crumb coverage	The amount of crumb that fully covers the shrimp product.	0-100% coverage.
	Surface uniformity/ irregularity	Lack of smoothness when viewed from a predefined distance.	Products given to allow for comparison and discussion of attribute: Smooth vanilla wafer, Rough chunky cookie.
	Particle size	The size of particles on the sample.	Scores were assigned to each product used as a reference: Corn starch 1.0, cornmeal 4.0, regular bread crumbs 6.0, whole wheat bread crumbs 8.0, panko breadcrumbs 9.0, rice krispies 15.0
	Surface colour uniformity	Coating colour evenness on the surface of the product.	Top of coconut macaroon, vanilla wafer, honey crisp apple, ginger snap.
	Surface colour	Surface coating colour from light to dark.	Top and bottom of coconut macaroon.

4.2.4 Statistical Analysis

All statistical analyses were carried out using XLSTAT statistical software 2018.3 (Addinsoft, Paris, France).

An analysis of variance (One-way ANOVA) with post-hoc Tukey HSD (honestly significant difference) was performed to identify any significant differences between samples. Principal Component Analysis (PCA) was performed to visualise any relationships among attributes and samples.

Multiple factor analysis (MFA) is a factorial method that has been shown to be useful for studying relationships between different sets of variables, different sets of samples and variables to samples (Ting et al., 2015). An advantage of MFA, is the ability to study both qualitative and quantitative data, but also remove any influences from the sets of variables. Therefore, different sets of variables (i.e. sensory and instrumental data) hold the same weight and influence in the analysis. Agglomerative hierarchical clustering (AHC) analysis was carried out in order to identify clusters within the sample set.

Partial least squares (PLS) regression was performed to study the regression of attributes in order to predict crispness. Model selection function was also incorporated to allow for appropriate variable selection, in order to determine the best model fit. Multicollinearity was confirmed with variance inflation factors (VIF) and tolerance values, therefore PLS regression was the appropriate method to apply. PLS regression was employed to understand which variables correlated positively or negatively to crispness. It is a recommended analysis if there are a high number of explanatory variables and high correlation between variables (Abdi, 2003; Meilgaard et al., 2016)

4.2.5 Instrumental data

Results from Chapter 3 focused on characterising eight samples instrumentally. The internal structure of the deep-fried coatings was evaluated to show how the internal morphology changes with breadcrumb size, as well as the physical and mechanical properties. X-ray MicroCT was used to quantify total porosity, pore size and structural thickness. Texture analysis and an acoustic envelope was used to quantify maximum compression force, area, sound pressure level and sound peaks. Changes in total porosity, pore size and structural thickness will subsequently affect the strength of the structure, the rate of oil and moisture transfer, the fracture behaviour and acoustic events.

4.3 Results and Discussion

4.3.1 Sensory assessment of texture and appearance variables

The mean scores, *p*-values and significant differences for all texture and appearance attributes are shown in Table 4.2 and 4.3. In terms of appearance attributes (Table 4.2), as breadcrumb size decreases from 4.0 mm to 355 m, ‘surface colour’, ‘colour uniformity’, ‘particle size’ and ‘surface irregularity’ all decrease significantly (*p*-value <0.0001). The only significant increase is ‘crumb coverage’ (*p*-value 0.002). Increasing crumb coverage can be explained as breadcrumb size decreases, crumbs become highly uniform in shape and size, this allows strong adhesion to the batter due to packing ability and therefore, surface coverage and surface uniformity (Fiszman, 2008). A smoother surface with highly packed

particles will result in less protrusions exposed during frying. Therefore, this explains a low surface irregularity, lightness in colour, colour uniformity and smaller particle size.
Larger breadcrumbs are amorphous in shape, size and have large porous protrusions. This explains the high surface irregularity and low crumb coverage. The breadcrumb protrusions have higher exposure to frying oil, therefore will darken in colour during due to the Maillard reaction. Hence, a high surface colour is scored but a low colour uniformity due to the breadcrumbs amorphous shape.

In terms of texture attributes (Table 4.3), as breadcrumb size decreases from 4.0 mm to 355 m, 'crispness' and 'hardness' decreases significantly (both *p*-value <0.0001). Alternatively, 'cohesiveness' increases significantly (*p*-value 0.029) and 'denseness' increases significantly (*p*-value 0.015). As stated previously, larger breadcrumbs have higher exposure to frying oil. Therefore, crispness and hardness is expected to be higher as moisture and oil exchange is prolonged. This drying process results in a dry and brittle coating with low moisture. Denseness and cohesiveness have a higher mean score for coatings with smaller breadcrumbs. This can be explained as increased packing ability allows particles to firmly stick to the batter, this results in less crumbling and cracking of the coating.

Table 4.2 Mean scores and p-values for appearance attributes of deep-fried battered and breaded shrimp of varying breadcrumb size. Different letters in the same column refer to a significant difference (p<0.05) according to Tukey's HSD

	Surface Colour	**Colour Uniformity**	**Particle Size**	**Surface Uniformity/Irregularity**	**Crumb Coverage**
4.0 mm	7.67^{a}	8.23^{a}	10.0^{a}	9.23^{a}	14.1^{c}
2.8 mm	7.73^{a}	8.10^{a}	9.44^{a}	8.81^{ab}	14.1^{c}
2.0 mm	7.31^{a}	7.42^{b}	8.50^{b}	8.21^{bc}	14.3^{bc}
1.4 mm	6.81^{b}	6.58^{c}	7.33^{c}	7.50^{c}	14.4^{abc}
1.0 mm	6.60^{c}	6.06^{cd}	6.38^{d}	6.46^{d}	14.7^{a}
710 µm	6.79^{b}	6.08^{c}	6.08^{d}	6.42^{de}	14.5^{ab}
500 µm	5.77^{c}	5.35^{e}	4.92^{e}	5.50^{ef}	14.6^{ab}
355 µm	5.75^{c}	5.40^{de}	4.40^{e}	5.38^{f}	14.5^{ab}
p-**value**	<0.001	<0.001	<0.001	<0.001	<0.01

Table 4.3 Mean scores for texture attributes of deep-fried battered and breaded shrimp of varying breadcrumb size. Different letters in the same column refer to a significant difference (p<0.05) according to Tukey's HSD

	Crispness	Hardness	Cohesiveness	Denseness
4.0 mm	9.10^{a}	9.06^{a}	4.13^{bc}	7.21^{a}
2.8 mm	8.90^{ab}	8.75^{ab}	3.85^{c}	7.33^{a}
2.0 mm	8.02^{bc}	8.38^{b}	3.94^{bc}	7.40^{ab}
1.4 mm	8.13^{bc}	8.42^{b}	4.33^{abc}	7.73^{abc}
1.0 mm	6.96^{de}	7.71^{c}	4.44^{abc}	7.65^{abc}
710 µm	7.38^{cd}	7.77^{c}	4.52^{ab}	8.21^{c}
500 µm	6.67^{de}	7.73^{c}	4.83^{a}	8.08^{c}
355 µm	6.25^{e}	7.35^{c}	4.83^{a}	7.98^{bc}
p-value	<0.0001	<0.001	<0.0001	<0.0001

4.3.2 Correlation of variables

Correlation PCA was used to study the overall structure of the dataset to allow a visual understanding of relationships between variables, between samples and between variables to samples. Figure 4.1 shows PC1 and PC2 to describe 92.41 % and 3.38 % of the data variability with an eigenvalue of 8.317 and 0.304. Therefore, the first two components were sufficient enough for interpreting both appearance and texture sensory data as they accounted for a total of 95.79% of the variation, respectively.

The sensory variables that best describe the appearance and texture variability in the samples are heavily loaded onto the first principal component as this component has a high number of attributes with high positive loadings. Hardness, crispness, surface irregularity, surface colour, surface uniformity and particle size are positively correlated to PC1, whilst crumb coverage, cohesiveness and denseness are negatively correlated to PC1.

Sample 4.0 mm and 2.8 mm are close in proximity, suggesting similarities that are characterised by hardness, crispness, surface irregularity, surface colour, colour uniformity and particle size. Sample 355 m, 500 m and 710 m are in the left quadrants and are in close proximity to each other, suggesting similarities characterised by crumb coverage, denseness and cohesiveness. Samples 2.0 mm, 1.4 mm and 1.0 mm do not appear to be in close proximity to any other sample or attribute but remain within the middle of all the samples.

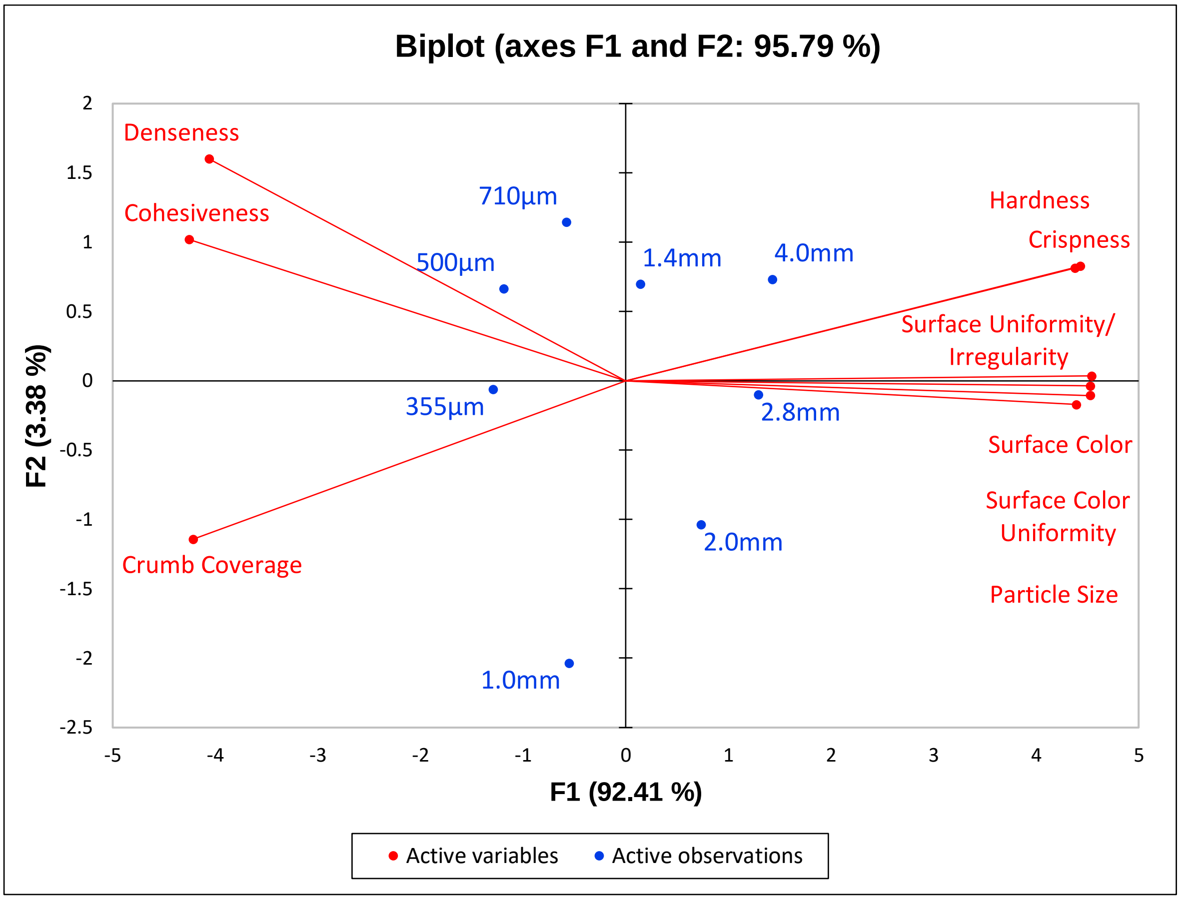


Figure 4.1 PCA biplot of first two principal components explaining 95.79 % of sensory texture and appearance attributes. Observations refer to samples of deep-fried battered and breaded coatings with varying breadcrumb size (blue). Variables refer to descriptive attributes (red).

In Chapter 3, the instrumental measurements of the same products were collected using X-ray MicroCT, texture analysis and an acoustic envelope detector. A combination of internal morphology characterisation, force-deformation and acoustic emission data have been used to characterise crispness instrumentally. Instrumental and sensory variables were studied together using PCA (Figure 4.2). Figure 4.2 displays samples 4.0 mm, 2.8 mm, 2.0 mm and 1.4 mm to be close in proximity, indicating similarities between all four. Figure 4.2 suggests 4.0 mm, 2.8 mm, 2.0 mm and 1.4 mm to score highly for total porosity, number of sound peaks, maximum force, drop in force, area and sound pressure level. Samples 710 m, 500 m and 355 m are in close proximity to each other but are scoring low for all instrumental attributes.

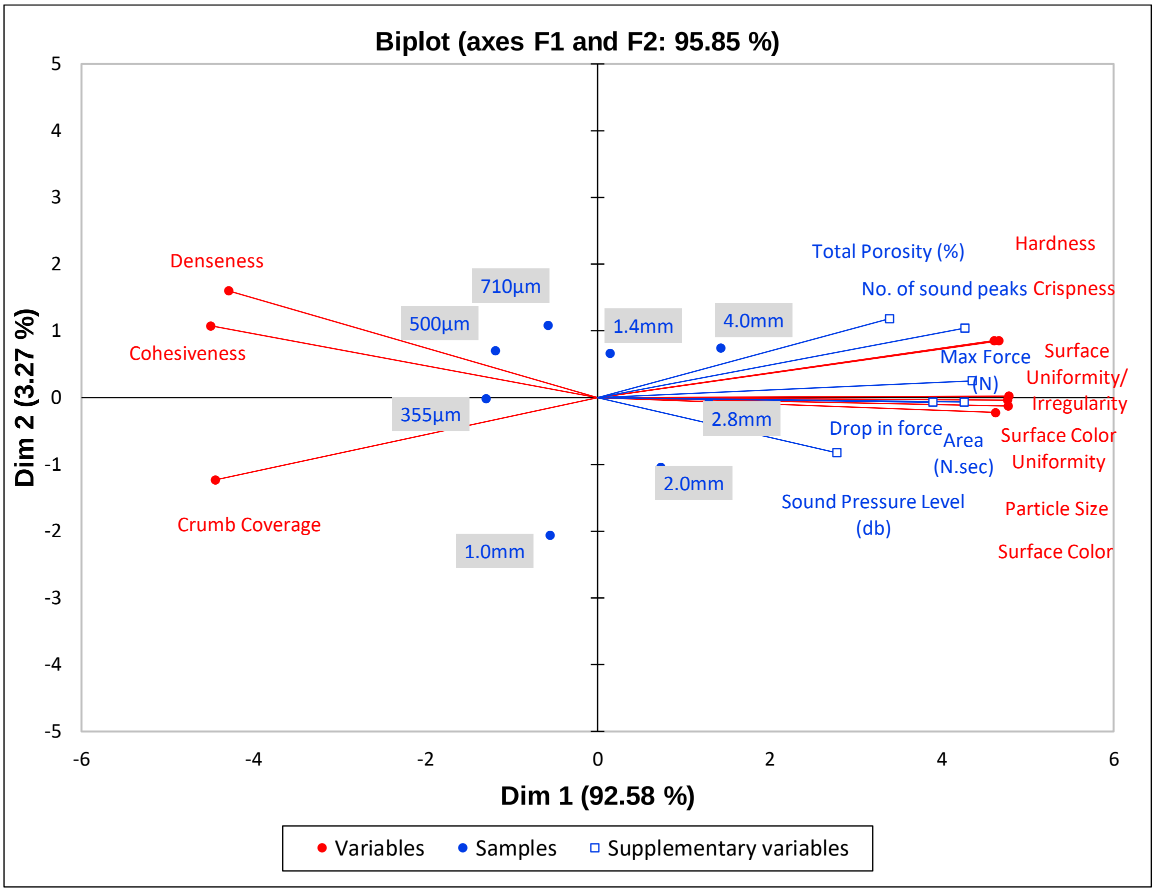


Figure 4.2 PCA biplot of first two principal components that explains 95.85% of variance for all sensory data and instrumental data.

As larger breadcrumbs are highly amorphous with surface irregularities that are exposed to frying oil. This prolonged oil and moisture exchange leads to deeper surface drying, therefore a harder and crispier crust will form. This explains the higher scores for 'surface colour', 'colour uniformity', 'crispness' and 'hardness'. The smaller breadcrumb coating sizes, such as 1.0 mm, 710 m, 500 m and 355 m scored highly for cohesiveness, denseness and crumb coverage. A higher packing ability will provide a stronger crust barrier against oil penetration (Dana & Saguy, 2006a), therefore more moisture is retained. This explains why 'crispness' and 'hardness' scored lower for the smaller breadcrumb coating sizes as oil and moisture has not occurred sufficiently enough to dry out the crust.

4.3.3 Clustering samples to highlight similarities

Agglomerative Hierarchical Clustering analysis is a classification method that investigates dissimilarities between observations (Qannari et al., 1997). Figure 4.3 shows that different clusters were identified when evaluating samples by either sensory measurements or instrumental measurements.

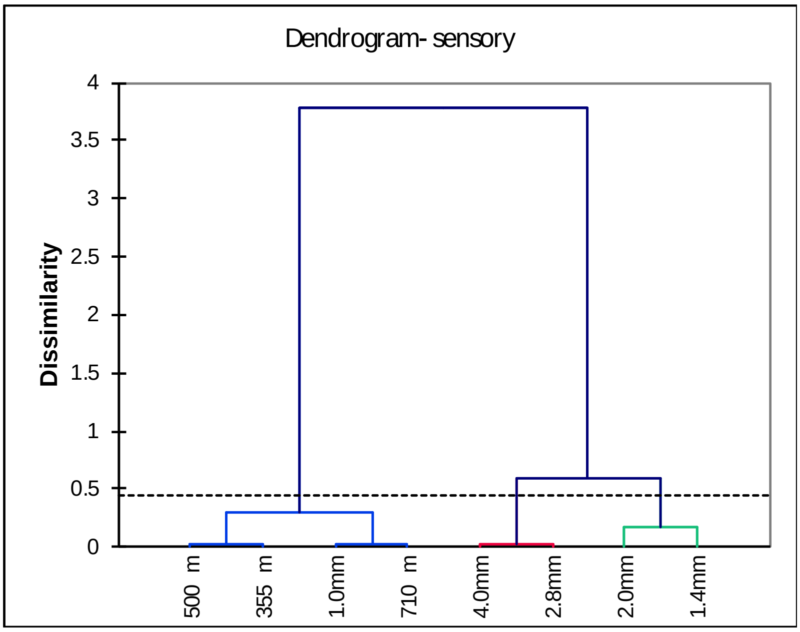
When evaluating samples with sensory measurements, clustering analysis results in three groups; 4.0 mm with 2.8 mm, 2.0 mm with 1.4 mm, and lastly 1.0 mm with 710 m, 500 m and 355 m. Instrumental measurements appear to find more clusters i.e. more dissimilarities between samples. Four clusters were identified; 4.0 mm as its own cluster, 2.8 mm with 2.0 mm, 1.4 mm as its own cluster and 1.0 mm with 710 m, 500 m and 355 m.

Figure 4.3a clusters 4.0 mm with 2.8 mm, these samples are the largest breadcrumb sizes and score highly for all instrumental variables. This is further explained as 4.0 mm and 2.8 mm are not significantly different in terms of crispness (*p*-value 0.999), hardness (*p*-value 0.667), cohesiveness (*p*-value 0.939) and denseness (*p*-value 1.00). Surface colour (*p*-value 1.00), particle size (*p*-value 0.321), surface irregularity (*p*-value 0.865), crumb coverage (*p*-value 1.00) and colour uniformity (*p*-value 0.999) are also not significantly different between sample 4.0 mm and 2.8mm. Figure 4.3b clusters 4.0 mm in to its own cluster, indicating that more differences are found instrumentally than via sensory testing.

Sensory cluster of 2.0 mm and 1.4 mm (Figure 4.3a) are not significantly different in terms of crispness (*p*-value 1.00), hardness (*p*-value 1.00), cohesiveness (*p*-value 0.646), denseness (*p*-value 0.841), surface irregularity (*p*-value 0.275) and crumb coverage (*p*-value 0.945).

Figure 4.3b shows 1.4 mm in its own cluster, this again indicates that instrumental measurements are more differentiating. Both sensory and instrumental dendrograms cluster 1.0 mm, 710 m, 500 m and 355 m, all of which are the smaller breadcrumb sizes. Table 4.2 shows these samples are not significantly different in terms of crumb coverage, denseness or hardness. The composition in both dendrograms are in fact similar, meaning that both show samples are clustering in order of breadcrumb size.

A)



B)

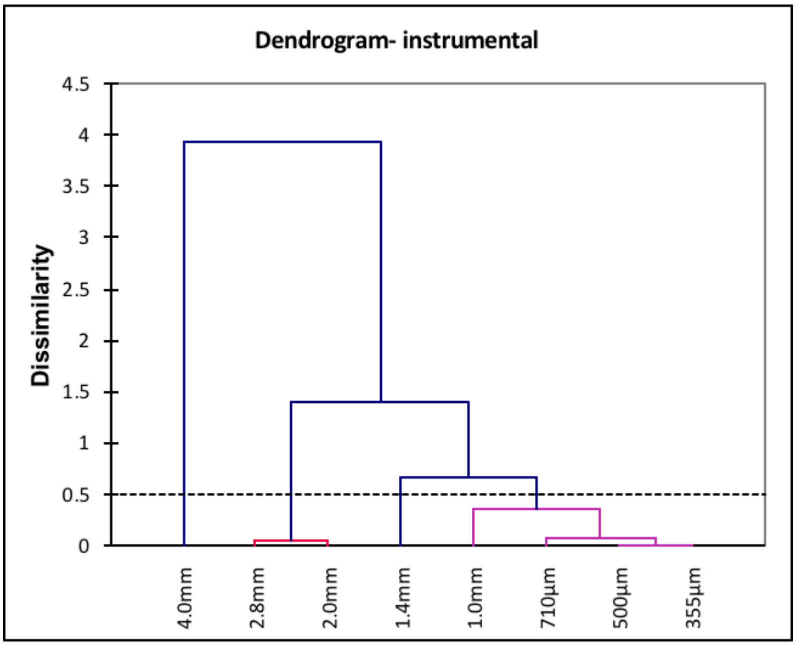


Figure 4.3 Dendrograms displaying the progressive clustering of samples when assessed by A) sensory measurements B) instrumental measurements. Truncated lines indicate where classes have been defined by Wards method.

