Investigating Product Behavior during Storage in Packaging Materials

A Study on Freshly Baked Croissants

PRIYANKA MEENA

MASTER´S THESIS

Packaging Logistics
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Food Innovation & Product Design

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Abstract

Food wastage during distribution, retail sale, and consumption is a concern of great worry. It not only affects the economics of businesses but also puts natural resources under severe stress. For example, in the UK some 800,000 tons of bakery products are purchased each year and never eaten, mainly due to short life span of the product.

Earlier investigations at Lantmännen Unibake, UK have identified the need of using appropriate packaging material for extending shelf life of pastries, such as croissants. However, there is a general lack of knowledge on the behavior of packed products in packaging materials that are currently available in the market. This thesis aims at bridging this gap in the knowledge following an empirical approach. It combines both quantitative and qualitative methods for analyzing product behavior.

The factors affecting the shelf life of baked croissants are loss of crispness of the crust, and increased firmness of the crumb. This is largely due to migration of water from crumb to crust during storage period. Currently *paper/polyethylene laminate*, *polyethylene terephthalate* and *polypropylene* materials are used to pack croissants by the In-store bakeries in the UK. However, the product shelf life is not more than 12 hrs. In the empirical studies conducted in this work, first, a market survey was done including visits to In-store bakeries in the UK market to identify various packaging materials and define the needs. Ten commercially available packaging materials were selected for investigation. The selected materials were described as monolayer film, multilayer flexible film and paper-base multilayer flexible film. The water vapor transmission rates of materials were in the range from 0 to 20 g m^{-2} day^{-1} (38 °C, 90% RH). Second, to understand the moisture migration phenomenon in unpacked and packed croissants quantitative measures such as croissants *moisture content* and *water activity* value were measured at 1 h, 6 h, 12 h, 24 h and 48 hrs after baking. Qualitative measures such as *texture analysis* and *sensory evaluation* were also performed to evaluate crispness of crust and firmness of crumb. The measurements for the materials were compared for differences with significance following the *analysis of variance* tests.

The study concludes that an optimal material for croissants packaging provides a controlled rate of moisture transfer in the product and the surroundings. The product crispness is lost at 6 h storage when it is packed, however, softness of crumb is preserved up to 24 h. The three suitable materials identified are: monolayer *oriented-polypropylene* film with perforations (WVTR of 10-14 g m^{-2} day^{-1}) and multilayer *oriented- polyethylene terephthalate* film with or without *ethylene vinyl alcohol* polymer (WVTR of 9.2-9.5 g m^{-2} day^{-1}). Using these materials the moisture migration phenomenon in croissants can be slowed down.

Executive Summary

Abstract

Very short shelf life of 'freshly' baked croissants is a growing concern for food retailers. It is affecting the economics of business, causing 10 to 40% in-store food wastage, and puts natural resources under severe stress. The factors affecting the shelf life are loss of crispness of the crust, and increased firmness of the crumb. This is largely due to migration of water from crumb to crust during storage period. Using appropriate packaging material the rate of moisture migration can be slowed down. Currently *paper/polyethylene laminate*, *polyethylene terephthalate* and *polypropylene* materials are used to pack croissants. However, the product shelf life is not more than 12 hrs. The study concluded that using monolayer *oriented-polypropylene* film with perforations (WVTR of 10-14 g m^{-2} day^{-1}) and multilayer *oriented- polyethylene terephthalate* film with or without *ethylene vinyl alcohol* polymer (WVTR of 9.2-9.5 g m^{-2} day^{-1}) the moisture migration phenomenon in croissants is slowed down. Further, the crispness of packed croissants was lost at 6 h storage, however softness of crumb is preserved up to 24 h.

Introduction

'Freshly' baked and unpacked croissants sold in the supermarkets today have a very short shelf life, of approximately 4 to 6 hrs. The consequence of short shelf life is increased food wastage in the stores that can range from 10 to 40%. This not only affects the economics of businesses but also puts natural resources under severe stress. For example, in the UK some 800,000 tons of bakery products are purchased each year and never eaten, mainly due to short life span of the product. Furthermore bakery products wastage has an ironic touch to it as discarded product is still suitable for human consumption. Identifying means to reduce wastage due to short shelf life of baked product is of key interest to the industry as well as for sustainable consumption.

The factors affecting the shelf life of baked croissants are loss of crispness of the crust, and increased firmness of the crumb. This is largely due to migration of water from crumb to crust during storage period. The migration of water can be slowed down by, for example, making changes in the formulation of product. However, this is often time consuming and an expensive process. Use of protective coatings such as, polysaccharides, fats, etc. is another alternative to slow down moisture migration. Yet another and a practical alternative is to use appropriate packaging material. Currently *paper/polyethylene laminate*, *polyethylene terephthalate* and *polypropylene* materials are used to pack croissants. However, the shelf life is not more than 12 hrs. Moreover, there is a lack of empirical evidence on how croissants change its properties during storage in packaging materials. In the absence of detailed empirical knowledge, it is not possible to find the most optimal packaging material. This thesis aims at bridging this gap in the knowledge following an empirical approach. It combines both quantitative and qualitative methods for analyzing product behavior.

Objective

The posed research question for study is could the migration of water in croissants be slowed down by use of packaging materials with varying water vapor barrier properties. At the same time, it is important that the croissants keep characteristic eating quality, i.e. crispness in the crust and softness of crumb up to 48 hrs. The study should be able to offer empirical evidence for making decisions on which material is best to extend the shelf life of croissants up to 48 hrs as demanded by the food retailers in the UK.

Method

In the empirical studies conducted in this work, first, a market survey was done including visits to In-store bakeries in the UK market to identify various packaging materials and define the needs. Ten commercially available packaging materials were selected for investigation. The selected packaging materials were described as monolayer film, multilayer flexible film and paper-base multilayer flexible film. The water vapor transmission rates of materials were in the range from 0 to 20 g m^{-2} day^{-1} (38 °C, 90% RH). Second, to understand the moisture migration phenomenon in unpacked and packed croissants quantitative measures such as croissant's *moisture content* and *water activity* value were measured at 1 h, 6 h, 12 h, 24 h and 48 hrs after baking. Qualitative measures such as *texture analysis* and *sensory evaluation* were also performed to evaluate crispness of crust and firmness of crumb. The measurements for the materials were compared for differences with significance following the *analysis of variance* tests.

Results and Discussions

It was found in the study that when croissants are packed the rate of moisture migration from crumb to the crust and subsequently to the surrounding atmosphere is slowed down. The slowed moisture migration is further influenced by the composition of packaging material and its water vapor barrier property. The product behavior during storage was acceptable in monolayer film and multilayer flexible film compared to the paper based multilayer flexible film. Further, it was observed that the packaging materials with very low and very high water vapor transmission rates are not suitable for croissants packaging.

Conclusion and Recommendations for future work

The study concludes that an optimal material for croissants packaging provides a controlled rate of moisture transfer in the product and the surroundings. The product crispness is lost at 6 h storage when it is packed, however, softness of crumb is preserved up to 24 h. The three suitable materials identified are: monolayer *oriented-polypropylene* film with perforations (WVTR of 10-14 g m^{-2} day^{-1}) and multilayer *oriented- polyethylene terephthalate* film with or without *ethylene vinyl alcohol* polymer (WVTR of 9.2-9.5 g m^{-2} day^{-1}). Using these materials the moisture migration phenomenon in croissants can be slowed down.

This study shows that approach to problems concerning moisture migration in the product requires understanding of the differences in the water activity within the product and its surrounding atmosphere. When selecting an optimal packaging material for a new product or a product with a formulation change the first step could be to obtain the product moisture sorption isotherm. This isotherm will give the critical values of moisture content and water activity. These critical values should be then tested for organoleptic acceptability using sensory evaluation methods.