4.3.4 Instrumental and sensory data relationships

Sensory and instrumental data were analysed jointly using multiple factor analysis (MFA) to study relationships between instrumental and sensory measurements. As shown in Figure

4.4, the first two dimensions explain a total variance of 88.51 %. Each sample is represented by a central point, two partial points are then projected away from the central point. Each projected end representing either sensory measurements or instrumental measurements. If the two projected points are in close proximity to one another, this indicates agreement between sensory and instrumental measurements. Alternatively, if the two projected points are far apart, this indicates discordance (Pagés & Husson, 2005). Figure 4.4 shows that sample 355 m to have the greatest agreement whilst sample 4.0 mm has the greatest discordance between its sensory and instrumental data.

In general, as breadcrumb size decreases, agreement between sensory and instrumental increases. This can be explained as coatings with large breadcrumbs are highly irregular in size, shape and surface coverage. Subsequently, this will affect its mechanical and physical properties upon frying as well as sensory perception. Therefore, higher variability can be expected from instrumental and sensory measurements. This is further supported by Figure 4.4, as the position of the instrumental point of sample 4.0 mm is the furthest point from all others, suggesting that the instrumental measurements for sample 4.0 mm are more different than all the other samples.

The length and orientation of the line provides an indication of how well sensory and instrumental measurements correlate (Cadena et al., 2013). The orientation of the lines suggests whether samples are similar or not e.g. samples 4.0 mm and 2.8 mm are more similar in terms of sensory measurements than instrumental measurements. Figure 4.4 also highlights the composition of the samples, from left quadrants to right quadrants, they are arranged according to breadcrumb size. This suggests that as breadcrumb size decreases from

4.0 mm to 355 m, the agreement between instrumental and sensory measurements increases.

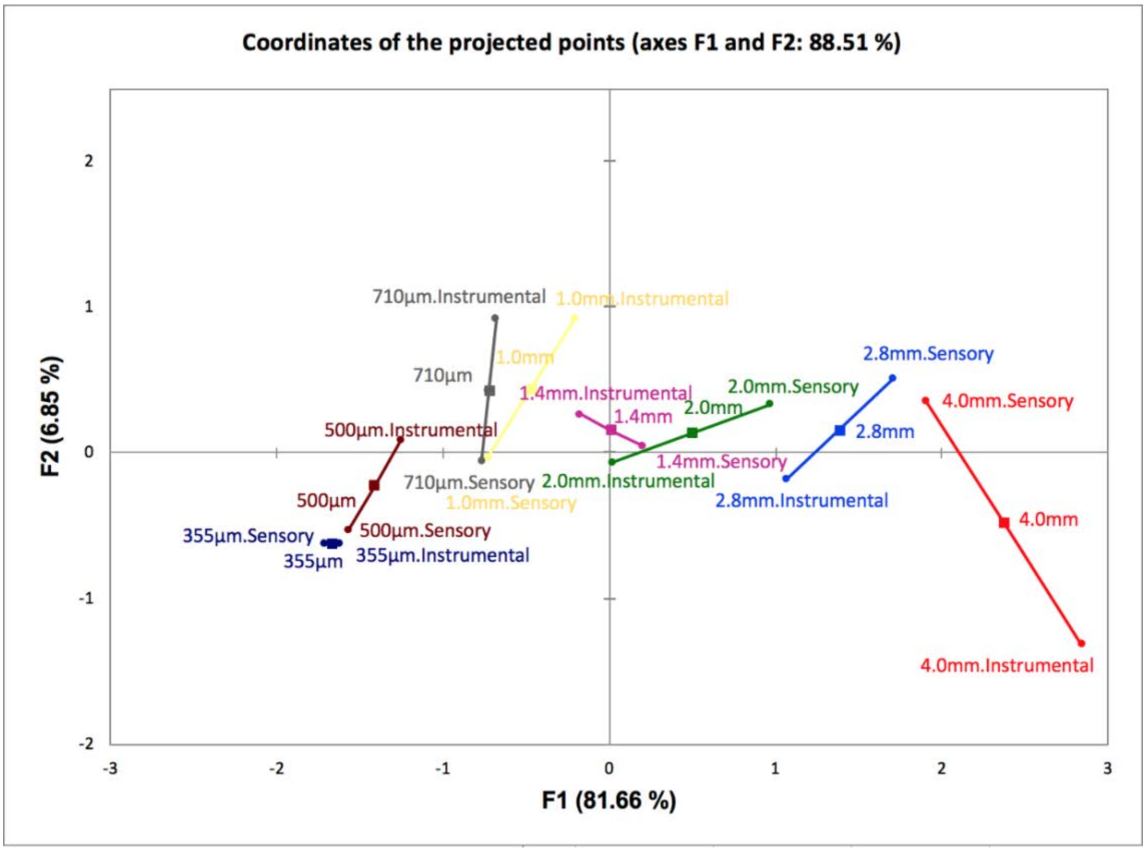


Figure 4.4 Two-dimension MFA plot illustrating the correlation of instrumental and sensory measurements of crispness for each sample.

The RV coefficient can be used to assess the global similarity between two matrices (Cadena et al., 2013). An overall RV value of 0.810 suggests that instrumental and sensory data are highly correlated. Table 4.4 highlights that X-ray microCT, texture analysis and acoustics correlate highly with sensory texture and appearance attributes. MFA results demonstrate how a combination of both types of testing allow for a fundamental understanding of how physical parameters relate to sensory parameters. Crispness is ultimately a result from the structural properties of the food product (Mallikarjunan, 2004).

Table 4.4 MFA RV coefficients highlighting correlations between types of instrumental measurements to types of sensory measurements

	X-ray MicroCT	Texture Analyzer	Acoustic	Sensory texture	Sensory Appearance	MFA
X-ray MicroCT	1.000					
Texture Analyzer	0.787	1.000				
Acoustic	0.614	0.618	1.000			
Sensory texture	0.484	0.788	0.727	1.000		
Sensory Appearance	0.518	0.799	0.717	0.971	1.000	
MFA	0.779	0.913	0.846	0.909	0.917	1.000

4.3.5 Predictive modelling of crispness using instrumental variables

Multiple linear regression was previously carried out to test for multicollinearity and to provide validation for using partial least squares (PLS) regression. PLS was used with the aim to predict sensory crispness from instrumental parameters (Eq.1). Crispness was selected as the dependent variable as it can be considered to be one of the most important attributes when assessing the quality and freshness of deep-fried battered and breaded goods (Mellema, 2003). Although, it can be noted that more than one dependent variable can be predicted using PLS regression (Meilgaard et al., 2016). The PLS correlation matrix (Table 4.5) shows crispness to be one of the most highly correlated attribute with porosity (r = 0.740), maximum force (r = 0.882), drop in force (r = 0.865), sound peaks (r = 0.926) and sound pressure level (r = 0.618). This further supports the relationship of instrumental measurements to sensory perception of crispness.

Table 4.5. PLS correlation matrix highlighting correlations between instrumental variables and sensory crispness

	Porosity	Max Force	Drop in force	No of sound peaks	Sound Pressure Level	Crispness
Porosity	**1.000**					
Max Force	0.897	**1.000**				
Drop in force	0.764	0.935	**1.000**			
No. of sound peaks	0.813	0.860	0.775	**1.000**		
Sound Pressure Level	0.554	0.530	0.523	0.494	**1.000**	
Crispness	0.740	0.882	0.865	0.926	0.618	**1.000**

The advantage of this predictive model (Eq. 4.1) means that mechanical and physical properties can be used to predict a textural property. Therefore, a sensory panel is not necessarily required and less input variables are needed for the simulation of the model. This is potentially less time-consuming and more cost-effective from an industrial persepective. When developing this predictive model, a combination of instrumental and sensory variables were considered prior to Equation 4.1. This was carried out to assure the validity of Equation 4.1, this data can be found in Appendix.

(Eq. 4.1)

A R^2 value of 0.854 indicates high predictive ability of this model (Henseler et al., 2009). This is also supported by a calculated Q^2cum value of 0.770, which also measures the goodness of fit and predictive quality. Sensory crispness of deep-fried battered and breaded shrimps could be predicted by re-simulation of this model. As shown in Figure 4.5, all instrumental variables are positively correlated with the predictive ability of Eq.1, the larger the column indicates a larger influence on the model. Figure 4.6 displays the predictive quality of the model with residual plots, all points lie within threshold (grey lines), this indicates high predictive ability.

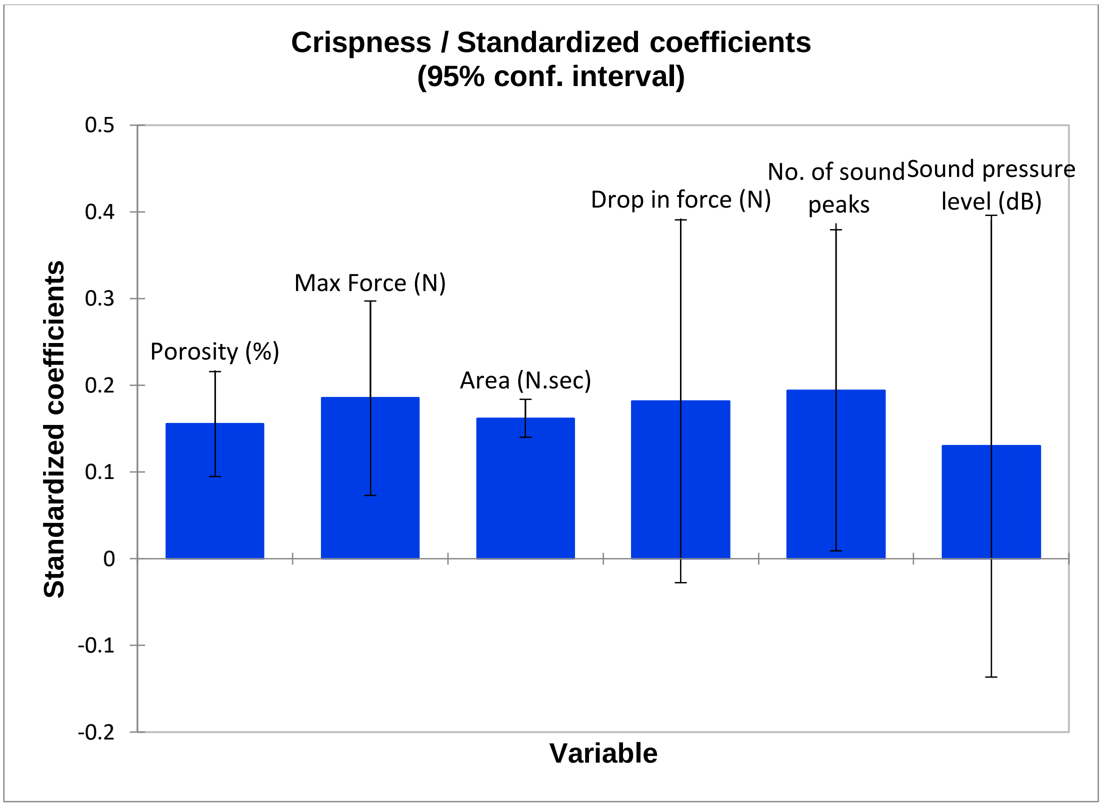


Figure 4.5 The standard coefficients of instrumental model associated to each dependent variable. Total porosity was collected from X-ray MicroCT. Max. force, area and Drop in force was collected from Texture Analyser. No. of sound peaks and Sound pressure level was collected from an Acoustic Envelope Detector.

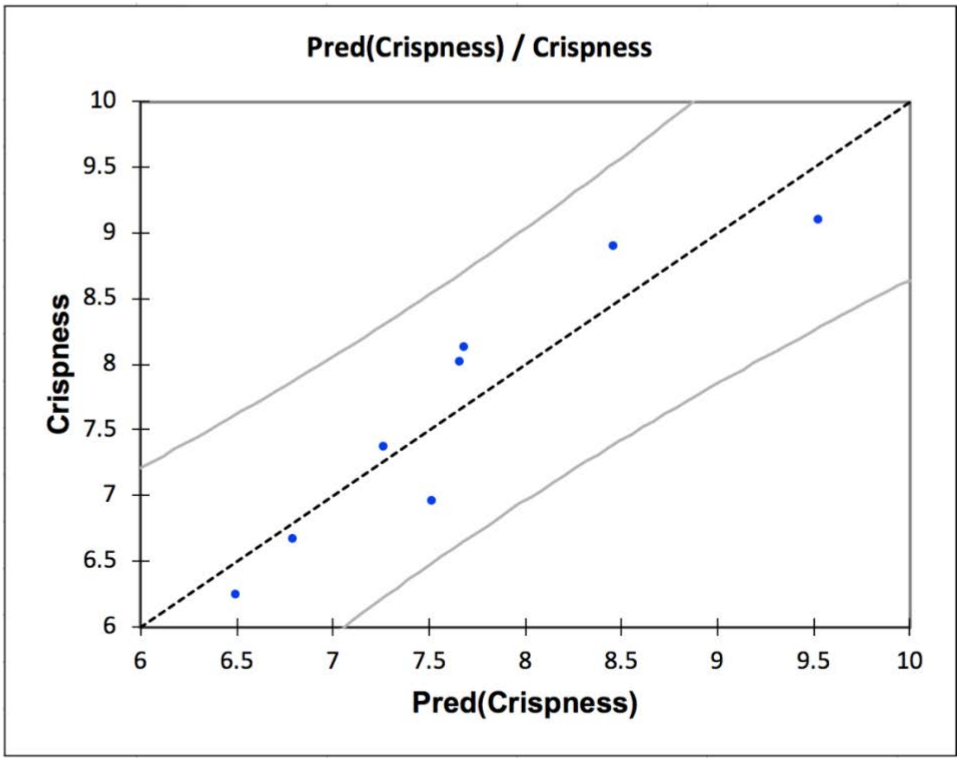


Figure 4.6 Residuals of predicted values of crispness vs observations for Eq.1 showing predictability of model

PLS regression has been previously used to correlate instrumental data and sensory data for meats (Castejón et al., 2015), fruits (Chang et al., 2018), dairy (Shiota et al., 2015) and dry snacks (Moghaddam et al., 2016). However, the use of PLS to predict crispness in deep-fried battered and breaded goods is limited.

4.4 Conclusion

In conclusion, the main contributors of crispness in deep-fried battered and breaded coatings have been investigated in this study. In terms of sensory attributes, PCA showed that crispness was highly correlated with hardness, particle size, surface colour, number of sound peaks, colour uniformity and surface uniformity, this was dependant on breadcrumb size.

MFA confirmed positive correlations between instrumental and sensory measurements, this was also dependant on breadcrumb size. AHC identified that coatings were clustering into three groups; large, intermediate and small breadcrumb size. These clusters share common sensory and instrumental attributes within their samples. Crispness was found to be one of the most highly correlated variables to instrumental data, this allowed a predictive model to be developed using PLS regression analysis. An instrumental predictive model that allows prediction of crispness will allow a degree of quality control in future products. The use of force-deformation coupled with acoustic events as well as internal morphology characterisation allows for a thorough understanding of how the microstructure relates to texture perception.

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Chapter 5: Understanding consumer perception of deep-fried battered and breaded coatings

Based on the work published as: Voong, K., Norton-Welch, A. & Mills, T. (2020). Understanding consumer perception of deep-fried battered and breaded coatings. *Journal of Texture studies*

5.1 Background

The aim of this chapter was to carry forward three batter and breaded coatings from the previous sensory study and evaluate consumer perception. The findings of this would ultimately provide the company with an insight into drivers of consumer choice, in terms of sensory attributes as well as any demographic drivers. The advantage of this insight allows for identification of potential target niches to develop new products or to further improve a current product. These three coatings are combined clusters from the original eight coating sizes and have been defined as cluster groups according to the results from agglomerative hierarchical clustering. The three coatings have been labelled as: coarse, medium and fine.

Consumer testing was carried out in Buffalo, US, this was chosen as oppose to UK because the product being researched is available to the US market. The advantage of consumer testing, provides an insight into consumer preference and liking. By creating a profile for each coating, this provides commercial value from a product development perspective and allow for identification of any attributes that need to be focused on. A panel of 185 consumers evaluated the three types of batter and breadcrumb coating using four hedonic and nine sensory attributes on a 9-point scale and a 5-point JAR-scale. Both texture and flavour attributes were assessed but the importance of crispness was focused on, as it is a textural parameter that provides an indication of freshness and quality.

Finally, the use of X-ray MicroCT, texture analysis and acoustic testing allowed for characterisation of physical and mechanical properties. This allows for an understanding of the different types of structure that consumers prefer. These structural differences explain differences in texture perception.

5.2 Materials & Methods

5.2.1 Materials

For consumer testing, sodium phosphate, predust flour, wheat flour and panko breadcrumbs were obtained from Kerry Ingredients, Beloit, WI. White shrimps were obtained and prepared at Rich Products, St Simons, GA.

For instrumental testing in the UK, sodium phosphate, predust flour, wheat flour and panko breadcrumbs were also obtained from Kerry Ingredients, Beloit, WI. White shrimps of a specification size of 50-60 and soya bean oil was obtained from Hyperama Plc, UK.

5.2.2 Preparation of samples for instrumental testing

Shrimps were defrosted at 4 ^{o}C overnight prior to use. Shrimps were butterflied and deveined before soaking in sodium phosphate solution for 1 hour (concentration of 10 wt %). After drainage, each shrimp was weighed to calculate the correct percentage required for the coating step. The amount of coating adhering to the sample prior to frying was calculated by the weight of coated sample divided by weight of sample before coating multiplied by 100. The pick-up percentage was expected to be 50 % ± 2 %. Shrimps were firstly coated with predust flour, then a liquid batter layer, followed by a final panko breadcrumb layer.

Panko breadcrumbs were sieved (Endecotts Ltd. London, England) into the following particle sizes: 4.0 mm and 2.8 mm (coarse), 2.0 mm and 1.4 mm (medium), 1.0 mm and 710 m, 500 m, 355 m (fine). Therefore, all shrimps had the same predust and batter layer but a varied breadcrumb coating layer. All samples were fried at 195 ^{o}C for 42 seconds in soya bean oil

(Fryer model NPDF3, Parry Catering Ltd UK). Deep-fat fryer was pre-heated for 1 hour prior to use.

5.2.3 Preparation of samples for consumer testing

All samples were prepared following the same procedure as stated in Section 5.2.2, these were then shipped from Rich Products, St. Simons, GA. to Rich Products, Buffalo, NY. for consumer testing. All battered and breaded shrimp were deep-fried in soya bean oil for 3 minutes at 190 ^{o}C. Three deep-fat fryers were used, one for each coating type (fine, medium and coarse). Deep-fat fryers were pre-heated for 1 hour prior to usage. Samples were kept under a heat lamp for an additional 5 minutes prior to consumer evaluation. Frying oil oleic acid was measured for each fryer to determine oil quality (results found in appendix 5.7).

5.2.4 Consumer testing

185 regular consumers (69 males, 116 females, aged over 25 years) of battered and breaded shrimp products were recruited from the Buffalo, NY area to evaluate three samples for acceptance and liking. Each sample was labelled with a 3 digit code and presented monadically during one test session. A total of eight test sessions were carried out over three days. Tests were carried out in individual tasting booths, palate cleansers of water and crackers were provided (deionised water and Keeber Zester unsalted saltine crackers).

Flavour, appearance, texture and overall liking were scored using the traditional 9-point scale (1= extremely dislike, 9= like extremely). Sensory attributes were scored using a 5-point JAR scale (1= not enough, 5= too much). The sensory attributes included saltiness, colour, amount of breading, size of breadcrumbs, sweetness, strength of seasoning, hardness, crispness and breading adhesion. 'Product expectations', 'product quality' and then after 'purchase intent' were assessed using a 5-point scale (1= much worse than expected, 5= much better than expected), (1= very poor, 5= very good), (1= definitely would not buy, 5= definitely would buy). Data was collected using Compusense Five version 5.6 (Guelph, Canada).

5.2.5 Data analysis

ANOVA (Analysis of variance) and post-hoc Tukey's HSD (honestly significant difference) was performed to assess for significant differences between samples in terms of liking and instrumental measurements (at 5 % significance). Penalty analysis was performed on JAR data to assess the impact of a sensory attribute scoring too high or too low on overall liking. JAR values were amalgamated into 3 groups: 1-2 were labelled as "not enough", 3 as "JAR" and 4-5 as "too much". Agglomerative hierarchical clustering (AHC) was performed on overall liking (Wards Method) to identifying consumer patterns. Chi-square analysis was carried out to test whether the distribution of consumers observed is dependent on an external variable. All analyses were carried out using XLSTAT statistical software 2019.3.1 (Addinsoft, Paris, France).

5.2.6 Moisture and oil content

Moisture content were determined by difference in weight before and after vacuum oven-drying overnight at 70 ^{o}C. Oil content was determined by Soxhlet extraction for 5-6 hours, then rotary evaporation for up to 30 minutes. Measurements were evaluated in three replicates for each sample.

5.2.7 Texture and sound characterisation

All batter and breaded coatings were peeled off each sample and cut into 20 mm circular shapes prior to testing. Compression testing was carried out using a TA XT Plus Texture Analyser (Stable Micro Systems Ltd. UK), with 5 kg load cell, 3 g trigger force, P40 cylindrical aluminium probe at a test speed of 0.5 mm/s. This experimental set up has been adapted from (Varela et al., 2006). Each sample was compressed to 60 % compression ratio with the top surface of the coating facing upwards.

Acoustic envelope detector (AED) (TA XT Plus, Stable Micro Systems Ltd. UK) was used for force-deformation acoustic measurements. A microphone (12 mm diameter) was positioned 7 cm horizontally of the platform. Calibration of the microphone was carried out using a sound calibrator at 94 dB and 114 dB at 1000 Hz. All background noise were filtered using 3.125 kHz corner frequency. A gain AED was set at 2 with a data acquisition of 550 pps. Ten replicates were performed for each sample. The parameters extracted: maximum force (N), area under force curve (N.sec), drops in force (>0.049 N), maximum sound pressure level (dB) and number of sound peaks (drop in sound pressure level >10 dB).