As for further study, it can be an objective and future work to evaluate product behavior in customized monolayer-packaging material with optimal number of holes and hole size. It is recommended to include packaging design as a factor in investigation and consideration to get consumer feedback or a larger group of subjects for conducting product sensorial evaluation.

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Priyanka Meena

Lund, June 2015

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List of Abbreviations and symbols

Abbreviations

Alu	Aluminum
APET	Amorphous Polyethylene Terephthalate
ASTM	American Society for Testing and Materials
EVOH	Ethylene Vinyl Alcohol
HDPE	High-Density Polyethylene
IoFs	Indices Of Failures
ISBs	In-Store Bakeries
LDPE	Low-Density Polyethylene
LLDPE	Linear Low-Density Polyethylene
OPET	Oriented Polyethylene Terephthalate
OSL	Organoleptic Shelf Life
PA	Polyamide, Nylon
PE	Polyethylene
PET	Polyethylene Terephthalate
PP	Polypropylenes
rPET	Recycled Polyethylene Terephthalate

Symbols

a_w	Water Activity	-
a_{wc}	Critical Water Activity	-
J	Force	*Joules*
P/X	Water Vapor Permeance	cm^3 $(mm\ mm^{-2})$ $s^{-1} atm^{-1}$
MC	Moisture content	%
RH	Relative Humidity	%
Sq. ft.	Square Foot	-
T_g	Glass Transition Temperature	°*C*
μ	Thickness	*micron*
WVTR	Water Vapor Transmission Rate	$g\ m^{-2}\ day^{-1}$

1 Introduction

Food wastage at the end of the food chain – during distribution, retail sale and final consumption – is a concern of worry as it not only affects the economics of the businesses but also putting severe pressure on land and natural resources. From an economic perspective, the estimates indicate that in waste prevention alone businesses could save £0.1 billion (WRAP 2015). On the environmental front, research conducted by the UK's Waste and Resources Action Programme (WRAP) estimates that saving 15 million tons of food from wastage would prevent 60 million tons CO_2 equivalent greenhouse gas emissions. The major sources of greenhouse gas emissions and abiotic depletion in food category are meat products (37.4% and 29.8% respectively), dairy products (17.3% and 16.9% respectively) and bread and cereal products (9.3% and 10.8% respectively) (WRAP 2013). The EU and the UK have set their targets to halve food waste by 2025.

In the European Union (EU) countries and the United Kingdom, food wastage has an ironic touch to it as discarded food is still suitable for human consumption (FAO 2011). Reviewing food waste in bakery category, in the UK alone 800,000 tons of bakery products are purchased each year and never eaten, mainly due to short life span of the products. It is the fourth largest category for food waste (WRAP 2011). The biggest single reason for supermarkets to discontinue bakery lines from their 'freshly' baked section is due to high wastage levels and not poor sales. This waste can range from 10-40% (SIK 2014). A rising concern to bakery waste reduction can be seen amongst the food retailers. Stores have adopted increased activity of bake-off i.e. using frozen pre-prove dough or part-baked dough instead of making the dough using raw ingredients. Another visible pattern is to bake less bread more often, rather than larger volumes in one go, which often go to waste.

Identifying means to reduce wastage due to short shelf life of baked product is of key interest to the industry as well as for sustainable consumption. Earlier investigations at Lantmännen Unibake, UK have identified the need of using appropriate packaging material for extending shelf life of pastries, such as croissants. However, there is a general lack of knowledge on the behavior of packed products in packaging materials that are currently available in the market. This thesis aims at bridging this gap in the knowledge following an empirical approach. In the rest of this chapter outline on the goals and scope of work has been provided.

1.1 Shelf Life of Baked Products

A crisp crust with softer crumb is a salient textural characteristic for croissants and other ‘freshly’ baked products, such as, crusty breads, cream-filled pastry, Danish pastry and pie. Texture loss due to moisture migration (e.g. loss) shortens product shelf life. This in turn makes the product undesirable for consumption and leads to wastage. The shelf life of ‘freshly’ baked croissants is around 4-6 hrs. The product does not show staling as commonly observed in case of bread during storage (Cauvain & Young 2011). But shorter shelf life has significant impact on the economy of the bakery businesses and on the environment (WRAP 2011; WRAP 2013; SIK 2014). It has been demonstrated that the main reason for moisture migration observed in baked products is *water activity* (a_w) *gradients* within the product and its environment (Roudaut and Debeaufort 2010; Katz and Labuza 1981). The moisture transfer occurs from the region with high a_w value to a region with low a_w value. This phenomenon is well documented in case of bread where softening of crust and hardening of the crumb are related to moisture redistribution occurring during storage (Cauvain and Young 2007b), (Cauvain and Young 2010). In composite or multi-component foods, such as breakfast cereals, biscuits and ice cream wafers the a_w gradient and rate of migration is minimize by lowering final moisture content or by use of humectants (Labuza and Hyman 1998; Roudaut and Debeaufort 2010; Bourlieu et al. 2008). Moisture exchange between a product and its surrounding atmosphere can be controlled by adequate packaging material (Coles et al. 2003; Paine and Paine 1992).

1.2 Current Knowledge

Critical water activity (a_{wc}) value at which the textural quality of baked products becomes organoleptically unacceptable (in taste, color, odor, and feel) has been reported for bread, a_w range: 0.954-0.961 (Baik and Chinachoti 2000), puff corn curls and potato chips, $a_w > 0.54$ (Kulchan et al. 2010), saltine crackers, a_w range: 0.35-0.5 (Katz and Labuza 1981), sponge cake, a_w value 0.88±0.01 (Dury-Brun et al. 2006). However, there are no precise limits in pastry and laminated products because the critical water activity varies according to product type. Moreover, it cannot be hard-fixed as consumer preference also influences the level of desirable moisture content in the product (Cauvain and Young 2008).

The effect of packaging material on restraining the moisture loss from pastry and laminated products has not been explained in the literature by the bakery technologists. The moisture barrier of packaging material is a critical property in bakery applications and various investigators have tried to impede the loss of moisture from product crust by wrapping in materials with low water permeability. However, there is a lack of empirical evidence on how product behavior changes during storage in packaging materials that are currently available in the market. In the absence of this knowledge, it is not possible to find the most optimal packaging material.

The literature review made in this thesis suggests that the moisture migration phenomenon in a product can be slowed down. (Cauvain and Young 2008) suggested following three approaches:

i. Lowering the rate of water transport to the crust. This entails changes in the formulation of product. However, this is often time consuming and an expensive process.
ii. Lowering the rate of water uptake by the crust. This is achieved by using protective coatings of polysaccharides, proteins, fats, etc. However, the use is limited to product types.
iii. Increasing the ratio of water activity of the crust over relative humidity of the environment. This can be achieved using an appropriate packaging material. A practical and less time consuming process.

This study takes the third approach and investigated whether moisture migration in croissants is slowed down by use of packaging material at the same time keep characteristic eating quality-crispness in the crust and softness of crumb.

1.3 Aim of this Thesis

The posed research question for study is can the migration of water in croissants be slowed down by use of packaging materials with varying water vapor barrier properties. The main objective of this thesis is to investigate the interaction between the baked product (croissants), the surroundings and the packaging material. The interactions are to be observed through deliberate product analysis of both quantitative and qualitative measures. Identifying the appropriate quantitative and qualitative measures is also a sub goal of this thesis. The study should be able to offer empirical evidence for making decisions on which material is best to extend the shelf life of pastries (croissants) up to 48 hrs as demanded by the food retailers in the UK.

1.4 Focus and Delimitations

The research work targets ‘freshly’ baked croissants sold in the In-store bakeries in the UK. The study is carried out in the baking facilities of Lantmännen Cerealia, Malmö. Frozen croissants are received from the Lantmännen Unibake, Belgium. The baking parameters and sensory evaluation scorecards are standards obtained from Lantmännen R&D labs. Commercial available packaging materials are selected for investigation. The material suppliers do not share the information on material water vapor permeability and composition percentage as this information is treated as confidential. The comparison made when discussing different materials is based on properties found in the literature. Material costs aren’t taken into consideration as only the best materials for shelf life extension is considered. Packaging prototype is developed to identify the needs and know if packaging design should be used as a factor in the empirical investigations in this work. The experiments are performed at ambient temperature and relative humidity conditions. The results of this thesis are therefore for readily applicable to the In-store bakeries.

1.5 Outline of Thesis

Chapter 2 provides the relevant literature on this topic. This includes product classification, manufacturing and shelf life consideration and approach to measure changes in product behavior.

Chapter 3 on Requirement Analysis identifies product and packaging needs by considering the manufacturing, marketing and supply chain perspective. It is the very first step in developing a framework for packaging development project. This Chapter discusses the survey and requirements analysis during the visits made by the author to the R&D facility in Belgium and the UK market where the croissants are sold.

Chapter 4 describes the approach and experimental design for the empirical investigation.

Chapter 5 presents the observations made during the experiments in the in-lab facility and discusses their relevance to the study at hand.

Chapter 6 summarizes the conclusion of this thesis and offers ideas for future work.

2 Frame of Reference

This chapter presents the literature and theoretical details relevant for meeting the objectives of this thesis as outlined in Chapter 1. The chapter starts with the description and manufacturing process of croissants. Existing knowledge on products similar to croissants could be useful to understand behaviors not yet well understood. Following this the factors affecting the products shelf life are discussed. Sufficient details are presented for calculation of various measurable parameters. Many of these measures will be part of the experiment design discussed later in this thesis.

2.1 What is a Croissant?

Information on product classification is necessary to gain knowledge on similar or related food category, and understanding of the food regulator requirements. Moreover the broader context in which product is referred in the literature needed to be narrow down.

Croissants and pastries are small size bakery products classified under 'fine bakery wares' by EU legislation. There is no legal definition for such a classification but attempts have been made in literature to provide a definition (Cauvain and Young 2007a) as shown in Figure 1. One such attempt divides pastry into two groups based on the proportions of fat in the recipe and resulting texture; (i) Short pastry (leavened pastry with fat content between 40-50 g/100 g flour, and a soft and tender texture) and (ii) Puff pastry (non-leavened pastry with fat content between 15 g/100 g flour, and a light and flaky texture). Croissants with other similar products, such as Danish pastries, torte cakes, quiche, crème horns, strudel etc., are grouped together under puff pastry. But Cauvain and Young preferred to separate croissants and Danish pastry from puff pastry, as the former two products contain bakers' yeast.

Thus, some literature refers croissants as 'yeasted pastry' or 'specialty fermented product'. Sometime it is also referred to as 'Laminated products' owing to its characteristic way of making using sheeting and folding process to form alternating and discrete layers of dough and fat. In a broader context it is grouped with other products like breads, cakes, biscuits, cookies and crackers under the term 'baked products'. In this study the classification of croissants is followed as illustrated in the Figure 1.

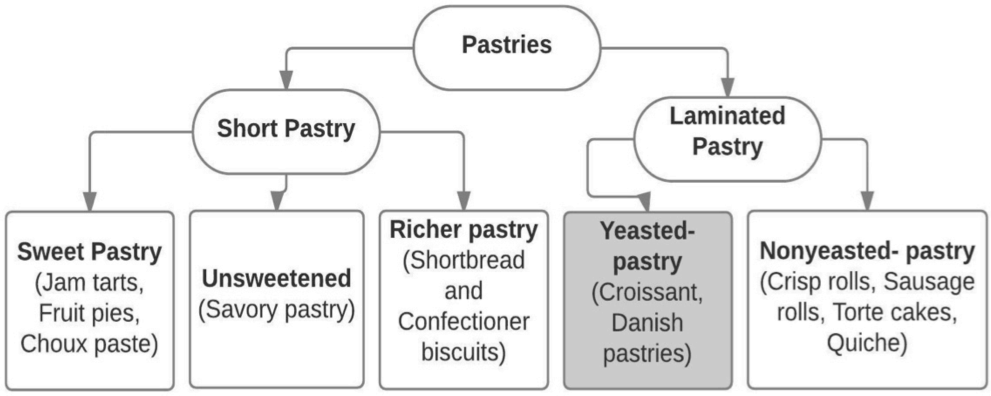


Figure 1: Illustration of the classification of croissants and pastries by (Sievert et al. 2007; Cauvain and Young 2007a). The study will follow this classification of croissant.

2.2 Process of manufacturing Croissants

The knowledge of product manufacturing process and quality assessment techniques used by food manufacturers is vital for experiment design. An overview of manufacturing process is given below and information on quality assessment techniques is discussed in the following chapter 4.

An overview of different steps involved in frozen dough croissant manufacturing and baking is represented in the Figure 2. The main controlling factors during production are: (i) water level in dough, (ii) laminating-fat temperature, and (iii) laminated-dough processing temperature. The major ingredients used on percent flour basis are: wheat flour (100%), shortening (8%), water (52%), yeast (6%), sugar (6%), salt (2%), emulsifiers (< 2%) and/or eggs (2%) and laminating butter/ margarine (50-57%). Further detail can be referred in (Sievert et al. 2007; Cauvain and Young 2007a).

The characteristic 'flaky' structure and crisp eating quality of croissant is a result of series of sheeting and folding process that forms alternating layers of dough and fat. Crackers and Marie-type laminated biscuits are also subjected to a similar form of dough folding and laminating process (Cauvain and Young 2008).