5.2.8 Microstructure characterisation with X-ray MicroCT

Samples of deep-fried coating were cut to fit inside a 6 mm plastic straw before covering in parafilm to prevent moisture loss. Samples were scanned at 59 kV, 100 A with no filter (Skyscan 1172, Bruker, Belgium). Software NRecon, CTAn and CTVox were used to reconstruct and analyse images. Measurements were evaluated in three replicates for each sample.

5.3 Results & Discussion

5.3.1 Microstructure of deep-fried batter and breaded coating

The microstructure of food describes the spatial organisation of the structural components and their interactions, which influence the physical and sensory properties of a product (Schoeman et al., 2016). MicroCT provides a non-invasive yet high resolution method to visualise cellular food material and allow for the following structural properties to be quantified: total porosity, pore size range and structural thickness.

Figure 5.1 shows total porosity of each deep-fried coating, this decreases significantly as breadcrumb coating becomes finer. Total porosity refers to the measure of void fraction within the entire structure or the ratio of empty space within a solid material compared to the total volume of solid (Rahimi et al., 2019). In battered and breaded fried food, a porous structure provides entry points for moisture and oil exchange, thereby influencing how much oil is absorbed.

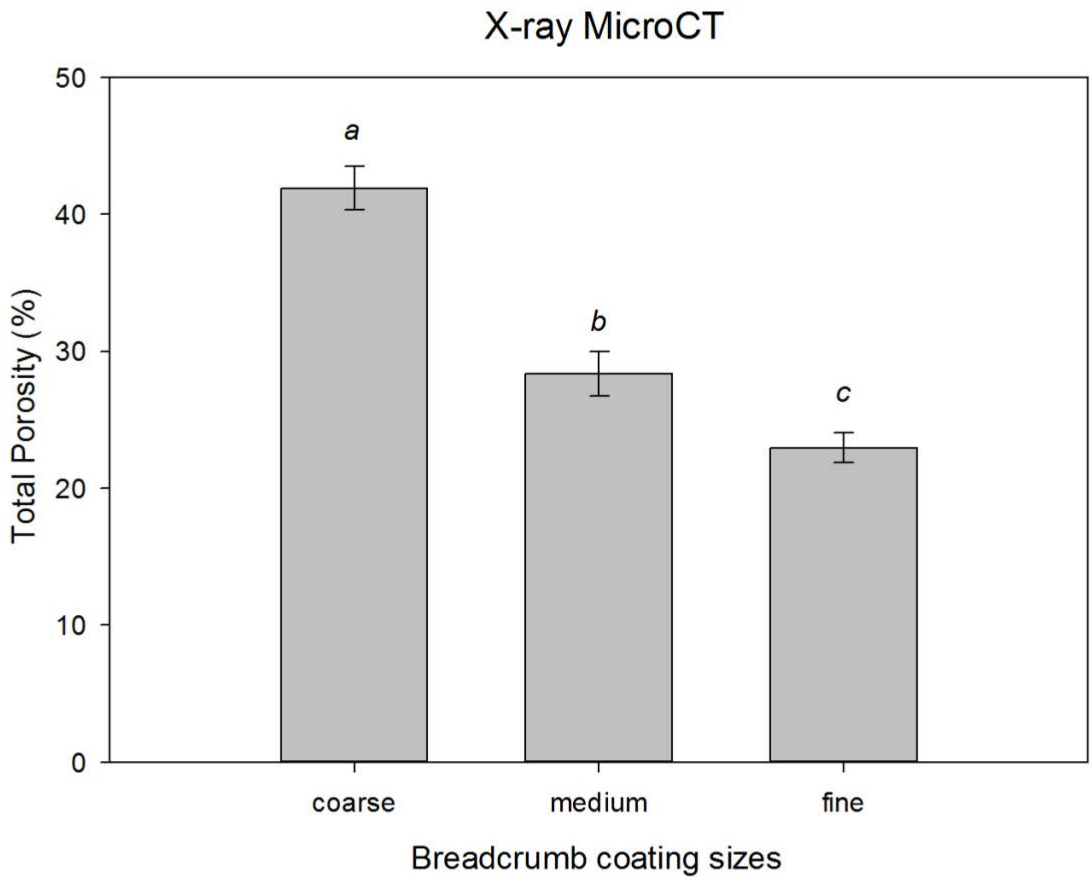


Figure 5.1 Total porosity of batter and breadcrumb coatings with decreasing breadcrumb cluster size. Error bars represent standard deviation. [abc]Different letters refer to significant differences (p<0.05) according to Tukey's HSD test.

Figure 5.2 and Figure 5.3 provide closer inspection of the internal structure of the deep-fried coatings. Both show a higher proportion of void fraction within the entire structure for coarse coatings than medium and fine. Figure 5.2 is a single 2D slice greyscale image of each coating, it highlights similarities and differences in internal morphology between the three samples. All samples have a high moisture inner layer contrasting a brittle porous crust with low moisture content. A porous structure is created by moisture and oil exchange, the resulting pore provides space for oil to accumulate, which is predominantly at the crust.

The mesoscopic structure of the crust is similar to that of homogenously dry crisp products (Van Vliet & Primo-Martin, 2011). 2D slice images provide a limited understanding of the internal structure, a 3D reconstruction allows visualisation of the bulk material, as shown in Figure 5.3.

Figure 5.3 highlights the differences in pore size range and structural thickness between the samples. Coarse breadcrumb coatings have large pores that are highly clustered together, i.e. lower structural thickness. Fine breadcrumb coatings contain small pores with a greater distance between them, i.e. there is a greater structural thickness.

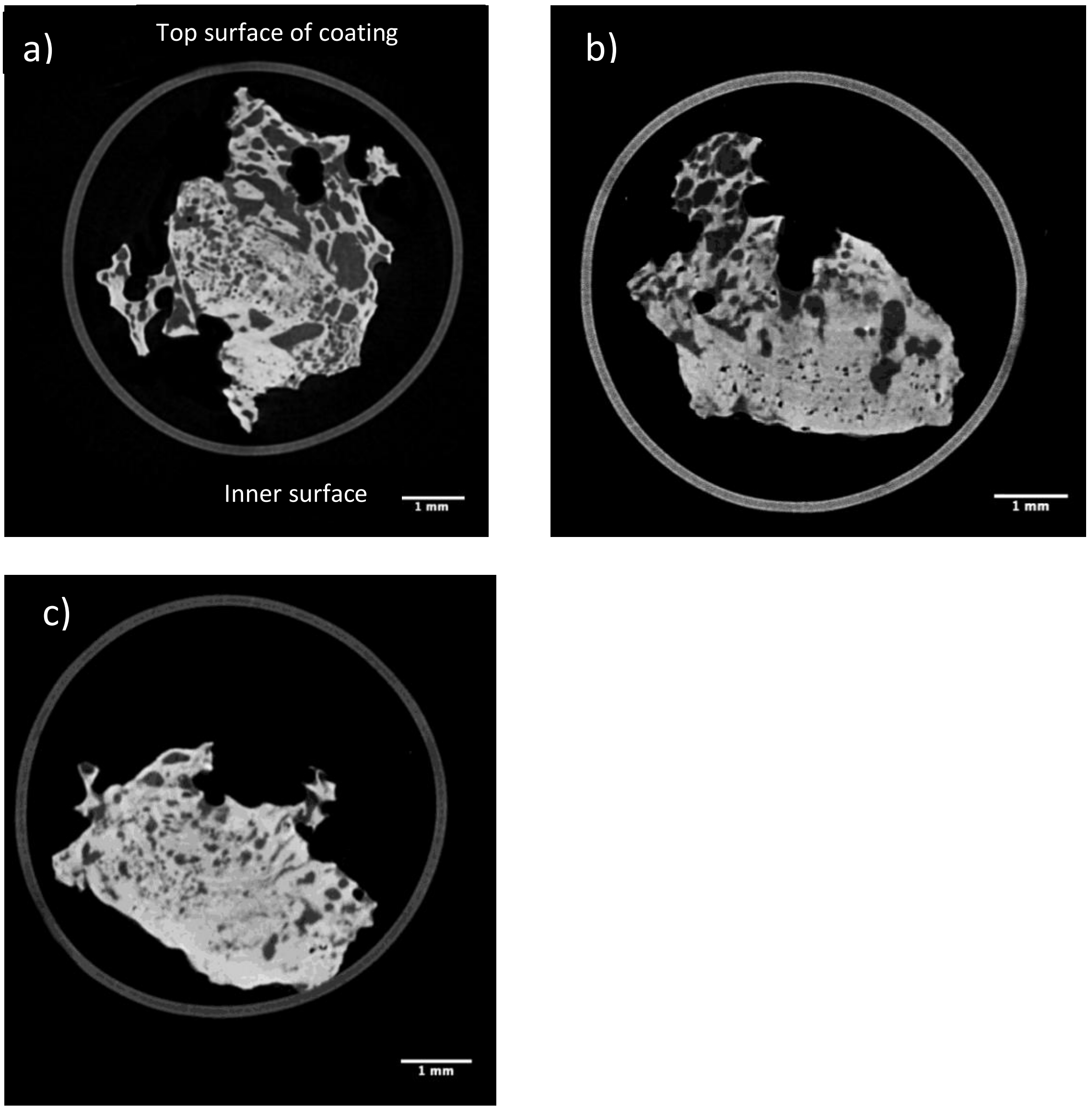


Figure 5.2 2D greyscale cross-section image of deep-fried batter and breaded coatings with a) coarse b) medium c) fine breadcrumb. Top surface of coating and inner surface of coating have been labelled.

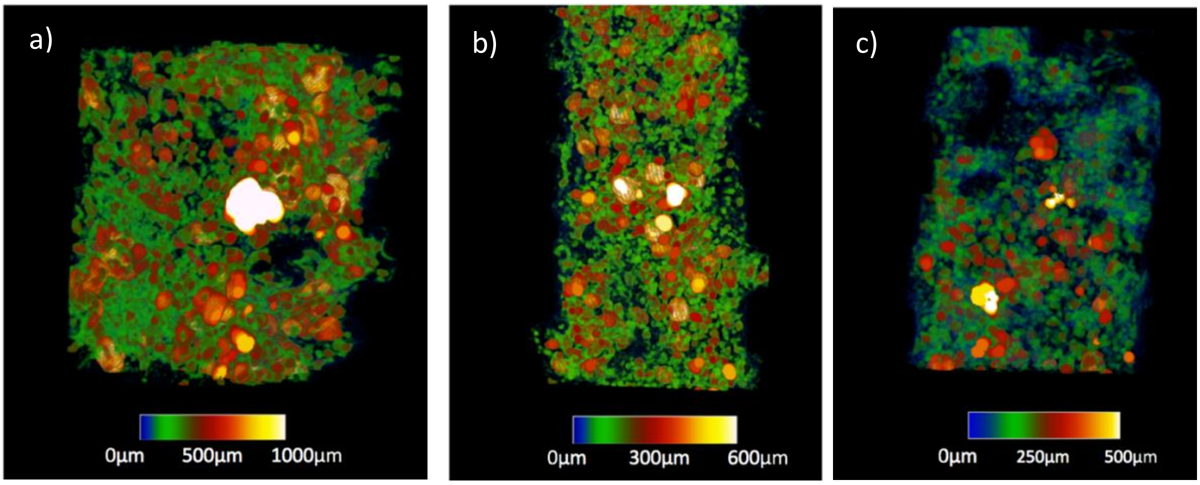


Figure 5.3 3D reconstructed cross-sections of deep-fried batter and breadcrumb coatings with a) coarse b) medium c) fine breadcrumbs. Colour scale bar highlights the differences in pore size. Note that scale bar range differs for each sample.

Table 5.1. Oil and moisture content of deep-fried battered and breaded coatings. represent standard deviation values

	Coarse coating	**Medium coating**	**Fine coating**
Oil content (%)	46 ±1.07	42.3 ±1.5	41.4 ±2.5
Moisture content (%)	23.7 ±1.2	26.5 ±1.9	27.0 ±2.8

The relationship between oil content and moisture content is inversely proportional i.e. as oil content decreases, moisture content increases. As breadcrumb size decreases, packing ability and size uniformity increases, thereby creating an even surface coverage and with tightly packed particles. These tightly packed particles create a strong barrier that resists oil and moisture exchange. Products with high surface roughness have been previously found to retain more oil after deep-fat frying (Moreno et al., 2010). Oil absorption is essentially a surface-related phenomenon determined by an equilibrium between surface drainage and suction which occurs during post-frying (Bouchon et al., 2003). Coarse breadcrumb coatings have geometrical irregularities due to these crumbs being amorphous in shape and size, these irregularities favour oil absorption kinetics. This is demonstrated in Figure 5.2, which highlights coarse breadcrumb coatings to have more oil accumulated within the large pores at the crust, in comparison to fine breadcrumb coatings. Table 5.1 also shows higher oil content in coarse coatings in comparison to fine. This subsequently results in a drier crust that will give a crisp texture.

Figure 5.4 shows each breadcrumb coating to have a different pore size range profile: fine ranges 9.88-345 m, medium ranges 9.88-543 m and coarse ranges 9.88-1020 m. Pore size range increases from fine, medium to coarse breadcrumb size. Alternatively, structural thickness increases as cluster size decreases (Figure 5.5), therefore the relationship with pore size range is inversely related. Figure 5.5 shows fine and medium to have similar structural thickness distribution profile, both range from 9.88-562 m, with 10 % peak from 88.8-108 m. Coarse breadcrumb coatings range from 9.88-543 m, with 55 % peak at 69.1-88.8 m. Coarse breadcrumb coatings have a lower structural thickness overall, suggesting that it is not only the thickness but the brittleness of this material that determines crispness.

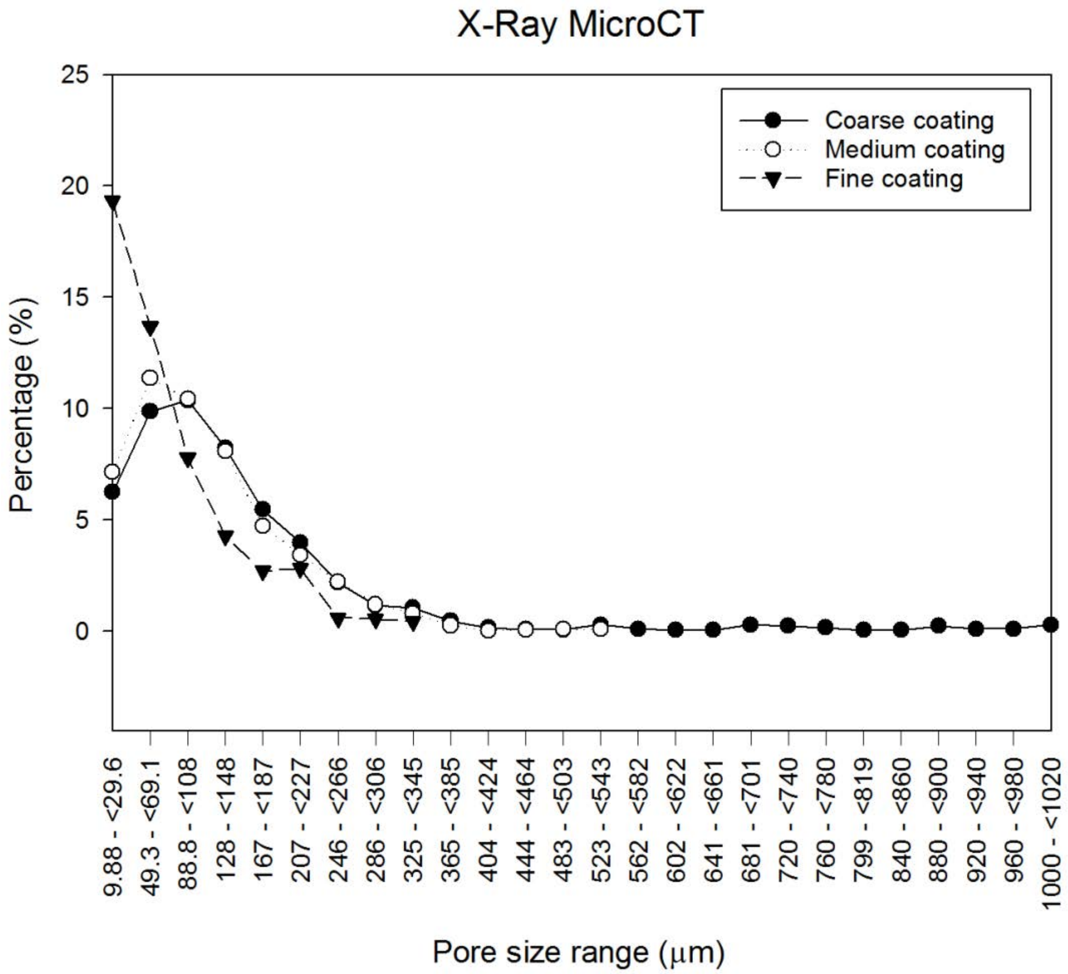


Figure 5.4. MicroCT analysis of pore size distribution of batter and breadcrumb coatings.

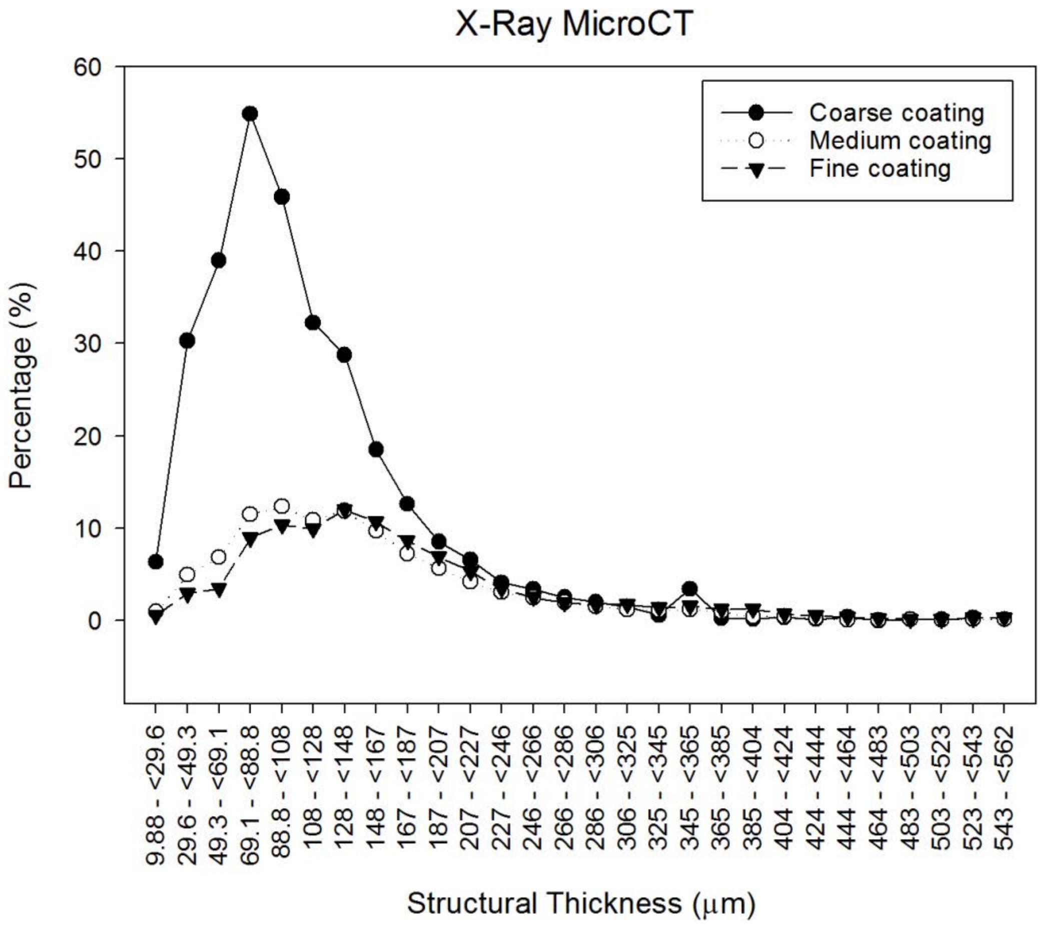
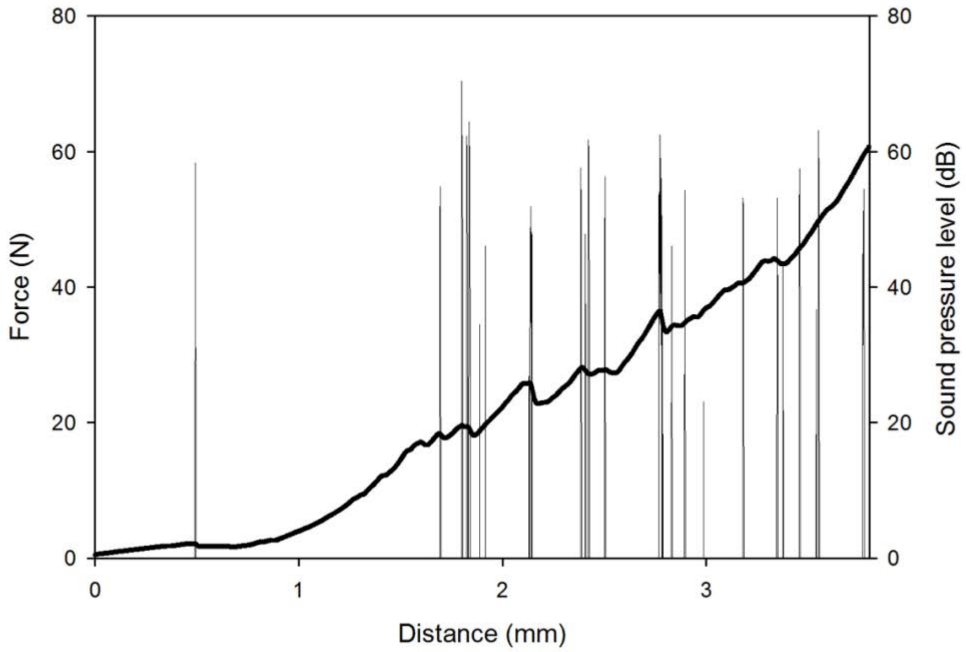


Figure 5.5 MicroCT analysis of structural thickness distribution for batter and breadcrumb coatings.

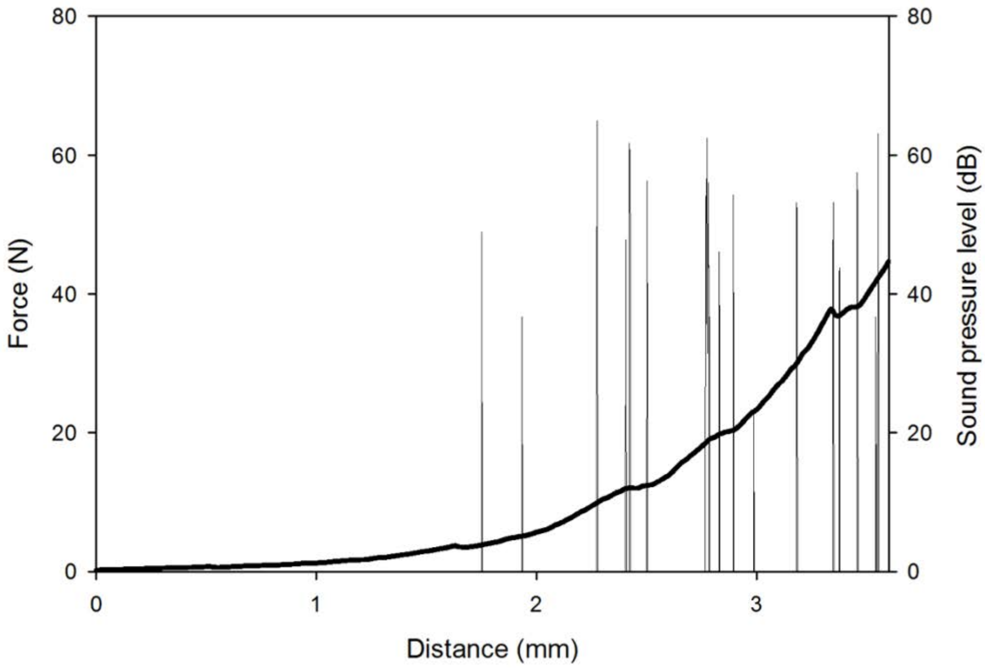
5.3.2 Textural and Acoustic properties

Figure 5.6 displays an example of a force displacement curve for coarse breadcrumb coatings. The crushing dynamics can be expected to be irregular as the surface is geometrically irregular (Sanahuja et al., 2018). Table 5.2 shows that as breadcrumb cluster size decreases, maximum force and area decrease, this refers to brittleness and energy required to fracture the structure. Maximum sound pressure level and number of sound peaks also decrease i.e. loudness decreases. Drop in force refers to the jaggedness of the force profile. A low drop in force value indicates a smoother force profile, which suggest less crack propagation sites occurring. This can be explained as finer coatings retain more moisture due to increased particle packing ability. A reduced rate of oil and water mass transfer results in a high moisture material that may be plasticised to a certain level. This means that a low stress may still be required to deform the sample and sound peaks are detected, but an overall lower sound pressure level is found (Sanahuja & Briesen, 2015).

A)



B)



C)

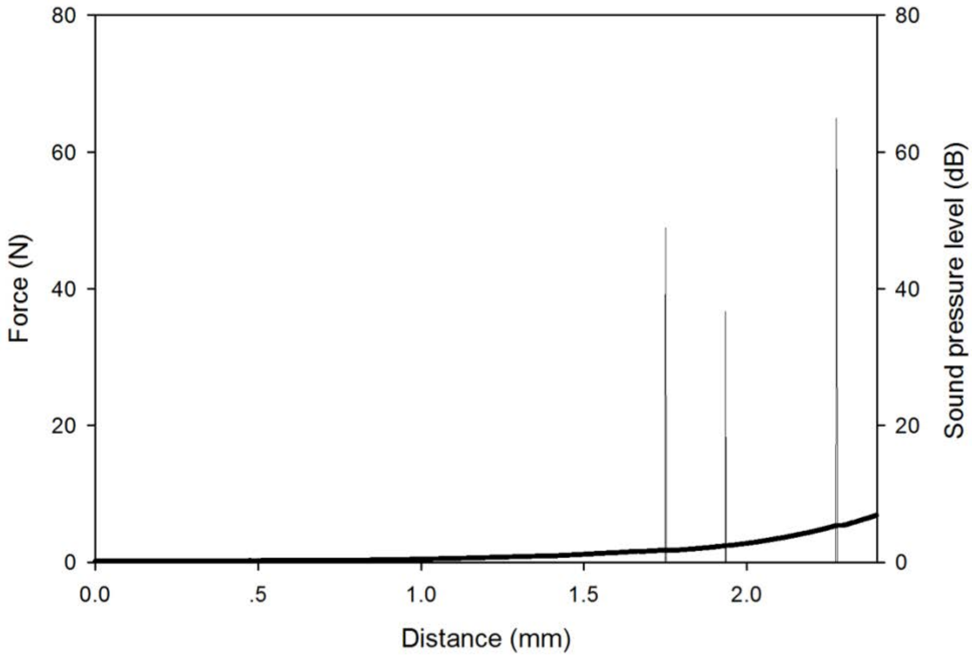


Figure 5.6 Force displacement curve of sound pressure level (dB), force (N) versus distance (mm) for A) coarse breadcrumb coating B) medium breadcrumb coatings C) fine breadcrumb coatings

Table 5.2. Mean values of mechanical and acoustic parameters from texture analyser and acoustic envelope detector. abcDifferent letters in the same column refer to significant differences (p<0.05) according to Tukey's Test.

	Maximum force (N)	Area (N.sec)	Maximum Sound pressure level (db)	Number of sound peaks	Drop in force (>0.049 N)
Coarse	53.6 ±7.0^{a}	130.0 ±16.3^{a}	73.6 ±6.4^{a}	35.5 ±13.5^{a}	0.841 ±0.39^{a}
Medium	47.5 ±6.6^{a}	94.6 ±28.5^{b}	66.8 ±4.4^{b}	24.7 ±11.5^{a}	0.359 ±0.16^{b}
Fine	10.5 ±4.0^{b}	12.7 ±7.3^{c}	65.6 ±6.3^{b}	7.9 ±6.9^{b}	0.076 ±0.08^{c}

5.3.3 Consumer acceptability

Table 5.3 presents liking scores for all samples. Medium breadcrumb coatings have the highest overall liking score as well as highest appearance, flavour and texture liking score. However, it is not significantly different to fine breadcrumb coatings.

Table 5.3 Mean scores of hedonic attributes and p-values of deep-fried battered and breaded shrimp of varying breadcrumb size. [ab]Different letters in the same column indicate a significant difference (p<0.05) according to Tukey's HSD.

	Overall liking	**Appearance Liking**	**Flavour liking**	**Texture liking**
Medium	6.721 ^{a}	6.359 ^{a}	6.751 ^{a}	6.774 ^{a}
Fine	6.634 ^{a}	6.048 ^{a}	6.571 ^{a}	6.364 ^{ab}
Coarse	5.880 ^{b}	4.927 ^{b}	5.926 ^{b}	5.916 ^{b}
Pr > F (Sample)	< 0.0001	< 0.0001	< 0.0001	< 0.0001

5.3.4 Penalty analysis of deep-fried battered and breaded shrimp

Table 5.4 shows the mean drops for each attribute when it is either too little (TL) or too much (TM). Mean drops indicate how much overall liking drops as a result of an attribute scoring too low or too high. For fine breadcrumb coatings, most consumers (52.97 %) rated 'size of breadcrumbs' as the only attribute to be 'too little' (much too small). However, a calculated *p*-value of 0.236 shows ' TL -size of breadcrumbs' as not significant. This means that for fine breadcrumbs, if the size of crumbs are rated as too small, this will not significantly reduce overall liking. All other attributes were rated as just-about-right for fine breadcrumb coatings. However, the following attributes show a significant mean drop when rated as too little: saltiness (0.828), strength of seasoning (0.989), hardness (0.946) and crispness (0.768). This means that if these attributes are rated as too little, the overall liking will be significantly reduced by the mean drop stated.

When considering medium breadcrumb coatings, the following attributes show a significant mean drop when rated as too much: colour (0.773) and hardness (1.426). The only significant mean drop when rated as too little is strength of seasoning (0.834). All other attributes have a majority rating of just-about-right. It can be noted that a negative value has been calculated for 'TM-sweetness', this is typical as the mean drops are calculated by the difference between the liking mean score for JAR minus "too much" or "too little". If the "too much" or "too little" value is higher than JAR, then a negative penalty is calculated. However, as -0.396 is represented by only 2.16% of consumer response, this is below the 20% threshold and does not necessarily need to be focused on for improvement.

When considering coarse breadcrumb coatings, majority of consumers rated the following attributes as too much: colour (83.78 %), hardness (51.35 %) and crispness (54.05 %). These three attributes show a mean drop that will significantly reduce overall liking if rated as too much: colour (1.432), hardness (2.157) and crispness (2.015). It can be noted that a mean drop for 'TL- crispness' has not been calculated, this is due to 0 % consumers scoring 'not crispy enough', therefore an overall penalty score was also not calculated. This demonstrates a strong consensus amongst consumers and use of the JAR scale. Although a mean drop for 'TL- crispness' was not calculated for crispness, a 'TM- crispness' was, this shows a rating of crispness being too much with significantly reduce overall liking. All other attributes had a majority rating of just-about-right. It can be noted that a negative value of -0.469 has been calculated for 'TM-breading adhesion'. This is represented by 40% of consumer response and can therefore be considered significant. However, upon further analysis, it was noted that the scales for breading adhesion were labelled as "not good", "slightly not good", "JAR", "good", "very good". This is considered as inaccurate labelling of JAR scale, therefore "breading adhesion should not be considered.

Table 5.4 Penalty analysis of just-about-right scores for fine, medium and coarse coatings. % of respondents are displayed against TL- too little, TM-too much and just-about right. Statistically significant means drops are highlighted in bold (at 5 % significance).

		Fine breadcrumbs		Medium breadcrumbs		Coarse breadcrumbs	
	Level	**%**	**Mean drops**	**%**	**Mean drops**	**%**	**Mean drops**
Colour	TL	6.49 %	1.223	1.08 %	0.583	0.54 %	5.103
	JAR	69.73 %		51.89 %		15.68 %	
	TM	23.78 %	0.443	47.03 %	**0.773**	83.78 %	**1.432**
Amount of Breading	TL	18.38 %	0.851	6.49 %	0.696	3.24 %	1.740
	JAR	69.19 %		79.46 %		51.89 %	
	TM	12.43 %	1.534	14.05 %	1.330	44.86 %	**1.428**
Size of breadcrumbs	TL	52.97 %	0.274	17.84 %	1.016	4.86 %	0.445
	JAR	45.41 %		76.76 %		60.54 %	
	TM	1.62 %	0.440	5.41 %	1.686	34.59 %	0.942
Saltiness	TL	27.03 %	**0.828**	13.51 %	0.526	16.22 %	0.653
	JAR	67.57 %		75.68 %		72.43 %	
	TM	5.41 %	1.528	10.81 %	0.936	11.35 %	1.806
Sweetness	TL	14.05 %	1.202	15.14 %	0.999	25.41 %	**1.311**
	JAR	81.62 %		82.70 %		71.35 %	
	TM	4.32 %	2.394	2.16 %	-0.394	3.24 %	3.144
Strength of Seasoning	TL	47.03 %	**0.989**	33.51 %	**0.834**	34.59 %	**1.410**
	JAR	47.03 %		60.00 %		53.51 %	
	TM	5.95 %	2.412	6.49 %	1.775	11.89 %	2.889
Hardness	TL	24.32 %	**0.946**	7.57 %	1.003	0.54 %	0.989
	JAR	71.35 %		72.43 %		48.11 %	
	TM	4.32 %	1.152	20.00 %	**1.426**	51.35 %	**2.157**
Crispiness	TL	30.27 %	**0.768**	8.11 %	0.497	0.00 %	-
	JAR	65.41 %		75.14 %		45.95 %	
	TM	4.32 %	0.893	16.76 %	1.254	54.05 %	**2.015**
Breading adhesion	TL	11.35 %	1.210	7.57 %	1.710	8.11 %	0.894
	JAR	51.89 %		56.76 %		51.89 %	
	TM	36.76 %	0.061	35.68 %	0.227	40.00 %	-0.469

Figure 5.7 displays the mean drop plots for each sample for comparison. Mean drops indicate how many points of overall liking is compensated if an attribute is not just-about-right. Key areas for product improvement are those attributes which have been scored as non-JAR by

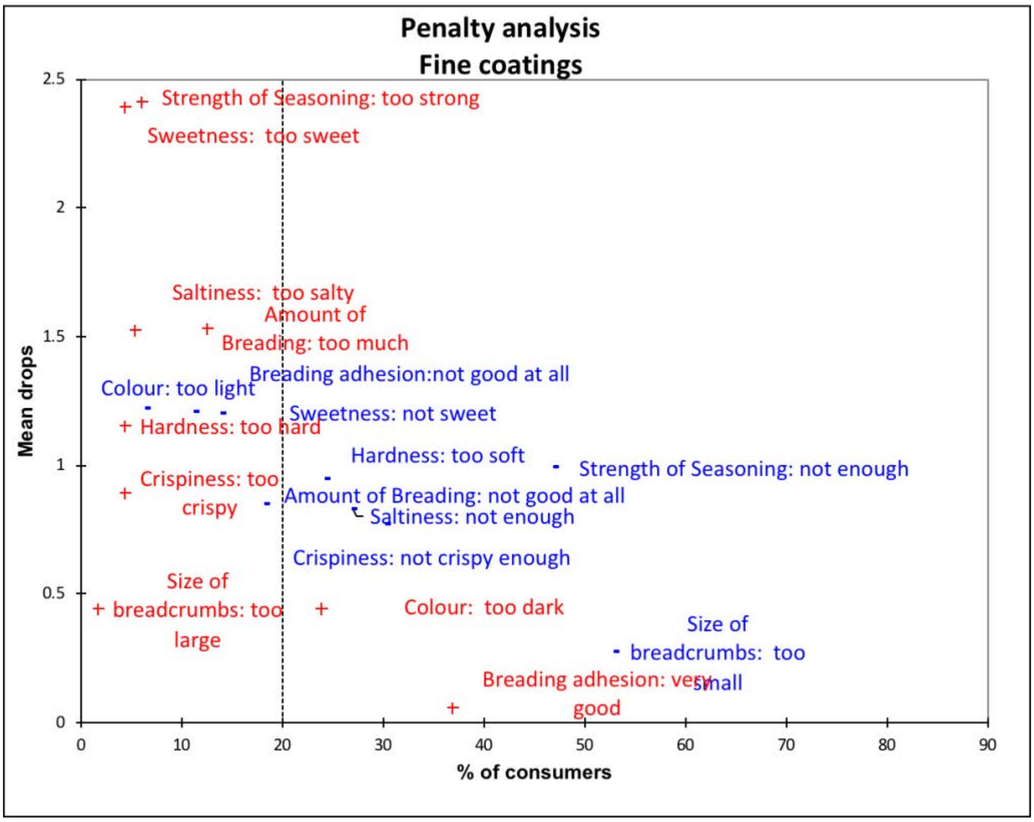
more than 20 % of respondents. A dashed line represents the 20 % of consumer, any attributes plotted to the right of this line were rated by more than 20 % of consumers. Therefore, these attributes located on the right can be focused on to improve overall liking (Gere et al., 2017). Furthermore, a high mean drop is also important and should be addressed first if located in the upper right corner of the plots (Gere et al., 2017).

Figure 5.7a shows mean drop plot for fine breadcrumb coatings. Attribute 'not enough-seasoning' is located towards the upper right corner, meaning it can be focused on for improving overall liking. As supported by Table 5.4, 47.03 % of consumers rated fine breadcrumb coatings as TL- strength of seasoning, this resulted in a mean drop of 0.989 if rated not enough. This can be explained as small sized breadcrumbs have a lower mass, less seasoning will be carried on the coating. Although 'much too small breadcrumbs' is located towards the upper right, it also has a low mean drop value, hence it does not significantly affect overall on the liking.

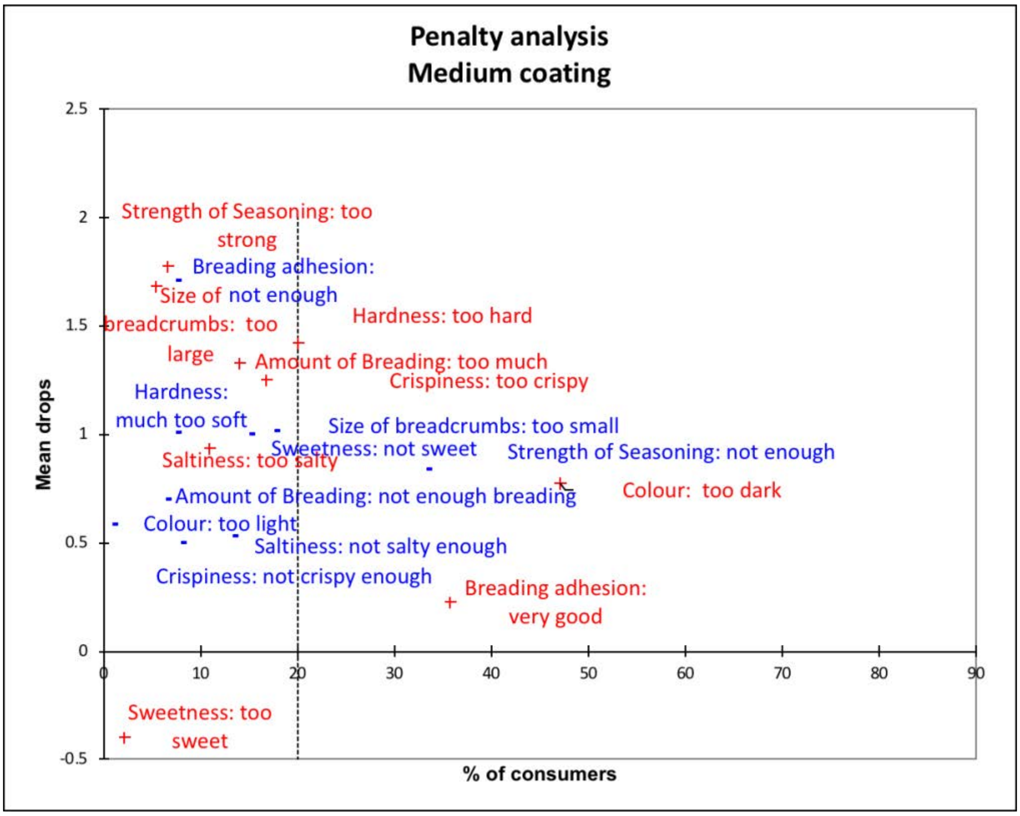
When considering medium breadcrumb coatings (Figure 5.7b), attributes 'not enough-seasoning', 'too dark- colour' and 'very good-breading adhesion' are located towards the right corner of the plot. However, 'very good-breading adhesion' was not highly penalised as it has a mean drop of 0.227 (Table 5.4) and does not significantly reduce overall liking. Both 'not enough-seasoning' and 'too dark-colour' will significantly reduce overall liking (Table 5.4). A darkness colour will be a result of deep-fat frying, as browning is typical of the Maillard reaction. It can be noted that 'too much- sweetness' has a negative mean drop value (-0.394), this can occur when there is a low percentage of respondents. This is supported Table 5.4, which highlights that only 2.16 % of respondents judged sweetness as too high. Therefore, 'too much-sweetness' should not be a an attribute to focus on if trying to improve overall liking.

When considering coarse breadcrumb coatings, 'too dark- colour', 'too hard-hardness' and 'too crispy- crispness' are all located towards the upper right corner. These attributes have respondents over 50 % and will significantly reduce overall liking if rated as too much. Increased colour will occur in larger breadcrumb coatings as these structures are highly amorphous with exposed protrusions. These protrusions have longer exposure time to frying oil, therefore will darken due to the Maillard reaction. This is supported by Figure 5.2 and Table 5.1 which highlights highly porous structures and high oil content is found within larger breadcrumb coatings. Therefore, coatings with irregular surface coverage will have higher exposure to cooking oil. This results in a darkened and dry crisp texture, which explains why consumers scored these coatings to be 'too dark- colour', 'too hard- hardness' and 'too crispy- crispness'. Dry and crispy structures are brittle, therefore when a stress is applied past a threshold, the structure will fracture. Crack propagation will then begin and beyond a certain velocity, the crack growth will become faster and splinter into multiple cracks due to the amorphous nature of the coating (Luyten & Vliet, 2006), this explains the high number of sound peaks, sound pressure level, fracture force and area (Table 5.2). This collectively explains high hardness and crispness score. Table 5.3 shows coarse breadcrumb coatings have the lowest overall liking, appearance, flavour and texture score. This shows that although crispness is an important attribute for deep-fried coatings, liking score is compensated when crispness is too high. This is supported by Table 5.4 and Figure 5.7c, which highlight crispness, hardness and colour need to be reduced in intensity.