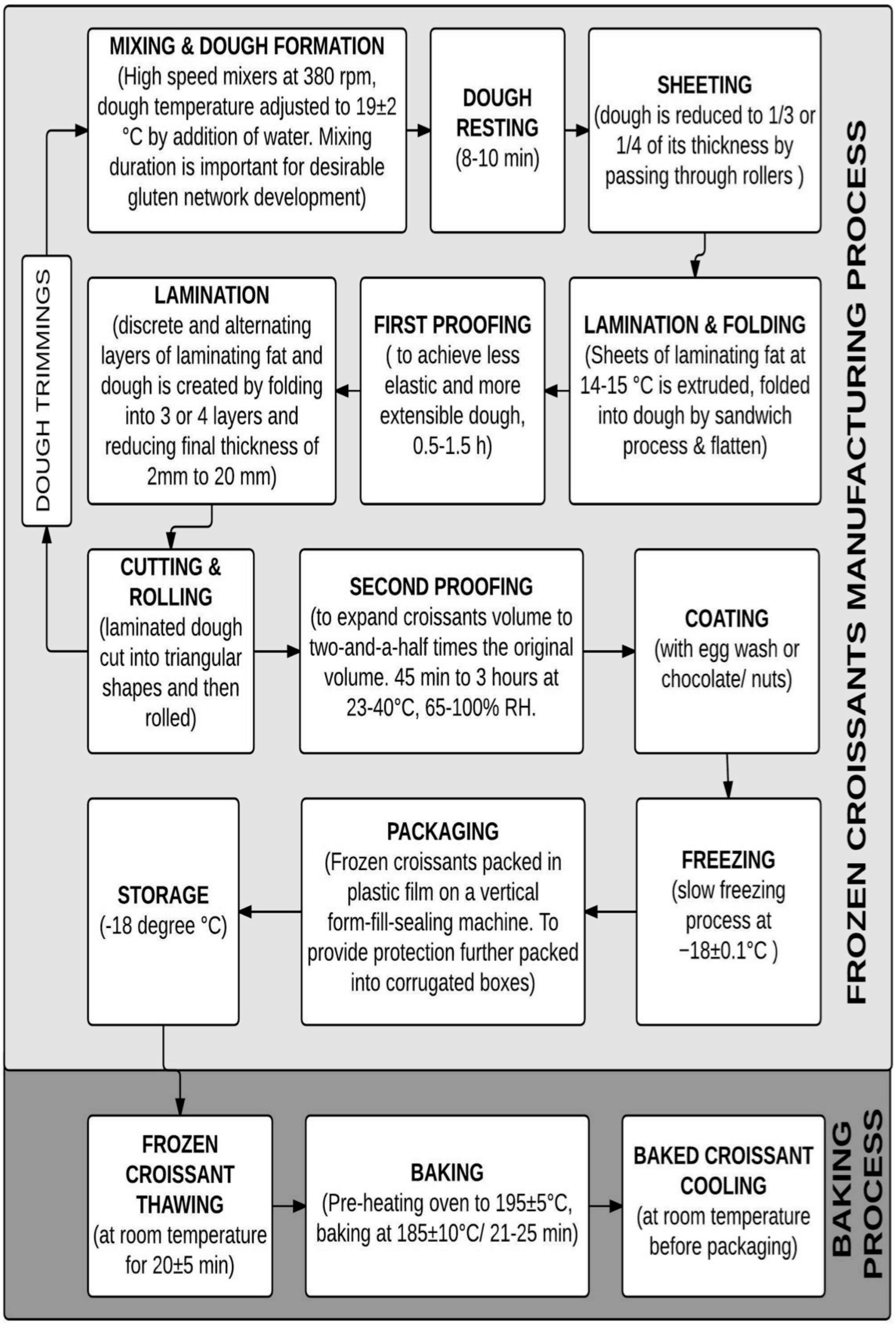


Figure 2: General flow chart of frozen-dough croissant manufacturing. Adapted from (Baking Industry Research Trust 2011; Cauvain 2001)

In comparison to the bread manufacturing, the amount of water added at the dough making stage is kept minimum because much of the water is baked out in the oven to give a crisp eating character to the croissants. The baking is performed at 180 ±5° C for 20±5 minutes. The level of fat used is much higher (up to 15% of butter fat or 16.6% margarine) and plays little role in formation of base dough characteristics. The fat, commonly known as roll-in-fat/laminating-fat, plays a significant role during baking. The formation of gluten network is not as extensive as in bread. Comparatively the dough has good extensibility, low elasticity and low resistance to deformation (Cauvain and Young 2008).

2.3 Shelf life Considerations

The shelf life of a baked product as defined by (Cauvain and Young 2010) is the duration for which it will retain an acceptable level of eating quality from a safety and organoleptic point of view. For baked products (i) Mould free shelf life (MFSL) and (ii) Organoleptic shelf life (OSL) are defined as the acceptable levels. Figure 3 provides a summary of factors – intrinsic, extrinsic and implicit – influencing shelf life of pastries and baked products. In this thesis the investigation is limited to intrinsic factors such as water activity and moisture content, and extrinsic factors such as packaging.

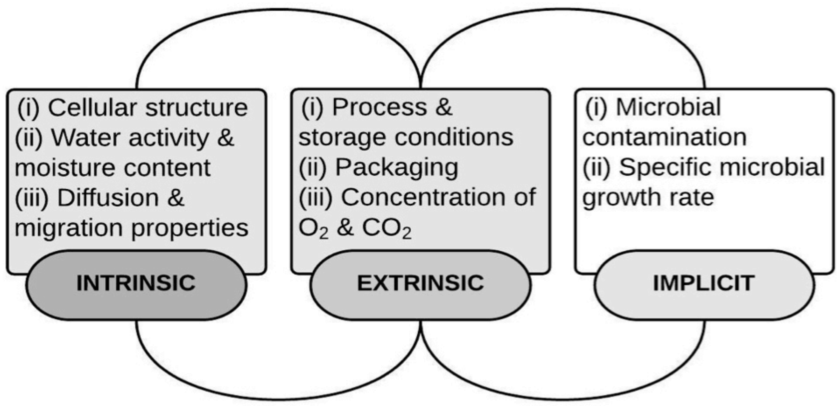


Figure 3: Factors influencing shelf life of pastries. Adapted from (Galić et al. 2009).

Shelf life estimation studies that involve evaluation of suitable packaging material or design, (Robertson 2011a) gave three step framework reference:

Step 1: Identify and Define the Indices of failure (IoFs) of the product.

Step 2: Quantify the magnitude of particular degradation in the product as quantitative or qualitative measures.

Step 3: Determine which of the selected IoFs the packaging material might influence, as packaging cannot prevent all undesirable changes in foods.

The layout of this section is based on aforementioned three steps. This section offers knowledge for selection of quantitative and qualitative measures that are used in experiment design.

2.3.1 Step 1: Defining Indices of Failure (IoFs)

IoFs are the quality attributes that indicate that the food is no longer acceptable to the consumer (Robertson 2011a). Identifying particular degradation in product is however the first step in defining the shelf life. Commonly observed IoFs in pastries and other baked products are summarized in Table 1 below:

Table 1: Indices of failure (IoFs) observed in croissants and baked products. Adapted from (Cauvain and Young 2010; Kong and Singh 2011)

Product category	Indices of failures	Deterioration mechanism
Croissants, Danish pastry	Loss of crispness, increase in crumb firmness	Moisture migration
Short-Pastries	Crust softening, shrinkage of filling, mould growth	Moisture uptake by crust and loss by filling
Unyeasted pastries	Crust softening, shrinkage of filling	Moisture migration
Biscuits, Crackers	(i) Loss of crispness (ii) Rancidity	(i) Moisture uptake (ii) Oxidation
Breads	(i) Stale texture and flavor (ii) Dry texture, mould growth	(i) Starch retrogradation (ii) Moisture migration
Cakes	(i) Dry/crumbly crumb (ii) Mould formation	(i) Moisture loss (ii) Microbial growth

2.3.2 Step 2: Quantifying the Magnitude of Degradation

Once identified the IoFs the next step is to select and quantify the particular degradation in product. The quantification of selected degradation in product can be done using objective (instrumental) and subjective (sensory) test methods.

The IoFs identified and selected in croissants is loss of crust crispness and increased crumb firmness during storage. Crispness of crust and moist/soft crumb is associated with product freshness (Cauvain and Young 2008; SIK 2014). Knowing croissants moisture content, water activity and relationship between the two measures it is possible to quantify the IoFs in croissants. The knowledge on MC and a_w further provides information on its influence on croissants texture.

2.3.2.1 Moisture Content and Water Activity

Moisture content of baked products is an important factor in determining their quality (Sievert et al. 2007). Microbial growth, organoleptic degradation, functional and structural qualities, non-enzymatic browning, lipid oxidation, textural changes, and aroma retention are all related to the moisture content. The percentage of total amount of water content in product is expressed as *moisture content* (MC). Traditional approaches to measure moisture content are (i) vacuum oven drying with a desiccant and (ii) titration method using Karl Fischer reagent. However, usage of electrical instruments for fast and accurate results is common in bakery industries. Infrared-direct heating meter is one such instrument that calculates moisture content based on the weight losses during a preset heating parameter. The percentage moisture content can be expressed using following mathematical expression, Equation 1 (Cauvain and Young 2008):

Equation 1:

$$Percentage\ moisture\ content, \%\ MC = \frac{[(M_o - M_t) \times 100]}{M_o}$$

Where M_o is the initial moisture content of product and M_t is the moisture content of product at time *t*.