A)


Penalty analysis
Fine coatings
Mean drops
% of consumers
Strength of Seasoning: too strong
Sweetness: too sweet
Saltiness: too salty
Amount of Breading: too much
Breading adhesion:not good at all
Colour: too light
Sweetness: not sweet
Hardness: too hard
Hardness: too soft
Strength of Seasoning: not enough
Crispiness: too crispy
Amount of Breading: not good at all
Saltiness: not enough
Crispiness: not crispy enough
Size of breadcrumbs: too large
Colour: too dark
Size of breadcrumbs: too small
Breading adhesion: very good

B)


Penalty analysis
Medium coating
Mean drops
% of consumers
Strength of Seasoning: too strong
Breading adhesion: not enough
Size of breadcrumbs: too large
Hardness: too hard
Amount of Breading: too much
Crispiness: too crispy
Hardness: much too soft
Size of breadcrumbs: too small
Sweetness: not sweet
Strength of Seasoning: not enough
Saltiness: too salty
Amount of Breading: not enough breading
Colour: too dark
Colour: too light
Saltiness: not salty enough
Crispiness: not crispy enough
Breading adhesion: very good
Sweetness: too sweet

C)

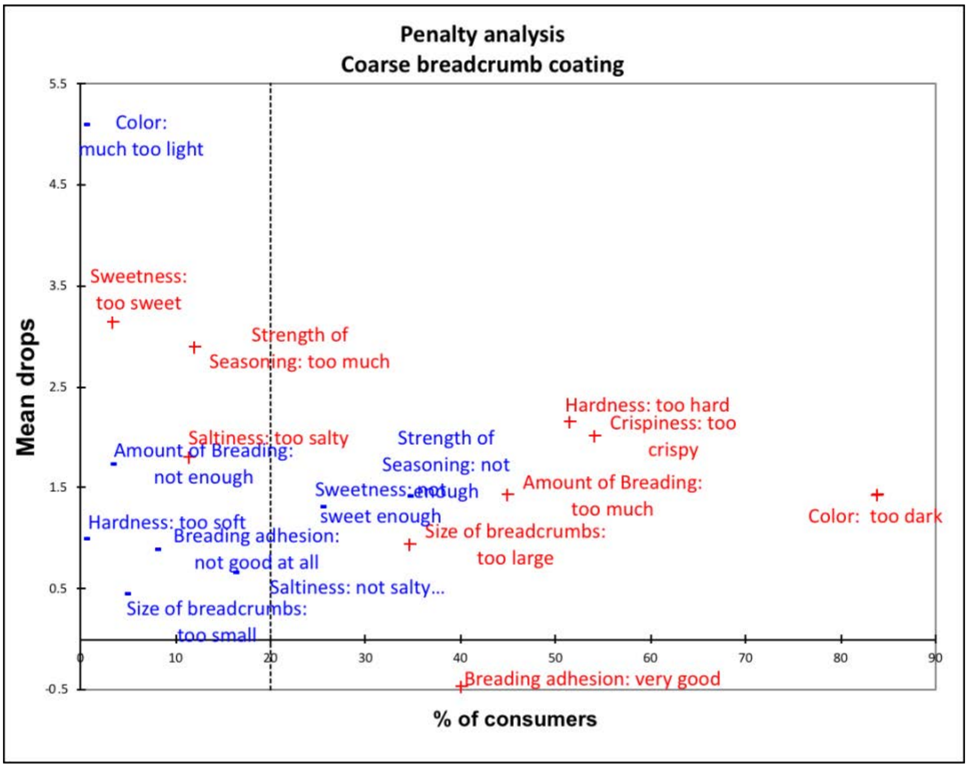


Figure 5.7 Mean drop plots of A) fine B) medium C) coarse breadcrumb coatings. Blue corresponds to not enough of an attribute, whilst red corresponds to too much of an attribute on JAR scale. The threshold of consumers over which the results are considered significant is marked with a dotted line.

5.3.5 Segmentation of consumers

Consumers were recruited from a similar geographic location and are regular consumers of the product. Agglomerative hierarchical clustering (AHC) was used to group consumers based on a certain response, this is useful for identifying trends or patterns (Schilling & Coggins, 2007). AHC confirmed three clusters based on similar liking profiles (Figure 5.8), each cluster having a higher mean score for one particular sample. Table 5.5 shows cluster 1 (49.2 % of respondents) have the highest liking for fine, then medium and lowest liking for coarse. Cluster 2 (21.6 % of respondents) prefer medium samples, followed by coarse and then fine. Cluster 3 (29.2 % of respondents) have a higher preference for coarse samples but also seem to like both fine and medium. This highlights preferences will differ amongst consumers, variations in taste and liking can be expected (Carr, 2004). Further AHC analysis was carried out to investigate other variables, this can be found in Appendix section.

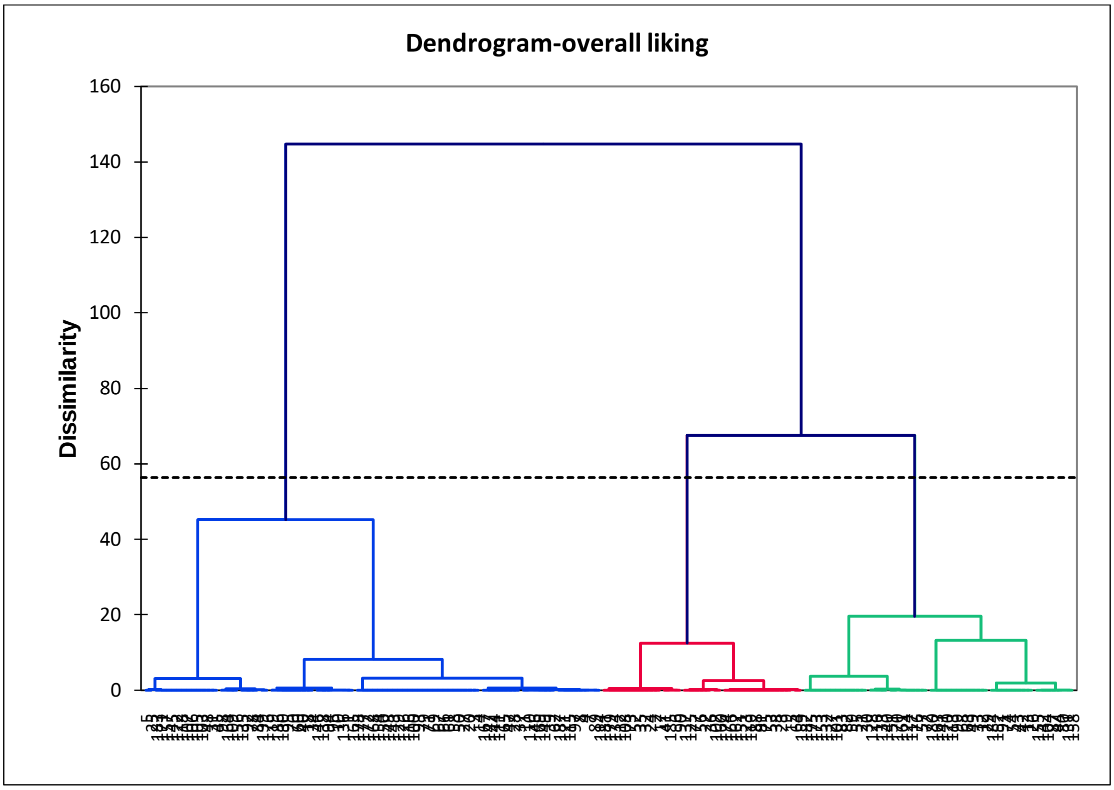
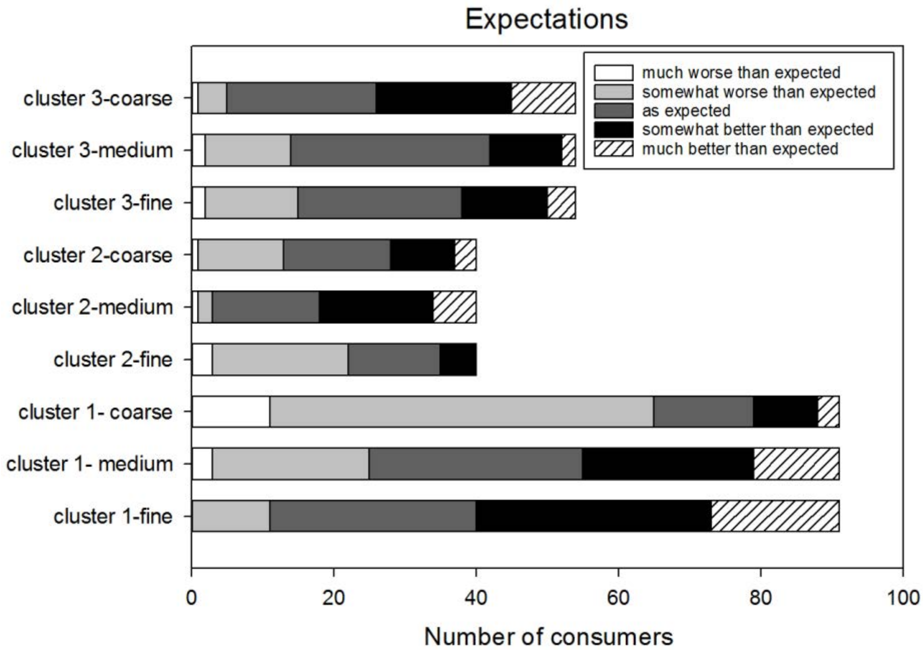


Figure 5.8 Dendrogram displaying the clustering of consumers when assessing overall liking. Dotted line indicates truncation into clusters. X axis displays individual consumer ID number, which has been blurred for confidentiality.

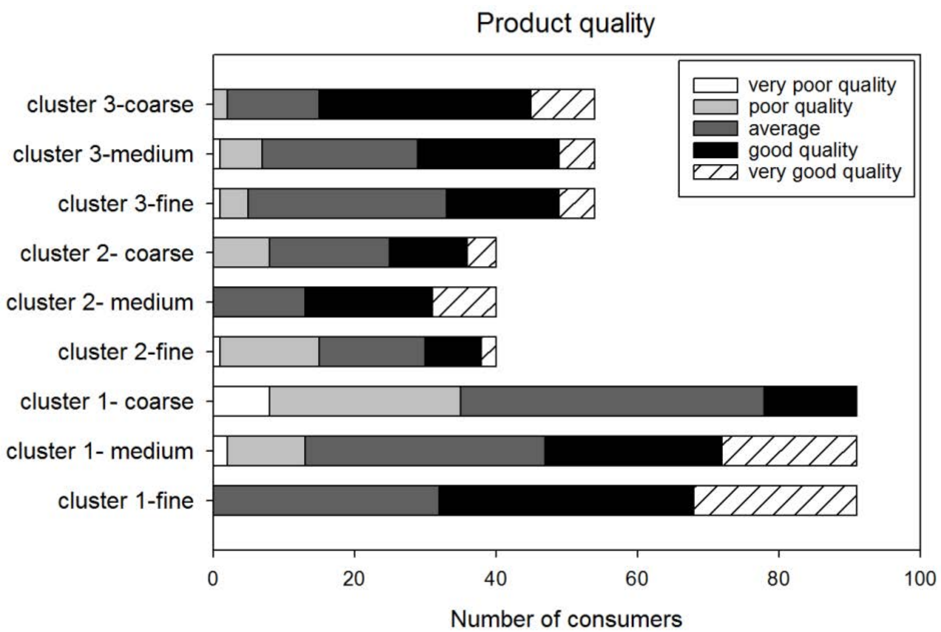
Table 5.5. Mean scores and percentages of respondents for each cluster group. Highest mean scores have been highlighted in bold. Total number of respondents = 185.

Cluster	Sample- fine	Sample- medium	Sample- coarse
1 - 49.2 %	**7.231**	6.538	4.560
2 - 21.6 %	5.525	**7.575**	6.500
3 - 29.2 %	6.407	6.370	**7.630**

A)


Expectations
much worse than expected
somewhat worse than expected
as expected
somewhat better than expected
much better than expected
cluster 3-coarse
cluster 3-medium
cluster 3-fine
cluster 2-coarse
cluster 2-medium
cluster 2-fine
cluster 1- coarse
cluster 1- medium
cluster 1-fine
0
20
40
60
80
100
Number of consumers

B)


Product quality
very poor quality
poor quality
average
good quality
very good quality
cluster 3-coarse
cluster 3-medium
cluster 3-fine
cluster 2- coarse
cluster 2- medium
cluster 2-fine
cluster 1- coarse
cluster 1- medium
cluster 1-fine
0
20
40
60
80
100
Number of consumers

C)

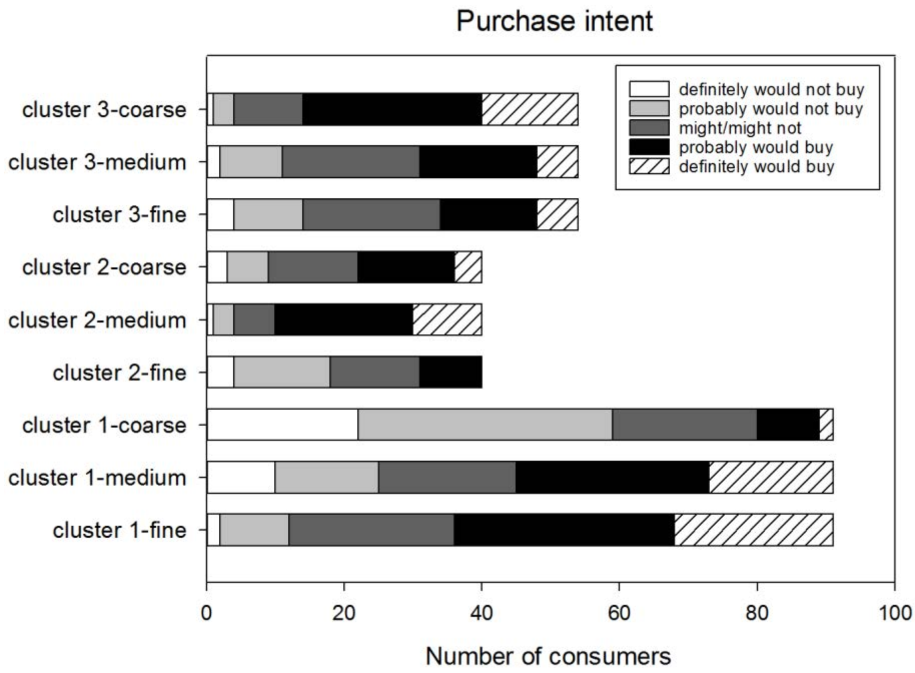


Figure 5.9 5-point scale scoring for A) met expectations B) product quality C) purchase intent of consumers within each cluster group.

Purchase intent, product expectation and product quality of samples were evaluated for each cluster group (Figure 5.9). Chi-square analysis confirms that there is a significant link between 'purchase intent' and cluster group, this link is significant for 'cluster 1' (*p*-value 0.00), 'cluster 2' (*p*-value 0.033) and 'cluster 3' (*p*-value 0.0001). This shows that based on a high liking score, consumers have the intention to purchase that particular sample. Chi-square also confirms that each cluster group is finding significant differences in 'product quality' between samples. This is significant for cluster 1 (*p*-value <0.0001), cluster 2 (*p*-value 0.001) but not cluster 3 (*p*-value 0.062). Cluster groups were also confirmed to be scoring samples significantly different based on how the sample 'met expectations'. This is significant for cluster 1 (*p*-value <0.0001), cluster 2 (*p*-value 0.001) but not cluster 3 (*p*-value 0.059), although this is only slightly insignificant.

Each cluster group with a higher liking score for a particular sample is related to its perceived 'product quality' and whether it 'met expectations'. This is true for cluster 1 and 2, who prefer fine and medium respectively. However, this is not true for cluster 3 and can be expected because as shown in Table 5.5, consumers in cluster 3 have a higher overall liking score for coarse samples but also like fine and medium.

When looking further into other demographic factors, chi-square analysis confirmed no significant link between cluster group and gender, although it can be noted this study had a participation of 61 % female and 38 % male. No significant links were found between cluster group and age, purchase frequency or purchase of competitor brands. Consumers are segregating according to attitudes not demographics.

5.4 Conclusion

This study contributed to the understanding of preferences of consumers towards the coating of deep-fried battered and breaded shrimp. Instrumental analysis highlights the structural differences between fine, medium and coarse breadcrumb coatings. All breadcrumb coatings share structural similarities, in that there is a porous crust with low moisture, this contrasts a high moisture core with low porosity. As breadcrumb cluster size increases, the following physical and mechanical properties increase: total porosity, pore size range, maximum compression force, area, sound pressure level, sound peaks and oil content. The following properties decrease when breadcrumb cluster size increases: structural thickness distribution and moisture content. These differences in internal morphology will affect textural properties and sensory perception. Crispness is a critical sensory attribute for the enjoyment and quality of deep-fried products. However, penalty analysis confirms that if crispness is scored too high, hedonic score decreases, as shown with 'coarse' samples. This study has shown that although crispness is a fundamental attribute, penalty analysis confirms that a combination of appearance related, texture related and flavour related attributes have a significant effect on the hedonic score. Therefore, crispness is not the most critical attribute when evaluating liking and acceptance of deep-fried coated shrimps.

'Medium' coatings had the highest overall liking score but AHC confirms three clusters of consumers based on overall liking, each with a higher preference for either 'fine', 'medium' and 'coarse'. Product quality, product expectations and purchase intent, significantly influenced liking (p <0.05) but other demographics such as age, gender and brand purchases did not. This suggest the influence of behavioural patterns are greater than demographic. Each coating has different physical and mechanical properties, highlighting the importance of how microstructure affects textural properties and then consumer acceptance. The findings of this research is applicable to food products that are deep-fried battered and breaded.

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Chapter 6: Future work recommendations and conclusions

6.1 Background for future work

The following work shows preliminary data for potential future work. The objective of this work was to develop an experimental set-up to capture the crack propagation in order to understand the fundamentals of crispness from a material science perspective.

6.2 Introduction

A dry crisp material is recognised as a brittle material that fractures under low strain with distinguishable fracture events. The structure of dry crisp materials are typically porous, resembling a cellular structure. These pores are air-filled and can be amorphous in shape and size, therefore heterogeneities in structural composition can be expected.

The solid phase surrounding the air cells consists of beams and struts which may contain smaller pores, cracks and differences in local composition (Luyten & Van Vliet, 2004). The result of this is irregularities in the solid phase with differences in thickness of cell walls. It is the presence of these irregularities that form weak spots that allow for crack propagation to occur, thus how a crisp texture is perceived.

As a fracture occurs, crack speed will accelerate and beyond a certain velocity, the crack growth becomes unstable and splinters until the surface of the material is no longer smooth (Luyten & Vliet, 2006). An accompanying acoustic emission is also produced as the crack pathway splinters. The cutting process can be distinguished into four phases: 1) full contact with cutting edge and product 2) the cutting force increases linearly 3) the resistance of the product and friction between the blade and product determines the cutting force 4) the product has completely fractured, the cutting force is zero (Schneider et al., 2002).

The use of high-speed cameras have been utilized to observe the crack speed within crisp foods. This allows a visual understanding of how the structure dictates the crack pathway and therefore how crispness as a texture is perceived. The advantage of this from a formulation perspective provides potential to manipulate the microstructure in order to control the crack pathway, thereby controlling crispness.

6.3 Materials and methods

6.3.1 Materials

Commercial dry crisp snacks were purchased from a Sainsburys supermarket. A range of potato and corn based snacks were chosen for their porous open network structure. Each corn or potato snack was sliced to reveal the cellular cross-section prior to testing.

6.3.2 Scanning electron microscopy (SEM)

Samples of dry crisp snacks were snapped to reveal a cross-section, before being secured to a platform using carbon tabs, before scanning at 5kV (Hitachi TM3030). No splutter coating was needed. All images were processed using TM3030Plus.

6.3.3. Texture analyser and sound emission analysis

A texture analyser (Stable Micro Systems Ltd., UK) was used to deform samples and to capture a force-deformation curve. All samples were held on a 3 point bend apparatus set to 1 cm width. A 3-point bend platform with a blade attachment was used, replacing the 3-point bend probe. Test speeds were carried out at 0.25 mm/s and compressed to 30 % strain.

Acoustic envelope detector (AED) (TA-XT Plus, Stable Micro Systems Ltd., UK) was used for force-displacement acoustic measurements and recorded using Texture Exponent. A Microphone (12 mm diameter) was positioned 7 cm horizontally from centre of platform. Calibrated using a sound calibrator at 94 dB and 114 dB at 1000 Hz. Any background noise was filtered using 3.125 kHz corner frequency. A gain of AED was set at 3 with data acquisition rate set to 500 points per second for force and sound measurements. Ten replicates were performed.

6.3.4 High-speed camera

Videos and images were captured using a Photron SA3, all images were processed Photron PFV FASTCAM Viewer (Ver. 3541). The lens attachment was Navitar, 2X F-mount, with a spatial resolution up to 4 µm/pixel with SA3. In order to increase resolution i.e. pixels, a higher frame rate and adjusting shutter speed is needed, which can result in lower resolution without a greater light source. Therefore, additional lighting was adjusted using GVM 560 LED Light panels.

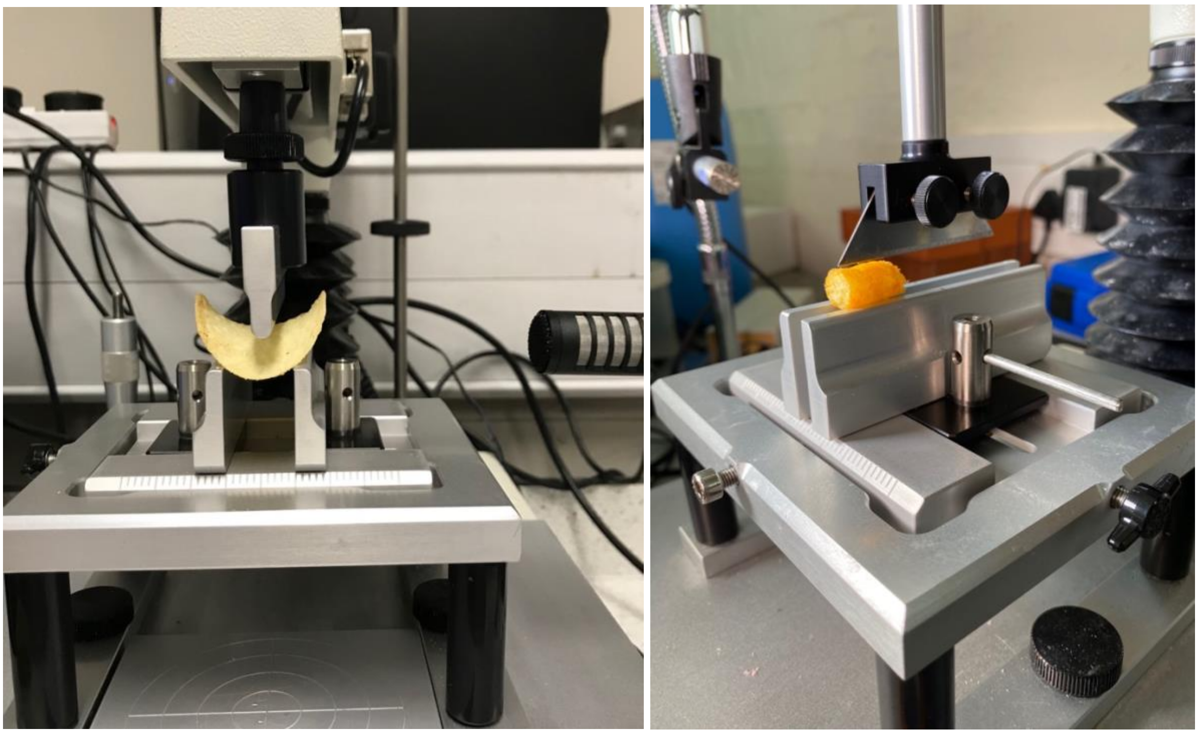


Figure 6.1 view of texture analyser arrangement using 3-point bend attachment, blade attachment and microphone. Samples include commercial potato snack and corn snack.