The *water activity* (a_w) of a product is commonly used to establish critical moisture content for mould free shelf life and organoleptic acceptance of baked products. It is a physical-chemical property of water in a product, and is mathematically expressed as shown in Equation 2 (Roudaut and Debeaufort 2010):

Equation 2:

$$water\ activtiy, \qquad a_w = \frac{p}{p_0} = \frac{\%\,ERH}{100}$$

Where *ERH* is the equilibrium relative humidity, p is the actual vapor pressure of water in the sample and p_o is the vapor pressure of pure water.

If value of a_w can be determined as critical a_w, based on the correlation between a_w and target quality parameter (for example, crispness of moisture-sensitive product), the shelf life can be studied by monitoring the change of a_w of the product. Also, by knowing the critical water activity limits of a product it is possible to calculate shelf life based on the relevant barrier properties of the packaging material or dictate the barrier specification of the package to obtain a desired shelf life. Water activity of a product is measured using either a resistive hygrometer or a dew point hygrometer (Roudaut and Debeaufort 2010). Table 2 provides information on MC and a_w values of croissants and other baked products.

Table 2: Moisture content and water activity level in croissant crust and crumb, and other baked products. (Cauvain and Young 2008; Dury-Brun et al. 2006; SIK 2014)

Product	MC	a_w
Croissants crust	8-10%	0.59-0.61
Croissants crumb	30-33%	0.92-0.94
Crackers, Cookies	5-10%	0.2-0.3
Danish pastries	Up to 15%	0.82-0.83
Flan, Quiche	Up to 15%	0.72
Bread	38-41 %	0.96-0.98
Sponge cake	34-36%	0.87-0.89

2.3.2.2 Relationship Between MC and a_w

An increase in MC is usually accompanied by an increase in a_w but the correspondence is not linear. For each bakery product, this unique and complex relationship between its MC and a_w is expressed at a given temperature as Moisture Sorption Isotherm (MSI). MSI is the key to understanding and controlling product formulation, stability, moisture sensitivity, and packaging design (Roudaut and Debeaufort 2010). In this work the literature review did not provide the information on MSI for croissants. However, considering its importance in context to shelf life considerations the discussion is provided below.

For most baked product (with a_w ranges in 0.6–0.85), MSI are sigmoidal in shape, as illustrated in Figure 4. Although products that contain large amounts of sugar or small soluble molecules have a J-shape isotherm curve shape. A detailed discussion of MSI can be obtained from American Association of Cereal Chemistry (AACC).

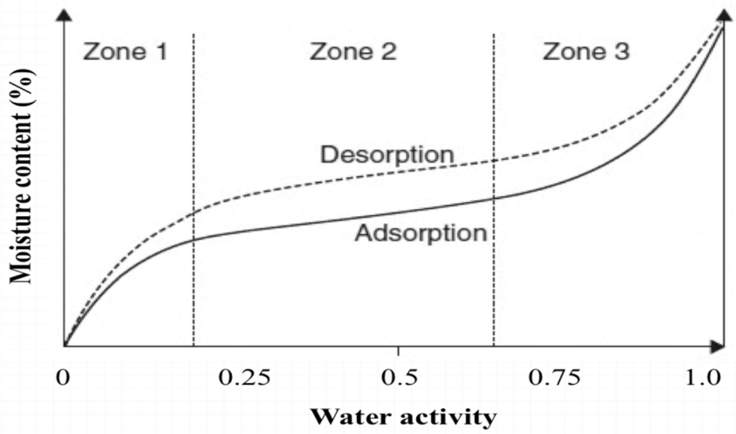


Figure 4: Typical food moisture sorption isotherm as a function of moisture content and water activity. Adapted from (Roudaut and Debeaufort 2010)

MSI is obtained from the equilibrium moisture content determined at several a_w levels at constant temperature in a controlled humidity chambers. An adsorption isotherm, the dotted-line curve in Figure 4, is obtained by placing completely dry baked-product into various atmospheres of increasing RH and measuring the weight gain caused by uptake of water. A desorption isotherm, solid-line curve in Figure 4 is obtained by placing an initially wet material under the same RH and then measuring the weight loss. The Zone 1 is '*monolayer adsorbed moisture*' which corresponds to van der Waals interactions between hydrophilic parts of the product and water molecules. Thus, this water is strongly bound, not available for microbial growth and represents the glassy state (discussed in section below) of product. Zone 2 is '*multilayer moisture*' held in the matrix by capillary condensation, is available as a solvent for low-molecular weight solutes and for biochemical reactions. This water does not freeze at normal freezing point. Zone 3 is '*free water*' in liquid state, available for microbial growth. More information can be referred in (Roudaut and Debeaufort 2010; Decagon Devices 2011).

Using information from the MSI curve and depending on the product's sensitivity to moisture and the type of conditions it may be exposed to the shelf life of packaged food can be estimated using the following Equation 3 and Equation 4 (Decagon Devices 2011):

Equation 3:

$$Shelf\ life\ of\ packaged\ product, \qquad T_{shelf} = -\tau \times \ln\left(\frac{h_a - a_{wc}}{h_a - a_{wo}}\right)$$

Where h_a is the humidity of the air, a_{wc} is the critical water activity of the product, a_{wo} is the initial water activity of the product, T is the time in the package and τ is the time constant, is given by Equation 4:

Equation 4:

$$Time\ constant, \qquad \tau = \frac{\alpha \times p_a \times M}{e_s \times A \times MVTR}$$

Where α is the slope of the moisture sorption isotherm, p_a is the atmospheric pressure, M is the total mass of product inside the package, e_s is the saturation water vapor pressure at package temperature, A is the package surface area and $MVTR$ is the *water vapor transmission rate* (g m^{-2} day^{-1}) discussed further in section 2.3.3.1.

It is important to note that the Equation 3 and Equation 4 can be used only under the assumption that the product and the environment are at the same temperature, and that the permeability of the package is low enough so that changes in water activity are uniform over the entire product inside the package (Decagon Devices 2011).

2.3.2.3 Influence of MC and a_w on Product Texture

The texture, *crispness* of crust and *softness* of crumb is a well known critical property of croissants and related pastry product. Consumers associate it with product freshness. Various studies on texture indicates that if the MC or a_w of the product increases, loss of crispness and increased firmness is then observed (Roudaut et al. 1998; Roudaut and Debeaufort 2010; Kulchan et al. 2010; Cauvain and Young 2008; Katz and Labuza 1981). In croissants the increase in MC of crust due to moisture migration (discussed in section 2.4) from the crumb results in loss of crispness of crust. Consequently firmness of crumb increases with progressive moisture loss until the thermodynamic equilibrium is achieved between the crust and crumb.

Texture can be measured by means of objective (instrumental) and subjective (sensory) test methods. As a definition, crispness may be associated with a combination of the high-pitched sounds and the crumbling of the product as it is crushed through (Roudaut and Debeaufort 2010). A number of instrumental (force-deformation measurements), acoustic and sensory methods are available to evaluate crispness. (Roudaut et al. 1998) suggested that best correlations of sensory and instrumental data for product crispness is obtained by using both acoustic and force-deformation measurements. Firmness is commonly measured using instrument, such as Texture Analyzer, where the sample is subjected to compression force, which mimics the subjective measurement of crumb texture made by the fingers during squeezing (Cauvain and Young 2010). Use of instrumental texture analysis tests as an indication of the sensory texture is common in biscuits and bread (Baik and Chinachoti 2000; Lawless and Heymann 1999). However, there is no scientific consensus about the test and probe types that can be correlated with the sensory texture of pastries.

The product texture, especially crispness of baked product, is strongly affected by its glass transition temperature (T_g) that is further influenced by its MC or a_w changes during storage (Sievert et al. 2007). T_g is a property exhibited by the amorphous regions within a product, which is not in a thermodynamic equilibrium unlike the crystalline glassy regions. During product storage these amorphous regions undergo state change in presence of the Zone 2/Zone 3 MC (Figure 4), causing change in product texture. To understand T_g '*state diagram*' is used, in this study the 'state diagram' for cereal material is adopted from D. Sievert (Sievert et al. 2007).

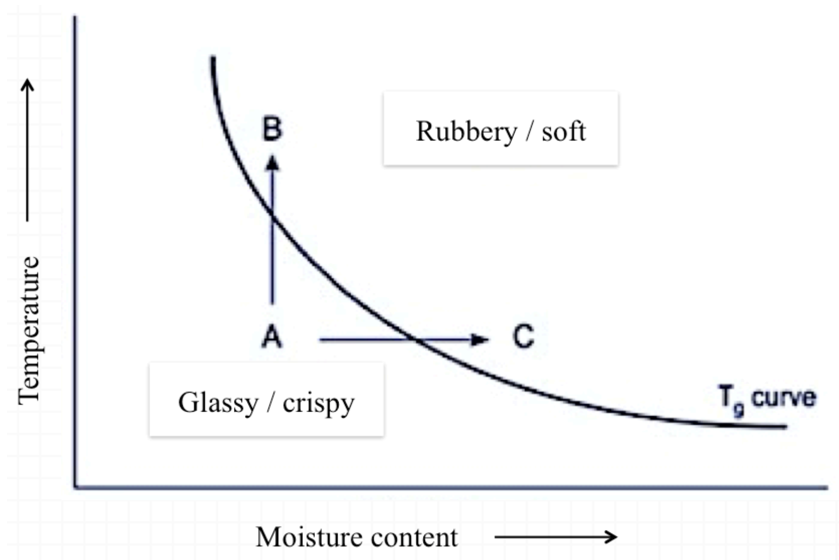


Figure 5: Idealized state diagram of a cereal material as a function of temperature and moisture content. An increase in temperature or moisture content results in texture change (Phase transition) from point A to B/C. Adapted from (Sievert et al. 2007)

In Figure 5, 'A' is the assumed starting point of a baked product with *Glassy/crispy* texture showing transition to a *rubbery/soft* texture as a result of temperature or moisture content increase.

$$Phase\ transition\colon\ A(Glassy/Crispy) \rightarrow B\ (Rubbery/Soft)$$

The *state diagram* described by (Sievert et al. 2007) defines the moisture content and temperature region at which food domain shows glassy (crispy) or rubbery (soft) behavior. From Figure 5 plot it can be seen that if product starts at point 'A' in the glassy (crispy) region and moisture content increases, the product goes from glassy to rubbery (soft), even if the temperature remains constant. Likewise if the temperature of product is raised, it will become soft. In other words, a baked product above its T_g will lose the crispness (Sievert et al. 2007). For example, when a crispy cracker of low water activity ($a_w = 0.4$) is in direct contact with jam of high water activity ($a_w = 0.84$), it absorbs water and becomes rubbery (Kim et al. 1998). Similar results are reported by E. E. Katz in chips, saltines, crackers and popcorn where product crispness is lost if water is gained to reach $a_w > 0.35$-0.5 (Katz and Labuza 1981). Dry foods in a semi-permeable pouch that allows influx of water vapor can show similar glass-to-rubber transitions (Nagi et al. 2012). There is no direct link between measured a_w and T_g but in general a product with highest a_w will also have the highest T_g (Cauvain and Young 2007a). This makes measurement of a_w of baked products even more important parameter for predicting its storage stability, potential changes in textural properties and in understanding moisture transfer.

2.3.2.4 Pastry Lift

The quality of laminated pastry is determined by the volume rise during baking. The rise in volume depends on moisture loss during baking and the resulting structural rigidity. During baking water in dough layers evaporates as steam. The generated steam diffuses through laminating-fat layers, but as the fat is melting steam gets trapped causing increase in vapor pressure. The increased vapor pressure force separate the dough layers giving pastry a lift. The resulting alveolar structure is characterized with large, irregular bubbles. Most of the expansion of laminated pastry occurs in first half of the baking time.

The pastry volume is measured using automated laser topography as an alternative to seed displacement method. It maps height, length, width and volume, and produces a 3-dimensional rotatable product image. Product weight, specific volume and density can also be reported. A simple mathematical expression for this is given in Equation 5 (Wickramarachchi et al. 2015):

Equation 5:

$$Specific\ volume = \frac{Baked\ pastry\ volume\ (cm^3)}{Paste\ weight\ before\ baking\ (g)}$$

2.3.3 Step 3: Packaging Considerations

The key properties of packaging material related to shelf life considerations discussed in this section are *barrier properties*, *surface area to volume ratio* and *closure integrity*.

2.3.3.1 Barrier Properties

The moisture barrier of packaging material is the critical property in bakery applications as baked products are sensitive to moisture. Plastic polymers used for moisture barrier include LDPE, LLDPE, or PP. Appendix 8.4 provides information on material properties. Applications, such as biscuit and crackers along with the moisture barrier also require aroma and taste barrier properties. Polyamide (nylon) is used for taste and aroma barrier. In bread bags, the LLDPE polymer's toughness allows down gauging (reducing material thickness), while LDPE allows good optics and printability (Butler and Morris 2013).

The moisture barrier property of packaging material is defined either as *water vapor permeance* (P/X) or as *water vapor transmission rate* (WVTR). Water vapor permeance is the property of the packaging 'polymer' and WVTR is the property of packaging 'material'. The mathematical expression for permeance of a monolayer material structure of uniform thickness is derived from Fick's first law, Equation 6 (Robertson 2011b):

Equation 6:

$$Water\ vapour\ Permeance, \qquad \frac{P}{X} = \frac{Q}{A \times t \times (\Delta p)}$$

Where P is the permeability coefficient of vapor through the polymer, X is the polymer thickness, Q is the amount of permeant (gas or vapor) passing through the polymer, A is the surface area, t is the time and (Δp) is the partial pressure gradient.

Equation 6 can also be used to estimate permeance for multilayer structure by first obtaining the permeability coefficient of each layer as shown Equation 7 (Butler and Morris 2013):

Equation 7

$$Net\ permeation, \qquad {}^{1}\!/_{P} = {}^{X_1}\!/_{P_1} + {}^{X_2}\!/_{P_2} + \cdots + {}^{X_n}\!/_{P_n}$$

Where X_n is the polymer n layer thickness ratio and P_n is the polymer permeation coefficient.

The permeability coefficient of a polymer is temperature dependent measure. Its value determined at one temperature may not be same at the other temperatures. (Robertson 2011b) provided the Arrhenius-type equation which is use to represent the relationship and temperature dependence of permeability coefficient, shown in Equation 8 (Robertson 2011b):

Equation 8:

$$P = P_0 \times e^{\left(-E_p/_{RT}\right)}$$

Where P_0 is the permeation value at given temperature, Ep is the apparent activation energy for permeation, R is the gas constant and T is the absolute temperature.

MVTR is the steady water vapor flow in unit time through unit area of a body, normal to specific parallel surfaces, under specific conditions of temperature and humidity at each surface (ASTM E96M-14). The water vapour transmission rate (WVTR) of material is calculated using the Equation 9 (Robertson 2011b):

Equation 9:

$$Water\ vapour\ transmission\ rate, \qquad WVTR = \frac{Q}{A \times t}$$

Where Q is the amount of permeant (water vapor) passing through the polymer, A is the surface area and t is the time.

When a comparison is required between two barrier polymers, the comparison should be based on an equal water vapor transmission rate and package surface areas at the target temperature and humidity conditions. (Butler and Morris 2013) gave following equation to determine the best barrier polymer value, Equation 10:

Equation 10:

$$To\ determine\ best\ barrier\ polymer\ value, \qquad WVTR = \frac{P}{X} \times \frac{A}{100}$$

Where, P is the permeability coefficient of vapor through the polymer, X is the polymer thickness and A is the surface area.