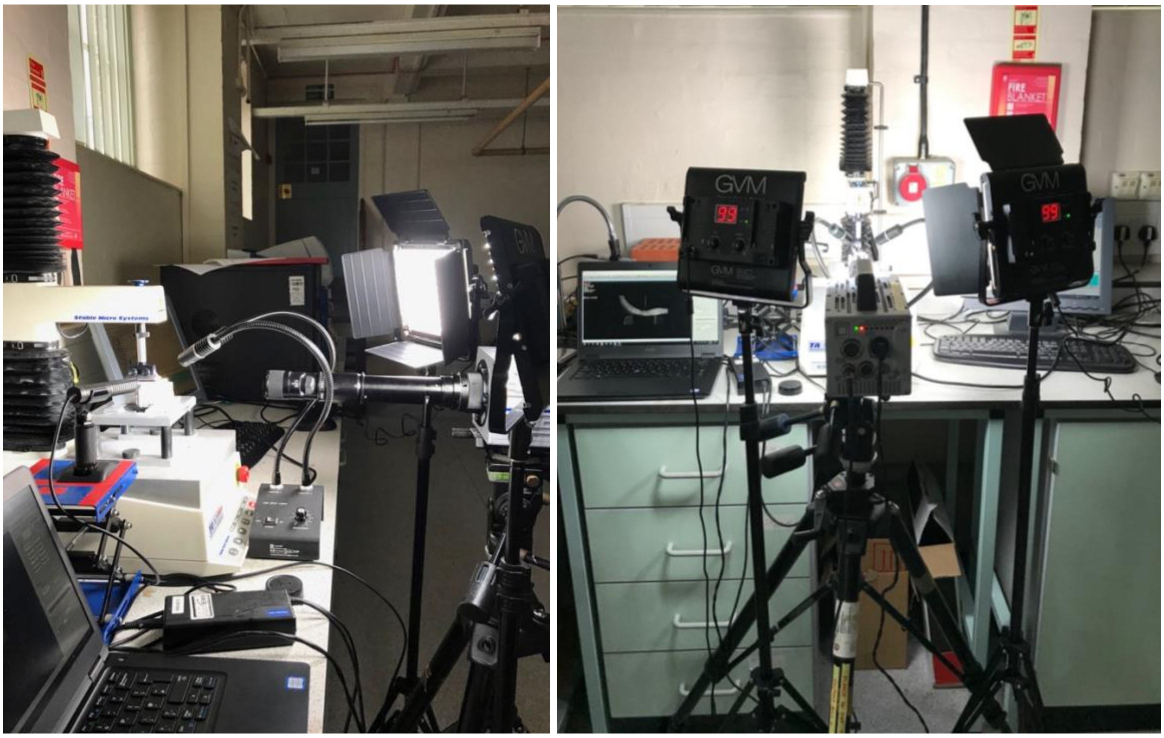


Figure 6.2 Arrangement of entire experimental set-up, including texture analyser, acoustic envelope, high-speed camera and lighting.

6.4 Results and discussion

In dry crisp materials, the volume fraction of air and the structure of the solid matrix determines the mechanical behaviour. In Figure 6.3, SEM clearly captures the cross section of a potato crisp at a microscale at high resolution. The internal morphology shows a porous structure with air-filled cavities. As shown in Figure 6.4, the capability of the experimental set-up captured macroscale not microscale. A large open cellular structure with defined macroscopic dimensions (Figure 6.4b) was favoured over a porous yet densely packed structure (Figure 6.4a), as it could be captured clearly for recordings.

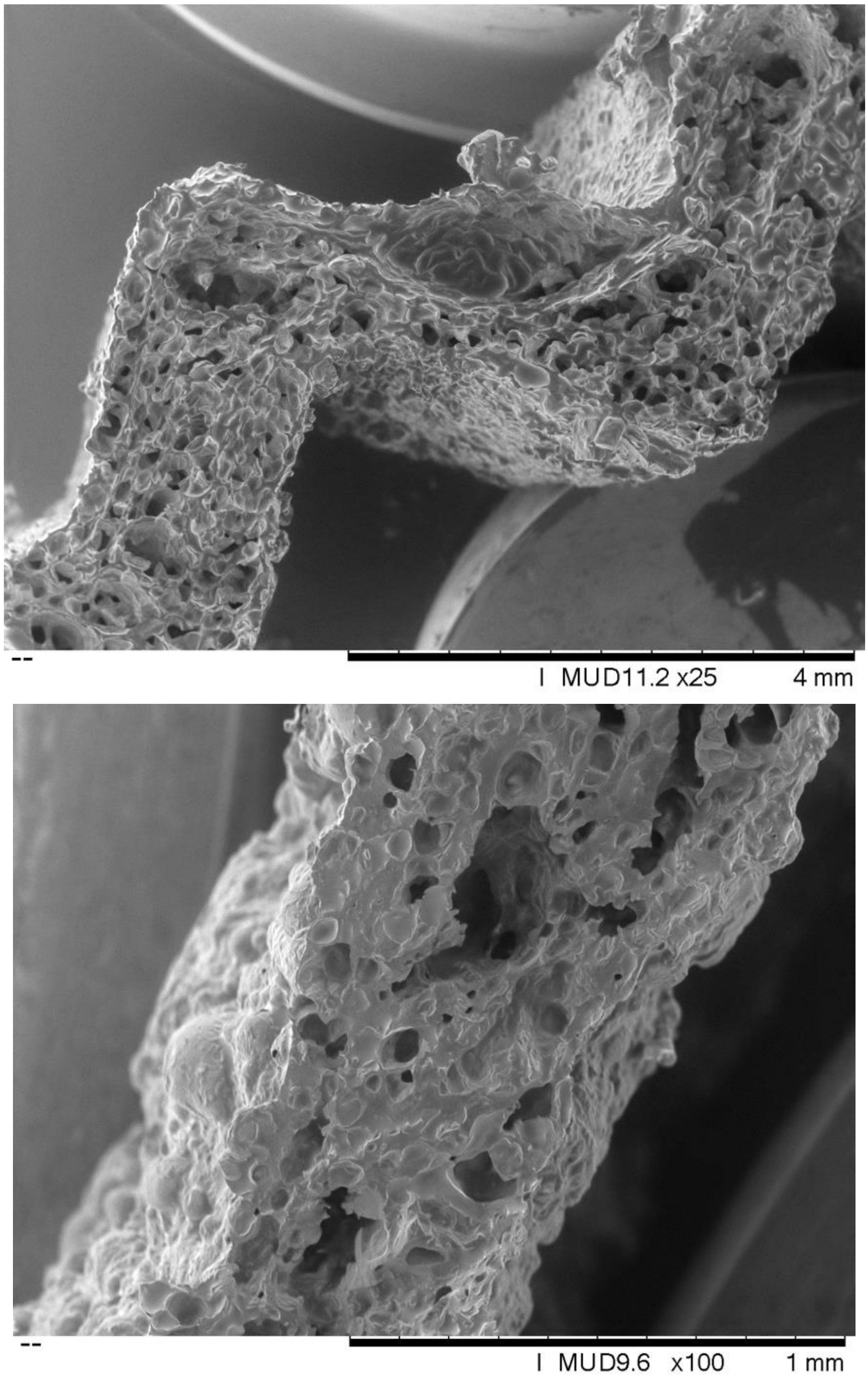
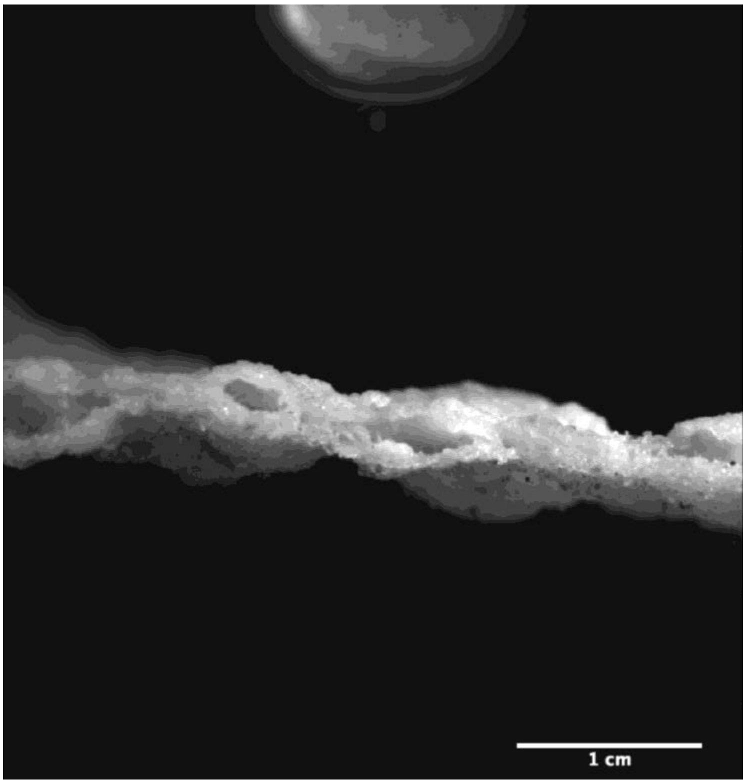


Figure 6.3 SEM image showing cross-section of dry ridged potato snack at x25 and x100 magnification. Note a porous structure is visible, with differences in cell wall thickness.

a)



b)

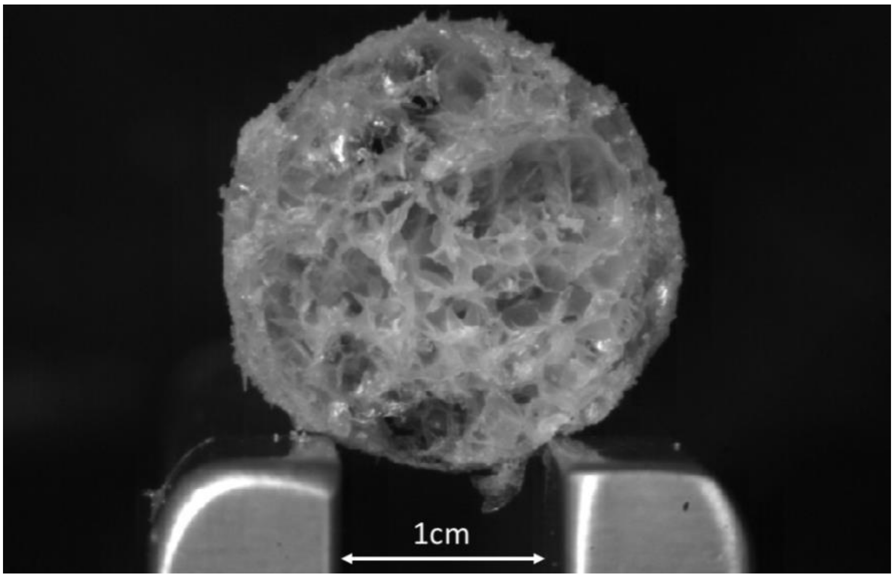


Figure 6.4 Comparison of snapshot of cross-section of a) potato snack b) corn snack samples captured on Photron SA3

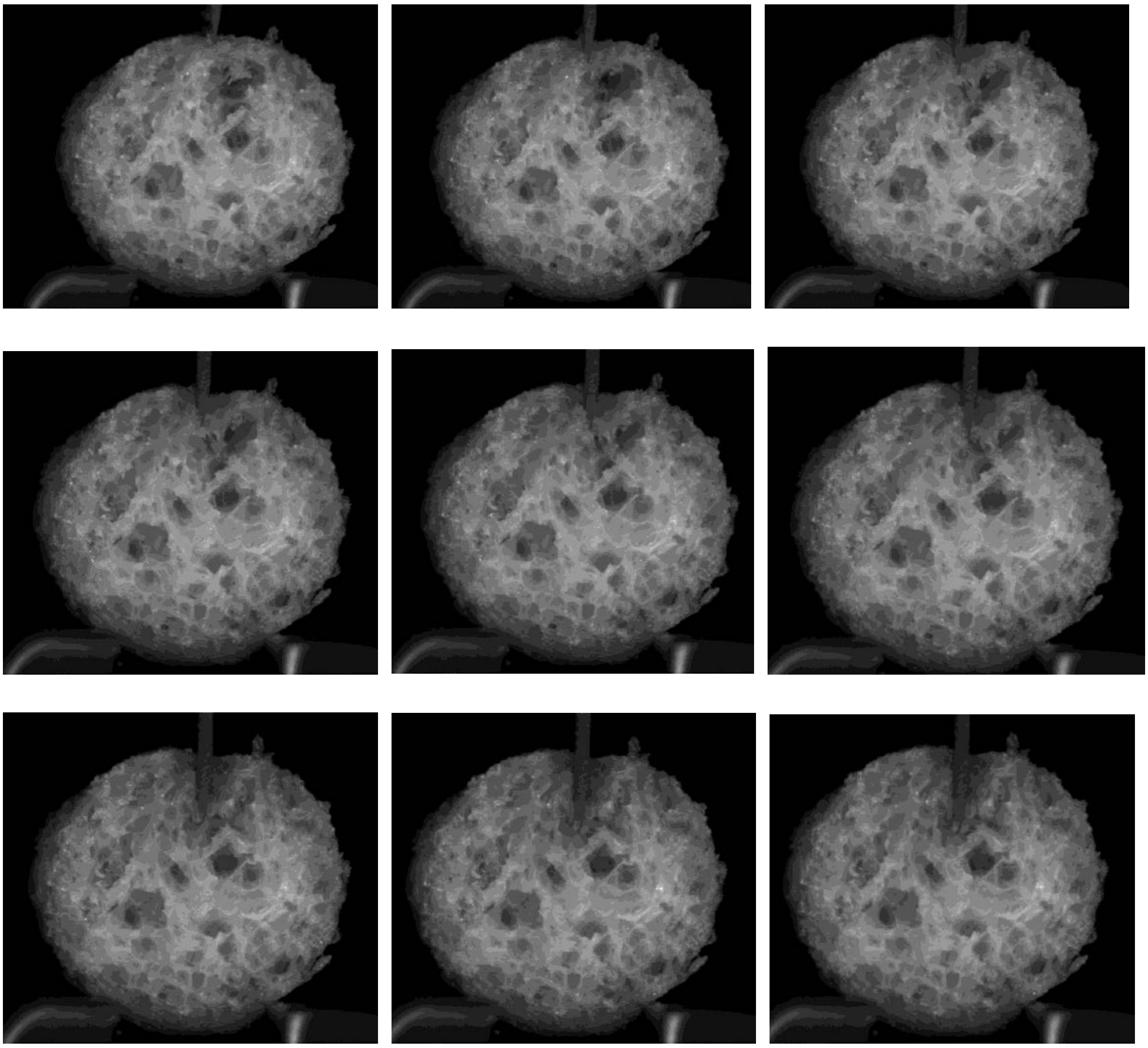


Figure 6.5 Snapshots of blade cutting into corn snack cross-section at 0.25 mm/s

Figure 6.5 highlights video snapshots of a corn snack being cut into. As the tip of the blade comes into contact with the surface of the product, compression stress will dominate in this contact area (Schuldt et al., 2018). The material will resist compression force but once the fracture tension of the material has exceeded, crack propagation is initiated. It has been previously hypothesized that fracture begins at the smallest beans that are between open air cells (Stokes & Donald, 2000). The continuous motion of the blade into newly cut material will result in shear stresses and lateral deformation (Schuldt et al., 2018). This explains why material surrounding the blade deforms and hence the crack pathway is splintering (Figure

6.5). The presence of inhomogeneities or defects in the structure will also favour mechanical failure as these are the regions were stress will be concentrated.

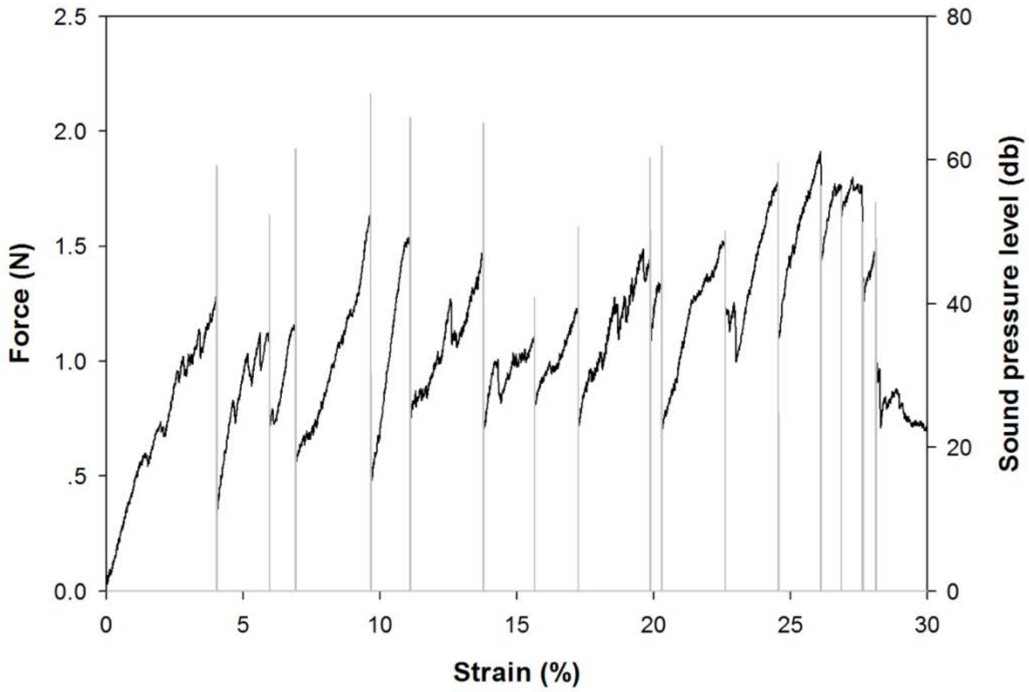


Figure 6.6 Force-displacement of sound pressure level (dB), force (N) versus distance (mm) for dry crisp product (corn snack). Changes in compression force represented by jagged force profile. Sound pressure level represented by peaks.

Table 6.1 Mean values for parameters extracted from texture analyser and acoustic envelope detector for dry crisp material

Max. Force (N)	Area (N.sec)	Force peaks (drops in force more than 0.049 N)	Max. SPL (dB)	Number of sound peaks
1.20 ± 0.44	7.23 ± 4.1	0.180 ± 0.045	59.9 ± 6.04	8.3 ± 4.1

The mechanical and acoustic parameters are presented in Table 6.1 with an example of the force-displacement profile in Figure 6.6. Hard solid foods typically behave elastically upon deformation at low strains (Van Vliet & Primo-Martin, 2011). The force deformation profiles shows a first visible drop in force at 0.56 N, this could show crack propagation initiating. As the force before becomes jagged due to the material being mechanically brittle, structural failure does not occur until 1.18 N, where the force drops immediately to 0.39 N. This is also accompanied with an acoustic peak reaching 59 dB. This can be explained that as energy dissipates from structural failure, it is released as sound energy that could trigger cracks in nearby structural elements. As the probe continues to penetrate, compression force increases until further cracks and splintering occurs. This continues until complete mechanical failure and a second drop in force occurs (1.07 to 0.80 N). At a maximum compression force of 1.20 N and maximum sound pressure level of 59 dB, this is considered low force yet high acoustic emission in comparison to measurements in chapter 3, 4 and 5. Thus reemphasising that crisp materials are highly brittle in yet high acoustic emission can be expected due to multiple cracking events occurring.

6.6 Conclusion

This observational study concludes a rudimentary experimental set up to capture crack propagation of dry crispness. Photron SA3 has an image resolution at frame rates up to 120,000 fps, therefore the capability is possible but further work is needed to optimise this experimental setup. The potential to study the effect of cutting velocity on fracture behaviour would be interest as well as crack speed. This is because the elastic and plastic deformation and fracture of the material as it is being cut will depend the material properties and cutting velocity. The speed at which material fractures is also related to oral processing and texture perception.

6.7 References

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6.8 Overall conclusions

A detailed conclusion has been given at the end of each results chapter. Chapter 6 aims to summarise the overall outcomes of this thesis and propose future recommendations that provide potential to build upon the work presented.

The aim of this research was to understand the major drivers of crispness in deep-fried battered and breaded coatings. The focus began at gaining a microstructural understanding of the coating itself. An understanding of the material properties was required in order to relate this is texture perception. As crispness is a textural property, the sensory perception was explored in order to correlate material properties to sensory attributes. The next logical step was to conduct a consumer study to understand consumer preference. The final chapter had a fundamental material science approach, with an aim to understand crack propagation of crispness. The main conclusions from each chapter are summarised below in the following sections.

6.8.1 Characterisation of deep-fried battered and breaded coatings

The structural composition of battered and breaded coatings

Battered and breaded coatings are a complex layered system. The crust layer is an open and porous network, that is responsible for the upper surface of the coatings having dry and crisp texture. Where moisture and oil exchange has not yet penetrated deeper within the coating, leaves an inner layer with high moisture and low porosity. This region will have a low rate of starch gelatinization and protein denaturation. The use of X-ray MicroCT, confocal microscopy, SEM, moisture and oil analysis was successfully applied to characterise and differentiate regions of internal morphology.

The effect of breadcrumb size on microstructure, mechanical and physical properties

By separating the panko breadcrumbs into fractions (4.0 mm, 2.8 mm, 1.4 mm, 1.0 mm, 710 µm, 500 µm, 355 µm), results have shown that varying panko breadcrumb size significantly affected total porosity, pore size, structural thickness and subsequently moisture and oil content. This in turn effects the coatings physical and mechanical properties, which suggests differences in texture perception. Results did in fact show significantly different fracture and acoustic patterns as breadcrumb coating size decreased. Thereby highlighting the effect of breadcrumb size and microstructure on mechanical and physical properties.

6.8.2 Understanding and relating instrumental measurements to crispness

The subsequent effect of breadcrumb size on sensory perception

The use of a trained panel successfully developed a tailored lexicon for battered and breaded shrimp. The use of descriptive profiling and principal component analysis identified how samples significantly differ in terms of appearance and texture. Thus confirming the significant effect of varying breadcrumb size on sensory perception. Results highlighted that the attribute crispness could be distinguished between samples.

Correlation between instrumental parameters and sensory parameters

A positive correlation between these two sets of methodologies suggests both sensory and instrumental measurements can be used to provide a more thorough understanding of the drivers of crispness. The use of multiple factor analysis shows that the strength of the correlation decreases with increasing breadcrumb size. This can be expected as the larger breadcrumbs are highly amorphous in shape and size but also contain irregularities in internal morphology. Alternatively, smaller particles of breadcrumbs are more uniform in shape and size, they will also have a higher packing ability. Panellists are therefore perceiving a highly uniform sample.

Predictive model for crispness using instrumental parameters

Partial least square regression was used to develop a predictive model for crispness. This allows for a crispness score to be re-simulated using total porosity, compression force, drop in force, sound peaks and sound pressure level. The advantage of this model allows for crispness to be predicted for future products, using only instrumental measurements. Although using a combination of sensory and instrumental variables to develop a predictive model is possible, the requirement of a trained panel is typically time consuming and costly. Therefore a predictive model using instrumental parameters can be considered cost-effective.

6.8.3 Consumer understanding of crispness of deep-fried coatings

Consumer clusters were not dependent on demographic data

Agglomerative hierarchical clustering confirmed consumers clustering into three groups, each with a higher liking score for each sample. When investigating further into whether the consumers within each cluster shared common traits, chi-squared analysis was used to confirm any significant links between demographic data. Interestingly, cluster group did not have any significant link with demographic data (age, gender, brand purchase, purchase frequency). Only consumers perception of ‘product quality’, ‘expectations’, and ‘purchase intent’ were significant.

Crispness is not considered the most important attribute when determining product acceptance

Although crispness is well established as a sign of quality and freshness in numerous deep-fried goods, results in this research has shown that when crispness is scored high, hedonic score is compensated. Penalty analysis confirms a combination of appearance and texture related attributes have a significant influence on consumer acceptance. This suggests the product acceptance is dependent on a multimodal perception. Therefore, the importance and influence of crispness on product acceptance should be considered in conjunction with other variables.

6.9 Future recommendations

Explore combination of large and small breadcrumb size coatings

By combining large and small breadcrumb sizes, voidage in the deep-fried coating will be filled. This will result in a highly compact coating with expected crisp texture and reduced oil absorption.

Validate predictive model for crispness

The use of a predictive model in this research would allow for product quality to be monitored, which has commercial benefits for Rich Products and Kerry Ingredients. However, this model needs to validated to prove its application for Seapak. There is then potential to apply crispness monitoring to similar deep-fried coated products.

Study wheat flour batter system and composition

Preliminary rheological work on wheat flour batters were carried out to investigate the viscoelastic properties. Glass transition temperatures were also studied and compared to simple batter systems. This work was not published in this thesis but there is potential further work to be carried out on the composition of the batter. The benefits would allow an understanding of ingredient functionality and the effect on crispness. The wheat flour to water ratio in this research is currently 1:4, with the inclusion of seasonings, gums and additives. The resulting batter is a viscous system that does not fully adhere to the substrate and subsequently drips off. There is potential to study the effect of altering this ratio, thereby affecting the viscosity, adhesion ability, cooking procedure and final texture. As batter falls off the substrate, there is product wastage and subsequently high cost loss. Therefore, the potential to reformulate this system with hydrocolloids could result in lower wastage whilst maintaining adhesive ability. The batter in this research has both an adhesive function and a crisp formation function. However, there is potential to manipulate this system to enhance crisp texture.

Optimise high speed cameras to capture and analyse crack propagation

The use of a blade has been shown to be the most prominent method to separate food products with defined macroscopic dimensions. However, there is potential to optimise capturing of the crack propagation process whilst coupled with texture analysis and acoustics. The following parameters need to be reviewed; fps, shutter speed, resolution, light source.

The ability to capture crack propagation with force-displacement and acoustics would allow for isolation of specific fracture events or splintering. Each fracture event or splinter may be able to be distinguished with an acoustic pattern (sound pressure level or frequency) or texture profile. Fundamentally, the mechanics of crisp texture could be further studied. This could also be applied not only to dry crisp but also wet crisp.

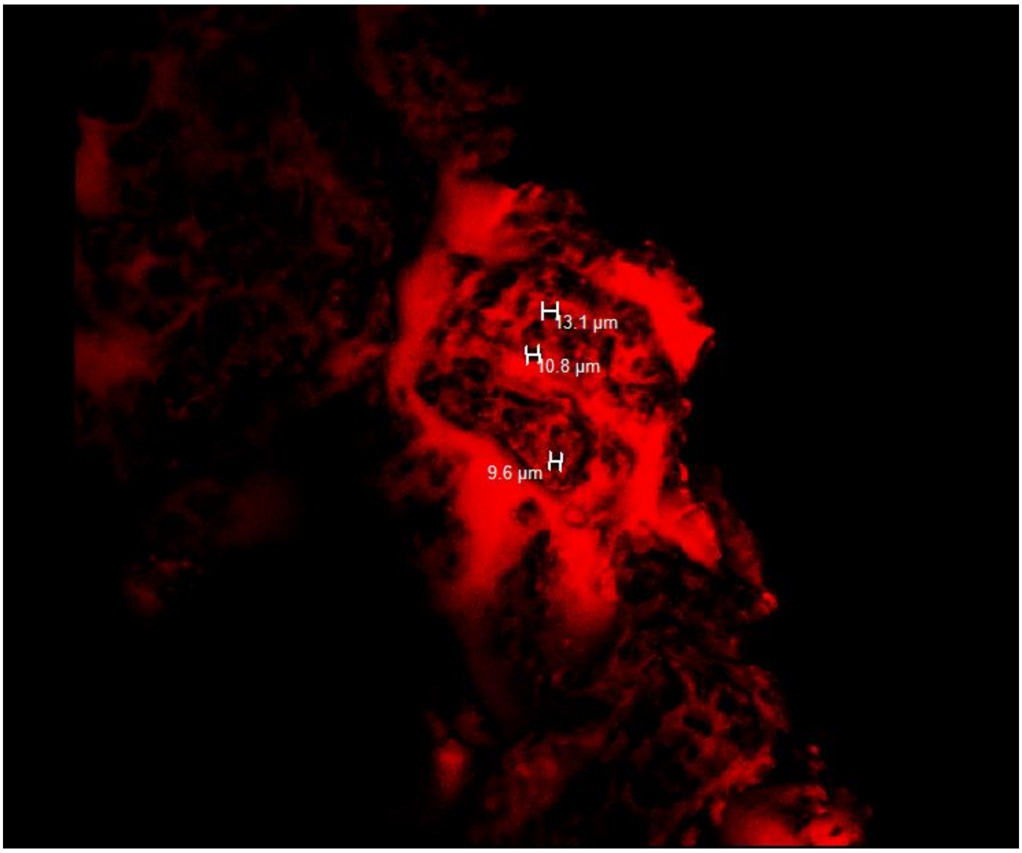
Investigate the effect of cutting velocity on crack and splintering

Higher cutting speeds could be investigated to mimic a realistic mastication process (~20 mm/s). The cutting velocity will also affect cutting force, a known factor to influence fracture behaviour. A cutting speed of 0.25 mm/s was used in this research, this was within the capacity of the fps used. To the best of our knowledge, cutting velocities of up to 10 m/s have been recorded with force-displacement data (Schuldt 2018). The difficulty of this is optimising the camera parameters to capture a higher cutting velocity

Further acoustic analysis

The AED attachment of the texture analyser used in this research had a sampling rate of 1/0.002 s (500 Hz). This would only allow for a low frequency range analysis. Therefore, equipment with a higher sampling frequency should be considered in order to study a wider frequency range and distinguish samples further based on acoustic signature. The expected frequency range for breaded coatings has been found to range between 2000-8000 Hz (Roudaut et al 1998).

7. Appendices



Supplementary Figure 8.1 Confocal image of deep-fried batter coating, Leica image analysis shows pore size can range from 3-9

Preliminary study using confocal scanning laser microscopy measured pore size, as pore size was below 10µm, X-ray microCT was appropriate for its high resolution and magnification ability.

7.1 Linear Regression

Supplementary Table 7.1 Multicolinearity statistics confirms multicollinearity.

	Porosity	Max Force	Area	Drop in force (N)	No of sound peaks	Sound P L	Cohesiveness	Denseness	Hardness	Crumb Coverage	Particle Size	Surface Color	Surface Color Uniformity	Surface Uniformity/ Irregularity
Tolerance	0.008	0.001	0.004	0.080	0.100	0.201	0.054	0.036	0.003	0.039	0.008	0.053	0.016	0.012
VIF	128.941	774.426	256.660	12.456	9.994	4.980	18.563	27.980	379.966	25.578	131.466	18.915	62.079	83.015

Supplementary Table 7.2 Summary of variable selection for crispness. R^2 value or 1.00 was calculated for highlighted variable selection for crispness. This is high and further suppores multicollinearity.

Nbr. of variables	Variables	MSE	R^2	Adjusted R^2	Mallows' Cp	Akaike's AIC	Schwarz's SBC	Amemiya's PC
1	Hardness	0.037	0.969	0.964	9.925	-24.758	-24.599	0.038
2	Hardness / Surface Color	0.018	0.988	0.983	3.619	-30.017	-29.779	0.019
3	Denseness / Hardness / Surface Color	0.011	0.994	0.989	2.792	-33.612	-33.294	0.012
4	Area / Sound P L / Hardness / Crumb Coverage	0.005	0.998	0.996	2.864	-40.994	-40.597	0.005
5	Porosity / Area / Drop in force (N) / Hardness / Surface Color	0.000	1.000	1.000	4.002	-88.293	-87.816	0.000
6	Porosity / Area / Drop in force (N) / Hardness / Crumb Coverage / Surface Color	0.000	1.000	1.000	6.000	**-108.121**	-107.565	0.000
6	Porosity / Area / Drop in force (N) / Hardness / Crumb Coverage / Surface Color	0.000	1.000	1.000	6.000	-108.121	-107.565	0.000
6	Porosity / Area / Drop in force (N) / Hardness / Crumb Coverage / Surface Color	0.000	1.000	1.000	6.000	-108.121	-107.565	0.000
6	Porosity / Area / Drop in force (N) / Hardness / Crumb Coverage / Surface Color	0.000	1.000	1.000	6.000	-108.121	-107.565	0.000
5	Porosity / Drop in force (N) / No of sound peaks / Cohesiveness / Denseness	0.007	0.998	0.993	4.880	-38.848	-38.371	0.007
6	Porosity / Drop in force (N) / No of sound peaks / Cohesiveness / Denseness / Crumb Coverage	0.011	0.998	0.989	6.703	-38.651	-38.094	0.008
6	Porosity / Drop in force (N) / No of sound peaks / Sound P L / Cohesiveness / Denseness	0.012	0.998	0.988	6.756	-38.063	-37.507	0.008
6	Max Force / Drop in force (N) / No of sound peaks / Sound P L / Cohesiveness / Denseness	0.015	0.998	0.986	6.924	-36.455	-35.899	0.010
5	Porosity / Max Force / No of sound peaks / Sound P L / Denseness	0.016	0.996	0.985	6.000	-32.282	-31.805	0.015

Tolerance score ranges 0-1, tolerances <0.1 and high VIF score suggest multicolinearity. Therefore, PLS regression is appropriate as it factors in multicollinearity, linear regression does not. Model variable selection can then be applied to review the most appropriate variables. This provides justification for selecting variables for PLS regression. Highlighted equation in Table 8.2 was selected by XLSTAT as statistically most appropriate for predicting crispness.

$R^2 = 1.00$

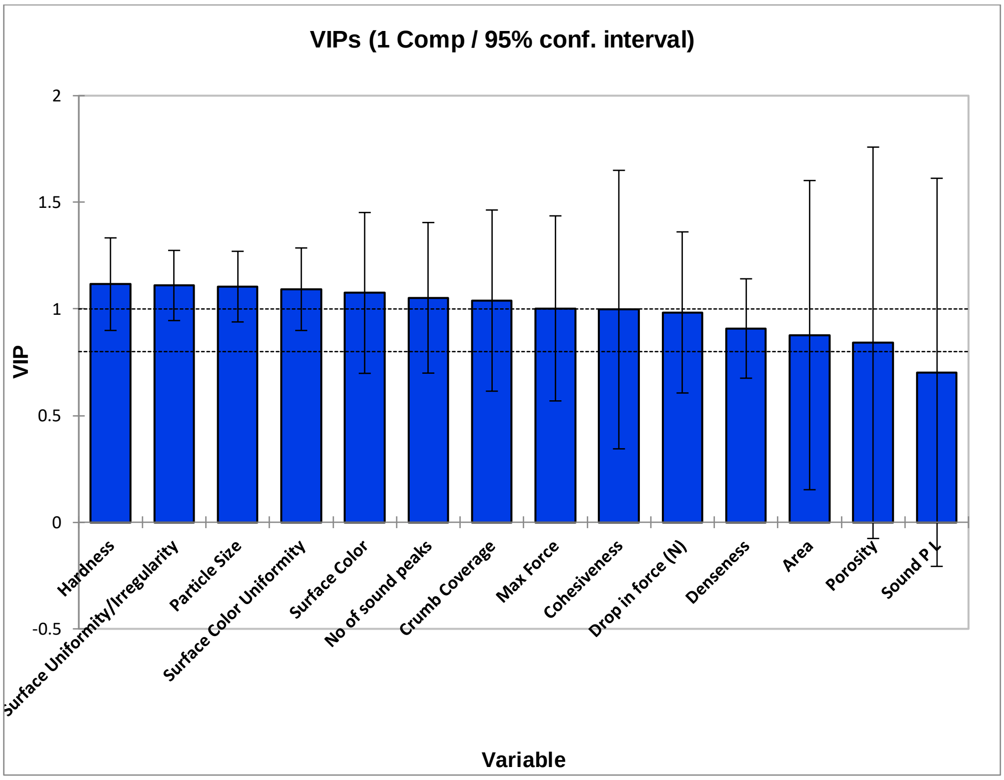
Supplementary equation 7.1

8.2 PLS regression

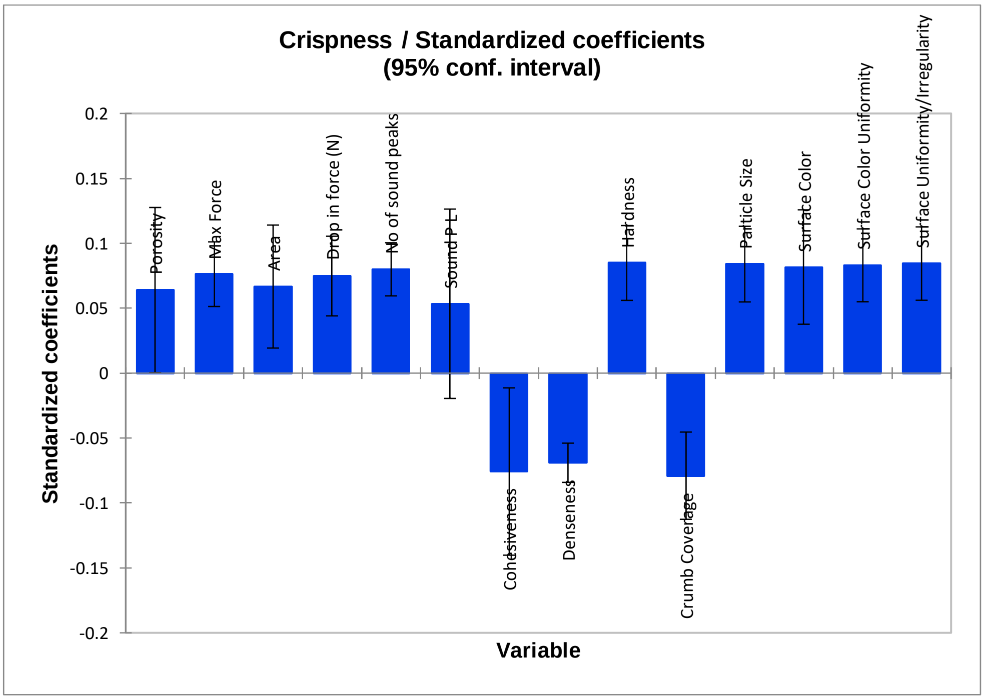
Supplementary Table 8.3 PLS Correlation matrix of all sensory and instrumental variables, highlighting the correlation with sensory crispness.

Variables	Porosity	Max Force	Area	Drop in force (N)	No of sound peaks	Sound P L	Cohesiveness	Denseness	Hardness	Crumb Coverage	Particle Size	Surface Color	Surface Color Uniformity	Surface Uniformity/ Irregularity	Crispness
Porosity	**1.000**	0.897	0.929	0.764	0.813	0.554	-0.463	-0.632	0.764	-0.670	0.737	0.672	0.720	0.725	0.740
Max Force	0.897	**1.000**	0.975	0.935	0.860	0.530	-0.747	-0.872	0.908	-0.862	0.922	0.847	0.925	0.910	0.882
Area	0.929	0.975	**1.000**	0.871	0.800	0.503	-0.631	-0.837	0.814	-0.753	0.837	0.750	0.835	0.819	0.772
Drop in force (N)	0.764	0.935	0.871	**1.000**	0.775	0.523	-0.766	-0.862	0.869	-0.824	0.892	0.834	0.909	0.876	0.865
No of sound peaks	0.813	0.860	0.800	0.775	**1.000**	0.494	-0.722	-0.788	0.950	-0.850	0.891	0.811	0.866	0.909	0.926
Sound P L	0.554	0.530	0.503	0.523	0.494	**1.000**	-0.599	-0.440	0.542	-0.294	0.636	0.720	0.563	0.593	0.618
Cohesiveness	-0.463	-0.747	-0.631	-0.766	-0.722	-0.599	**1.000**	0.851	-0.835	0.813	-0.932	-0.951	-0.932	-0.932	-0.877
Denseness	-0.632	-0.872	-0.837	-0.862	-0.788	-0.440	0.851	**1.000**	-0.835	0.776	-0.898	-0.812	-0.897	-0.893	-0.799
Hardness	0.764	0.908	0.814	0.869	0.950	0.542	-0.835	-0.835	**1.000**	-0.915	0.962	0.892	0.947	0.967	0.982
Crumb Coverage	-0.670	-0.862	-0.753	-0.824	-0.850	-0.294	0.813	0.776	-0.915	**1.000**	-0.899	-0.850	-0.935	-0.920	-0.914
Particle Size	0.737	0.922	0.837	0.892	0.891	0.636	-0.932	-0.898	0.962	-0.899	**1.000**	0.970	0.991	0.997	0.972
Surface Color	0.672	0.847	0.750	0.834	0.811	0.720	-0.951	-0.812	0.892	-0.850	0.970	**1.000**	0.965	0.965	0.946
Surface Color Uniformity	0.720	0.925	0.835	0.909	0.866	0.563	-0.932	-0.897	0.947	-0.935	0.991	0.965	**1.000**	0.991	0.961
Surface Uniformity/Irregularity	0.725	0.910	0.819	0.876	0.909	0.593	-0.932	-0.893	0.967	-0.920	0.997	0.965	0.991	**1.000**	0.977
Crispness	0.740	0.882	0.772	0.865	0.926	0.618	-0.877	-0.799	0.982	-0.914	0.972	0.946	0.961	0.977	**1.000**

a)



b)



Supplementary Figure 8.2 VIP scores and standard coefficients for the predictive model when all variables (sensory and instrumental) are considered.

Equation of predictive model when factoring all sensory and instrumental variables, a R^2 value of 0.936 was calculated (Eq. 7.2). However, this equation is not practical from an industrial perspective, therefore it needed to be simplified.

Removing denseness, cohesiveness and crumb coverage as they have the highest negative correlation with crispness (Eq. 8.3). An R^2 value of 0.944 is still high, suggesting the negative correlation of denseness, cohesiveness and crumb coverage on crispness does not have a significant effect.