2.3.3.2 Surface Area To Volume Ratio

The literature review made in this study further suggests that dimensions of the package may influence the shelf life of baked products. For same product packed in different volume/ weight in package with varying sizes, a smallest package will have the shortest shelf life. This is due to the inevitably greater surface area per unit volume of smaller packages (Robertson 2011b). Therefore bakery packages tend to be rectangular in shape. A spherical shape can minimize the surface area of package but it is not commonly used considering the negative impact on supply chain efficiency. Also, to have similar shelf life of product packed in different package sizes it is important to consider different packaging materials that can offer similar properties.

2.3.3.3 Package Closures and Seal Integrity

In baked products, like biscuit and crackers, adequate closure or sealing of the package is essential to avoid moisture uptake by the product. In case of bread, moisture uptake is not a concern therefore a twist-and-clip type closure is acceptable. Paper bags are coated with PP layers to enable closure by heat-seal and increase barrier properties. Typically, EVOH polymers are used for sealability in bakery application (McKeen 2013).

Heat-seal property of material is influence by polymer's thermal and rheological properties, seal-bar temperature, pressure and configuration and package design (McKeen 2013). A thicker packaging structure will require longer time for a given seal-bar temperature to reach a same heat-seal strength as thinner structure. Heat sealability of polymer is important when using vertical form-fill-sealing machines. The filled product weight puts a force on the seal while polymer is still hot. Thus ability of polymer to maintain seal integrity is important consideration in material selection. It is equally important in horizontal form-fill-seal (HFFS) application, particularly in gusseted areas where the material film is folded.

Resealable packages for 'freshly' baked cookies have added the convenience feature but once opened the moisture uptake by product reduces its organoleptic shelf life. However, various resealing closures promises pack integrity after opening. Some of the common types of resealing closures are shown in Figure 6 below. These closures are made of LDPE or HDPE material offering intuitive sealing (self mating, multi align and audible sound).

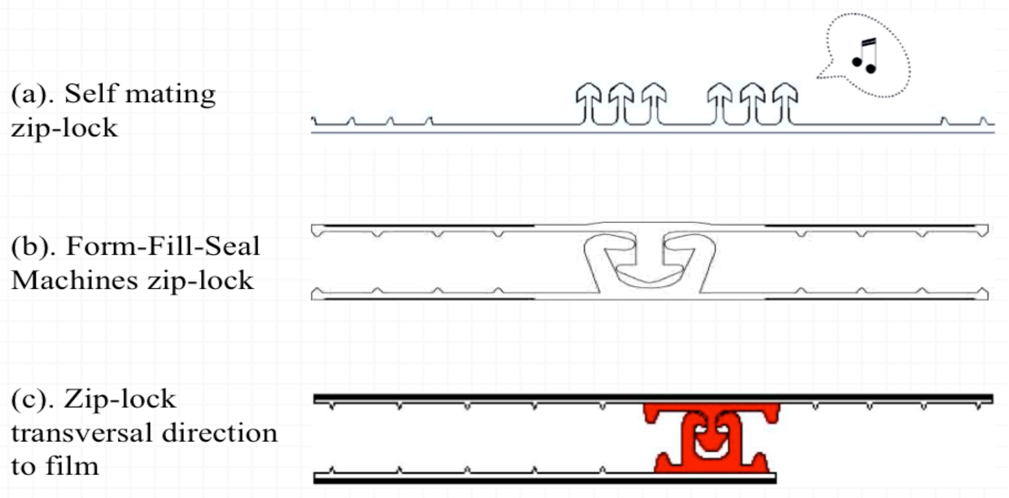


Figure 6: Resealing closure profiles from Zip-Pak®, UK. (Photo source Zip-Pak®, UK)

2.4 Mechanism of Moisture Migration

In literature references it has been demonstrated that as long as there is a water activity (a_w) gradient within a food and/or its surrounding atmosphere water transfer will occur to reach a thermodynamic equilibrium state during product storage (Roudaut and Debeaufort 2010; Sievert et al. 2007; Risbo 2003). It is a complex phenomenon. The transfer occurs from the phase with a high a_w to the phase with a low a_w. In baked products directly after baking there is a gradient in a_w within the product, i.e. between the crumb (interior) and the crust (surface), and the surrounding atmosphere. It has been reported in the literature that moisture migration in baked products occurs in one of the following three ways (Cauvain and Young 2008):

i. By direct diffusion from the component with the higher MC to the one with the lower MC.

ii. By vapor phase transfer; where moisture migrates from the component with the higher equilibrium relative humidity (ERH) to the one with lower ERH.

iii. By the formation of surface water through syneresis within a gel as a result of crystallization or aggregation of polymers. However, detailed information on this particular migration phenomenon could not be found in the products studied in this study.

2.4.1 By Direct Diffusion

The direct diffusion of moisture arises when two or more components differing in a_w are in direct contact. The moisture diffusion may occur at macroscopic level following capillary action (Labuza and Hyman, 1998). When the difference in water activity is not large water will move at a relatively moderate pace. For example, (Cauvain and Young 2008) stated that in sponge cake (a_w = 0.85) in contact with cream filling (a_w = 0.95), with difference of 0.10 a_w between the two components the equilibration will take some time to occur. But when the difference in water activity is very large, for example biscuit (a_w = 0.3) with filling (a_w = 0.95), the moisture moves much rapidly, making product soggy due to higher difference (0.65). The movement of water is assisted by gravity in all the cases. They further mentioned that the rate of moisture diffusion is influenced by product porosity. Therefore it can be said that porous microstructure of croissant acts like many small capillary tubes for moisture diffusion to occur at faster rate causing crust to become soggy over a matter of hours rather than days. Similar conclusion is drawn for sweetened pastry when baking powder addition to increase porosity showed rapid softening of pastry during storage (Cauvain and Young 2008).

The basic equation governing diffusion process is well known Fick's laws. The velocity with which water will move in a food matrix is strongly related to its structure and the temperature. Fick's first law of diffusion gives the movement of water through a binary solid mixture under a constant vapor pressure gradient, Equation 11 (Roudaut and Debeaufort 2010):

Equation 11:

$$Fick's\ law\ of\ moisture\ diffusion, \qquad J = -D\frac{dC}{dx}$$

Where *J* is the flux defined as amount of moisture exchanged per unit of time per unit area [g (H_2O) sec^{-1} m^{-2}], *C* is the concentration as mass per unit volume, *x* is the distance transversed by the concentration gradient, *D* is the effective moisture diffusivity or diffusion coefficient and *dC/dx* is the concentration gradient.

2.4.2 By Vapor Phase Transfer

Moisture migration by vapour phase transfer is most evident with wrapped products where moisture is re-distributed within the food and package headspace. In un-wrapped product water vapor evaporating from the surface is lost to the atmosphere. Permeability of packaging material influences moisture migration rate by affecting the relative humidity of the atmosphere surrounding the product. Packaging material with lower MVTR tends to create a high RH in the package atmosphere; this lowers the rate of moisture loss from individual components as the whole system move to an equilibrium state (Robertson 2011b). The greater the permeability, the longer the crispness of apple pie pastries is maintained. However, shrinkage in filling size was observed (Cauvain and Young 2008).

The three major driving force behind vapor phase moisture transfer comes from, (i) the difference in the component ERHs, (ii) the RH of the in the package headspace, (iii) the product moisture mass to air volume ratio in pack. Porosity of product may not play similar role in moisture migration by vapor phase transfer in packaged product. The exact reason is not known but complex and not uniform microstructure structure makes it difficult to give an explanation. The rate at which moisture moves between components decreased in savory pies as the storage temperature is decreased (Cauvain and Young 2008).