$R^2 = 0.936$

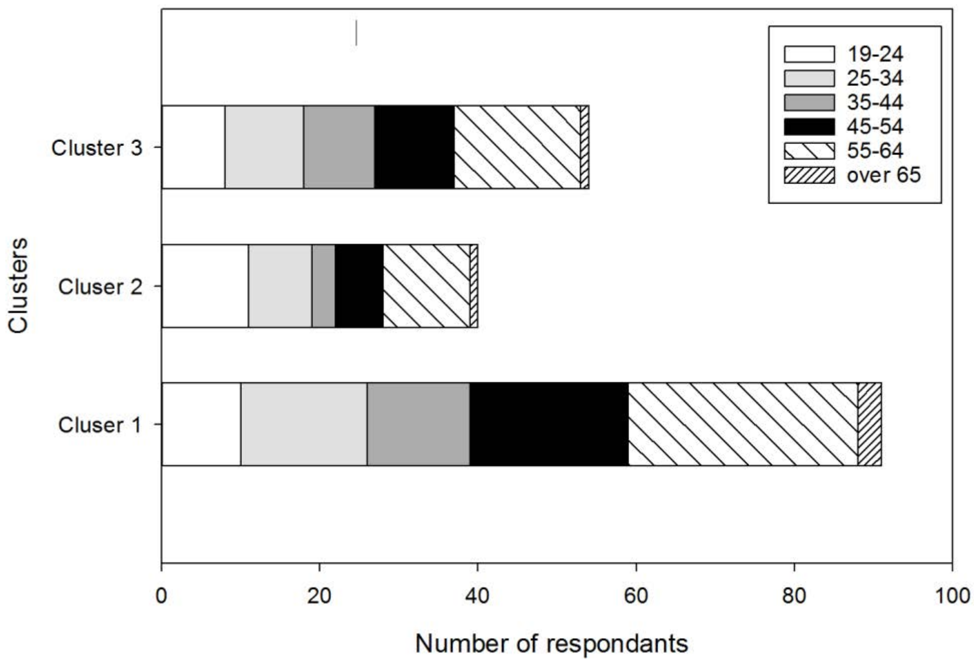
Supplementary equation 7.2

$R^2 = 0.944$

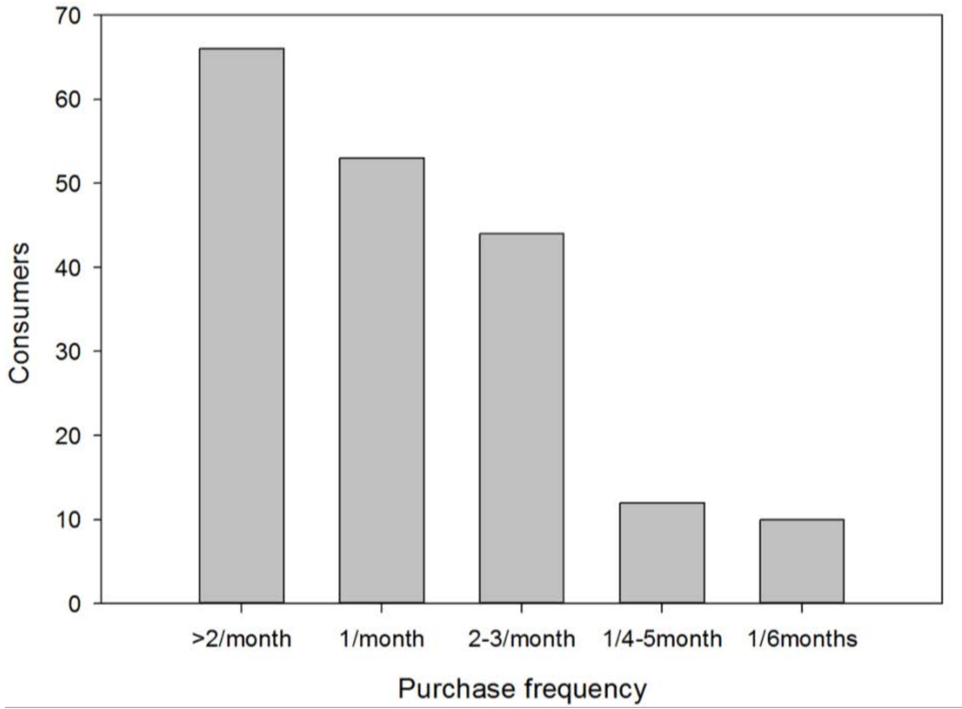
Supplementary equation 8.3

Supplementary Table 7.4 Results of chi-square and t-test confirming significant links between demographic data

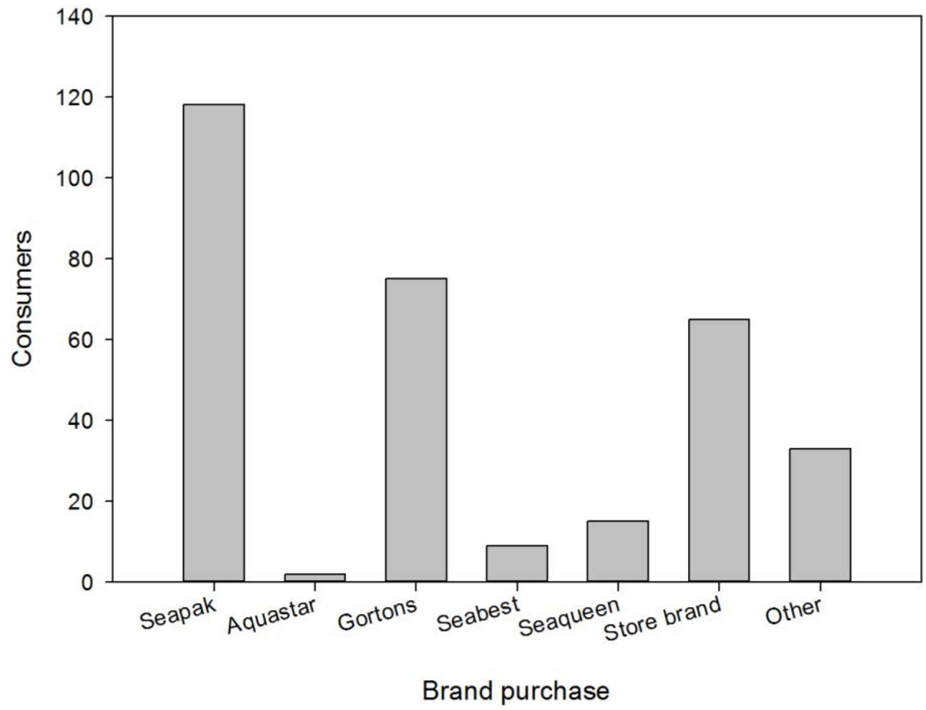
Variable	Observed Chi-square	Actual chi-square	p-value
Cluster group - age	7.650	18.307	0.700
Cluster group - gender	0.865	5.991	0.679
Cluster group – purchase frequency	8.804	15.507	0.359
Cluster group – brands	11.929	21.026	0.451
Purchase frequency - age	20.650	31.410	0.418
Gender- brand	2.005	12.592	0.919
Gender – purchase frequency	4.374	9.488	0.358
Gender- overall liking: fine	*t-test*		0.753
medium			0.626
coarse			0.644
Purchase intent-fine	27.917	15.507	**0.000**
Purchase intent-medium	16.715	15.507	**0.033**
Purchase intent- coarse	72.101	15.507	**<0.0001**
Cluster 1-expectations	78.601	15.507	**<0.0001**
Cluster 2-expectations	27.259	15.507	**0.001**
Cluster 3-expectations	14.986	15.507	0.059
Cluster 1-product quality	73.696	15.507	**<0.0001**
Cluster 2-product quality	25.458	15.507	**0.001**
Cluster 3-product quality	14.840	15.507	0.062



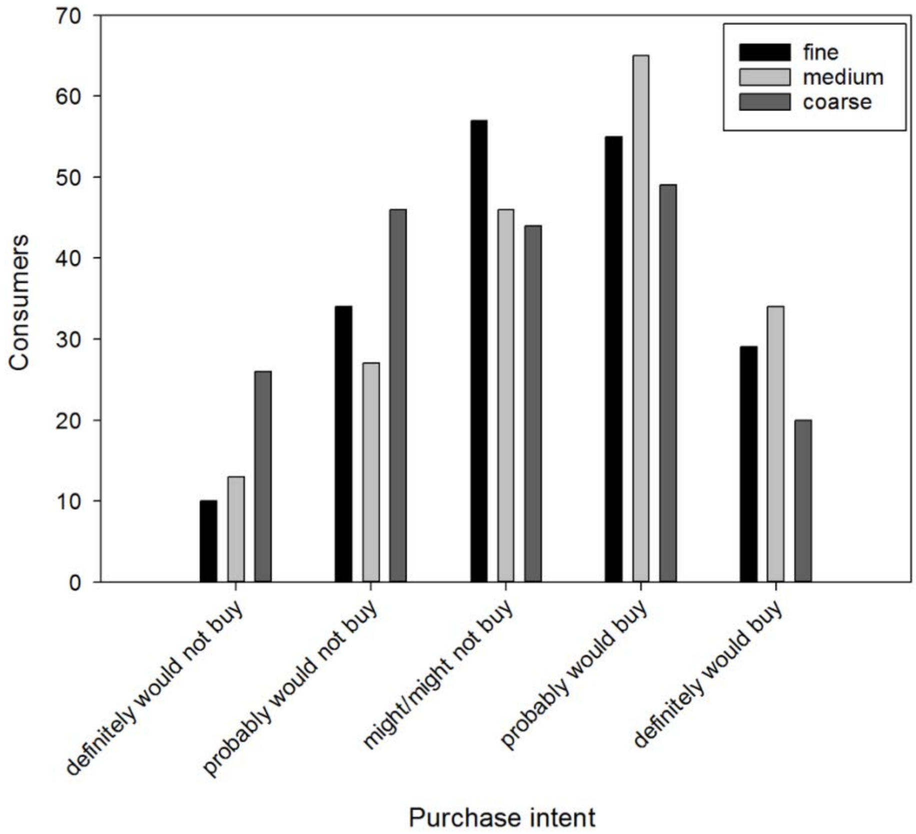
Supplementary Figure 8.3 Ages of consumers within each cluster group



Supplementary Figure 8.4 The purchase frequency of frozen snack/appetizers amongst all consumers.



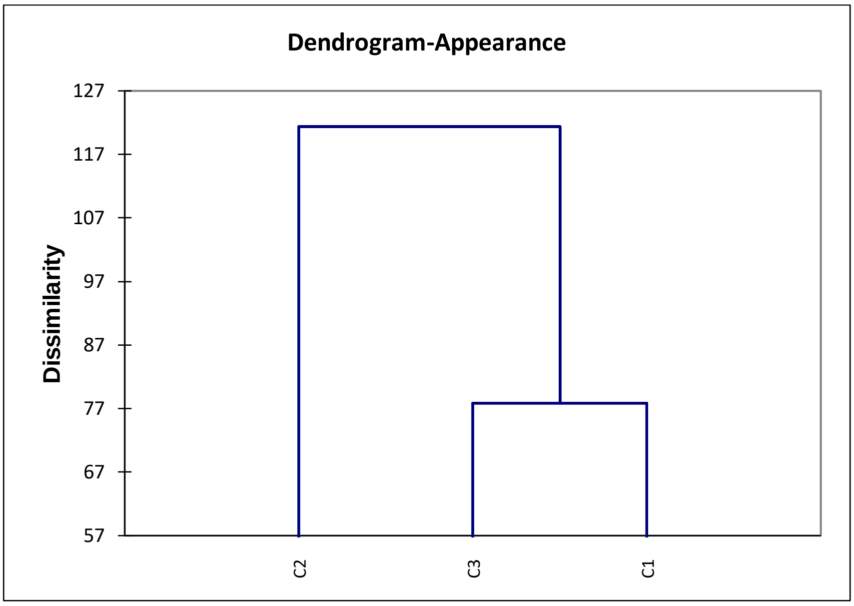
Supplementary Figure 8.5 CATA results showing current brands that consumers purchase, highlighting that Seapak has the highest brand purchase.



Supplementary Figure 8.6 Comparison of purchase intent of each sample.

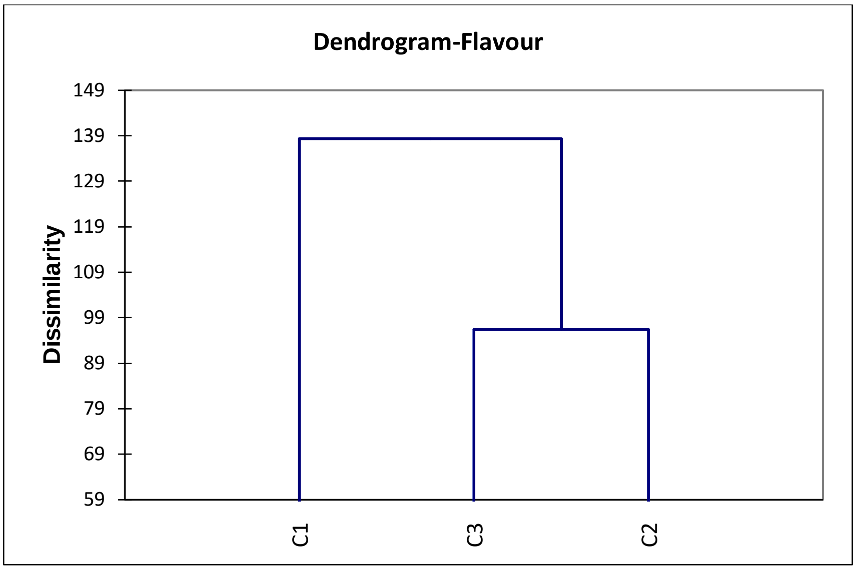
Supplementary Figure 5.4 displays the purchase intent of consumers upon evaluating each sample. ‘Medium’ samples appear to have the highest predicted success based on 53% of consumers would ‘probably buy’ or ‘definitely buy’. Consumers appear to be the most unsure about ‘fine’ samples as 31% of consumers stated ‘might/might not buy’. However, 45% of consumers stated they ‘probably would buy’ or ‘definitely would buy’. High purchase intent is also supported by high hedonic scores, as well as with penalty analysis, which highlights a high majority of consumers rate the sensory attributes of ‘medium’ samples to be just-about-right.

‘Coarse’ samples have the lowest purchase intent with 39% of consumers stating they ‘probably would not buy’ or ‘definitely would not’. However, with 37% of consumers stating 'probably would buy' or 'definitely would buy', this highlights that 'coarse' samples would suit a range of range of consumers but 'medium' samples appear to have the highest purchase intent.



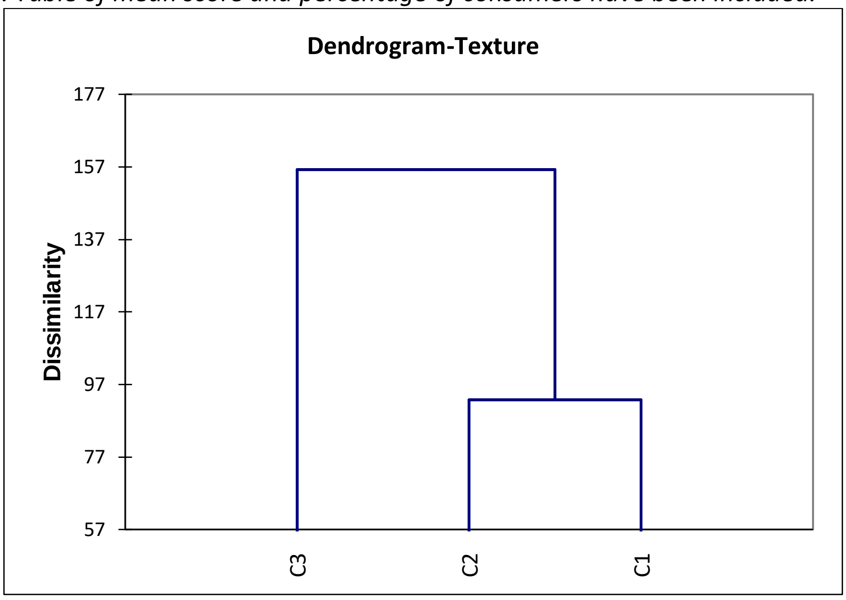
Class	Appearance sample - Fine	Appearance sample- Medium	Appearance sample- Coarse
1 = 54.1 %	6.360	6.770	3.760
2 = 29.7 %	4.800	6.691	6.727
3 = 16.2 %	7.267	4.433	5.667

Supplementary Figure 8.7 and Table 8.5 Agglomerative cluster analysis of consumers overall liking on samples appearance. Table of mean score and percentage of consumers have been included.



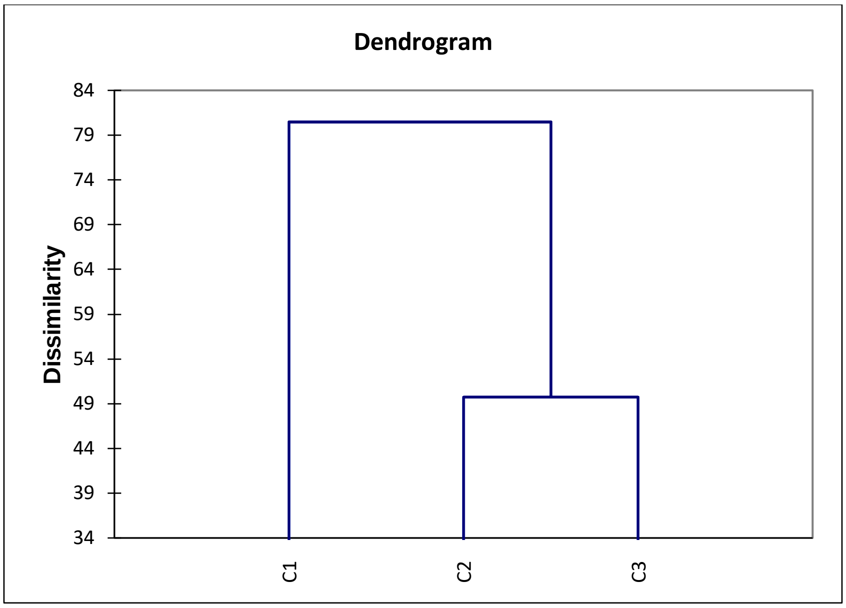
Class	Flavor sample -Fine	Flavor sample-Medium	Flavor sample-Coarse
1 = 21.6 %	7.525	5.225	6.775
2 = 25.4 %	4.936	6.723	7.532
3 = 52.9 %	6.939	7.327	4.816

Supplementary Figure 8.8 and Table 8.6 Agglomerative cluster analysis of consumers overall liking on samples flavour. Table of mean score and percentage of consumers have been included.



Class	Texture sample -fine	Texture sample -medium	Texture sample -coarse
1 = 37.2 %	6.565	**7.507**	4.043
2 = 30.2 %	**7.607**	5.571	6.375
3 = 32.4 %	4.900	7.033	**7.667**

Supplementary Figure 8.9 and Table 8.7 Agglomerative cluster analysis of consumers overall liking on samples texture. Table of mean score and percentage of consumers have been included.



Class	Colour sample -fine	Colour sample -medium	Colour sample -coarse
1 = 39.5 %	2.822	**4.000**	4.123
2 = 15.1 %	**3.607**	3.321	3.286
3 = 45.4 %	3.357	3.131	**4.405**

Supplementary Figure 8.10 and Table 8.8 Agglomerative cluster analysis of consumers JAR scoring on samples colour. Overall liking of colour was not tested. 1= much too light, 5 = much too dark.

Supplementary Table 8.9 Analysis of fatty acid % in frying oil of each fryer used in consumer study. High oleic acid refers to high monosaturated fats. Total average of 0.26 was calculated

Oil from Fryer #		**Reading off NaOH buret**	**mls of 0.1 N NaOH**	**AVG mls of 0.1 N NaOH = % Fatty Acid as Oleic**
1	start	15.6	0.3	0.3
	end	15.9		
	start	41.6	0.3	
	end	41.9		
2	start	41.9	0.2	0.25
	end	42.1		
	start	42.2	0.3	
	end	42.5		
3	start	42.5	0.25	0.225
	end	42.75		
	start	42.9	0.2	
	end	43.1		
				0.26

8.3 Ethics approval

Sensory and consumer work carried out in U.S. were approved using the sponsor companies internal ethics approval system. All participants recruited were screened according to age, gender, geographical location, allergies, dietary requirements, familiarity with brand. Prior to all sensory and consumer tests, panellists were presented with an information sheet detailing the objectives of the study. Panellists were also asked to sign a consent form confirming their awareness of the test requirements.

An example of the participant information sheet and consent form used are detailed below:

Participant information sheet

Researcher & Supervisors:
Amy Voong- University of Birmingham- [redacted]
Prof. Ian Norton-University of Birmingham-[redacted]
Dr. Tom Mills- University of Birmingham- [redacted]
Dr. Abigail Norton- University of Birmingham- [redacted]

Dear Sir/Madam
You have been invited to take part in a research study that aims to understand crispness perception.

What is the purpose of this study?
Crispness is an important and desirable textural characteristic that signifies freshness and high quality fried foods. Its perception is a combination of sound, texture and appearance and is therefore complex to characterise. This study aims to identify what the key attributes of a crisp product are and understand which attributes are the key drivers of crispness perception.

Do I have to take part?
It is entirely up to you if you choose to take part. You can choose to withdraw from the study without having to justify your decision. Participants can take part in either or both discriminative and descriptive testing. Descriptive testing will require additional training sessions and so will be more time-consuming. If you choose to withdraw, compensation will not be given as this is awarded for full participation.

What do I need to be aware of?
The product been assessed is a seafood product, therefore you need to make the panel leader aware if you have an intolerance to seafood or gluten.

What will happen if I take part?
The first part in this study will ask you to take part in a visual assessment of a product, which will take approximately 1 hour. The second part ask you to part-take in a group training session to develop a list of attributes to describe a key product, the purpose of this is to bring a consensus within the group of definitions of an attribute. After training, you will be asked individually to profile products using the list of generated attributes. Profiling sessions will require you to ingest the product, you will take part in 3 sessions, each session will take approximately 2 hours.

Will I be compensated for my time?
Yes, you will be compensated for full participation, this will be £20 per session.

What happens to the information collected in this study?
The information collected will contribute to towards a wider scope project carried out at University of Birmingham. All the information collected will be kept strictly confidential

Who is sponsoring this project?
This project is being funded by an industrial food partner.

We thank you for taking the time to read this sheet and considering taking part in this research study.

Project: Deep-fried coatings

Consent to take part in research

I voluntarily agree to participate in this research study. ☐

I understand that even if I agree to participate, I can freely withdraw at any time without being penalized or giving reason. ☐

I understand that withdrawing will result in not receiving compensation as this is given for full participation. ☐

I have had the purpose of the project explained to me and have had the opportunity to ask questions. ☐

I understand that I am free to contact any of the people involved in this study for further clarification or information. ☐

I understand that if I am participating in descriptive testing, I will be asked to ingest a seafood product. ☐

I understand that all information I provide in this study will be treated confidentially. ☐

I understand that any report of results from this study will keep my identity anonymous. This will be ensured by changing my name on the data collected. ☐

I understand that the signed consent form and all information that I provide will be retained with the manager of the project for the duration of the research project. All information will be held at University of Birmingham. ☐

I understand that if I inform the researcher that myself or anyone else is at risk or harm, they may report this to the relevant authorities. This will be discussed with me but may be required to report without my consent. ☐

Name of research participant (BLOCK CAPTIAL)	Signature of research participant	Date
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Name of researcher (BLOCK CAPTIAL)	Signature of researcher	Date