Thus, during storage moisture migration in pastries can occur by the mechanism of vapour phase transfer and direct diffusion as described above. The moisture gain or loss from one region or food component to another region will continuously occur in order to reach thermodynamic equilibrium with the surrounding food components and the environment. Two main factors influencing the amount and rate of moisture migration are water activity equilibrium (thermodynamics) and factors affecting the diffusion rate (dynamics of mass transfer). Water activity gradient is a driving force for water movement from regions of high water activity to regions of low water activity.

2.4.2.1 How To Minimize Moisture Migration?

The rate of moisture exchange and/or the overall moisture gain or loss in bakery products may be achieved by following three approaches (Cauvain and Young 2008):

i. Lowering the rate of water transport to the crust. This entails changes in the formulation of product. However, this is often time consuming and an expensive process.
ii. Lowering the rate of water uptake by the crust. This is achieved by using protective coatings of polysaccharides, proteins, fats, etc. However, the use is limited to product types.
iii. Increasing the ratio of water activity of the crust over relative humidity of the environment. This can be achieved using an appropriate packaging material.

Use of packaging materials to control the moisture migration phenomenon is a practical approach and less time consuming process. Packaging materials have been developed to prevent water/gases exchange with the surrounding atmosphere. The permeability of the packaging material controls the dynamics of these transfers. Packaging material with lower MVTR or very high moisture barrier tends to create a high RH in the package atmosphere; this lowers the rate of moisture loss from product. However, a high RH in the package may also lead to microbial growth (Robertson 2011b).

3 Requirements Analysis

Identifying product and packaging needs by considering the manufacturing, marketing and supply chain perspective is the very first step in developing a framework for packaging development project (Coles et al. 2003). In this Chapter information collected from author's visit to product manufacturing plant in Belgium and visit to retail markets in the UK is provided. A simple questionnaire was used (Appendix 8.3) to collect the details that could be useful for defining the product and packaging requirements. The experts at the Lantmännen Unibake, UK, answered the questionnaire. The expert group consisted of the Innovation director, the category manager, and the product developer. This information was used in identifying packaging material and could be investigated in the empirical studies conducted as part of this work. Accordingly a brief for packaging material suppliers was prepared. References to secondary data from literature and online resources are provided whenever necessary.

3.1 UK Retail Bakery Market

The primary source of information for packaging material selection was collected from visits to the following retail stores in the UK: Tesco PLC, ASDA Stores Ltd., Sainsbury's, Morrisons and Waitrose. This section provides brief information on retail stores format and key bakery sector where croissant is sold as 'freshly' baked as well as wrapped/packaged product. The section ends with information on common forms of packaging material observed in the market during these visit.

3.1.1 Market Segment and Key Bakery Sector

3.1.1.1 Market Segment

The UK retail bakery market is worth £3.6 billion a year and is one of the largest markets within food industry (The Federation of Bakers 2013). The bakery market breaks down into four main categories: bread, bakery snacks, rolls and baps, and breads of the world. Croissants and pastries fall under bakery snacks, which is the second largest bakery category worth £711 million. This category includes traditional bakery products, such as hot cross buns, crumpets, scones, pancakes and muffin through to more contemporary products such as brioche and pain au chocolat.

Top five retail stores in the UK are: Tesco PLC, ASDA Stores Ltd., Sainsbury's, Morrisons and Waitrose. Figure 7 illustrates the respective market share. However, fast growing discount chains like ALDI and LIDL are offering intense competition in the supermarket bakery sector.

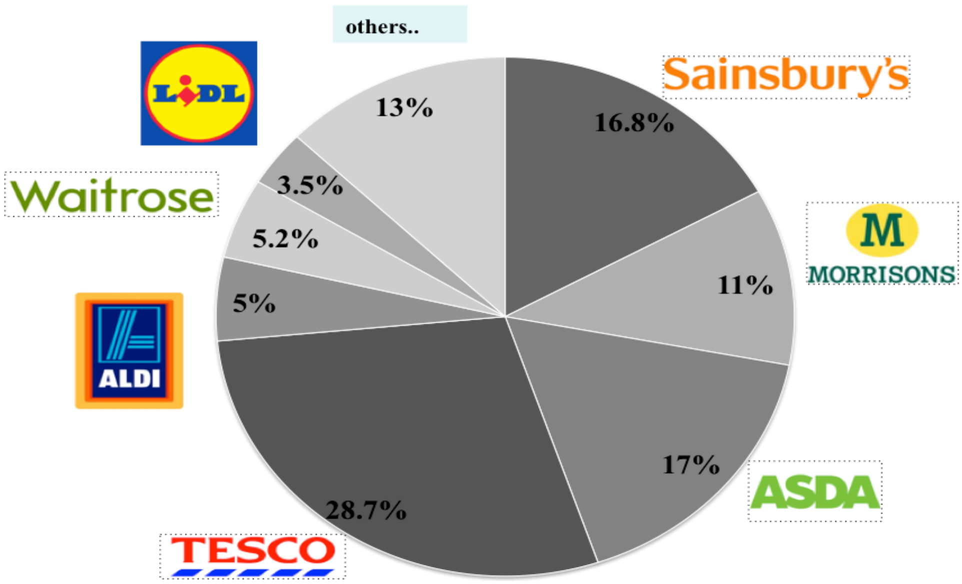


Figure 7: Top five grocery retail stores in UK, % market share. (Source: The Grocer 2015).

These retail stores operate in different formats differentiated by size of the store (area in sq. ft.), range of food and non-food products sold and target consumer segment. For instance, Tesco operates via six different store formats, viz., Tesco Extra, Tesco Superstores, Tesco Metro, Tesco Express, One-Stop and Tesco Home plus targeting mass consumer segments as well as niche segment like online and on-the-move consumer segment. ASDA stores on the other hand have an approach to target niche consumer segment and operates commonly via supermarket and hypermarket format. These stores are located mainly outside of the town. Sainsbury's operate commonly via local convenience stores usually located in the city center.

It is required to have an understanding of different store formats because their product and packaging requirements differ from each other. For instance, a Tesco One-stop store with floor area of 1,500 sq. ft. and catering to on-the-move consumers will offer limited shelf size, space and product display compared to a Tesco Extra stores that have larger area of 112,000-185,500 sq. ft. Thus, Tesco One-stop would need smaller pack sizes or single serve packaging format. On the other hand, larger stores would prefer bigger pack size. Furthermore, cost of manufacturing smaller pack would be relatively higher compared to a bulk pack because of more material and energy is used. The distribution channels used for product supply also differ with the store formats. Larger stores are supplied directly from the main warehouse where as smaller stores have distribution centers located closer to the stores. The cumulative effect of these differences is on the margins earned on selling price of the product. Consequently the choice of expensive or a cost effective material for product packaging is affected.

3.1.1.2 Key Bakery Sectors

The three principal sectors that make up the UK baking industry are: wrapped bakery sector (80% by volume), In-store bakery sector (17% by volume), and the craft bakers sector (3% by volume) (The Federation of Bakers 2013). First two sectors are discussed below as they were selected in this study.

Croissants that are plant manufactured and then supplied to the stores as wrapped product comes under wrapped bakery sector (WBs). The In-store bakeries (ISBs), also known as 'fresh bakeries', are established within the stores that bake croissants either using frozen dough croissants or 'freshly' prepared dough from using raw ingredients. Since the scope of this study focuses on ISBs, the '*Euphorium bakery*' visited in Tesco store, cf. Figure 8 has been further discussed. The In-store bakery bakes 7-10 different type of products every day. The products vary from breads, multigrain loaves, baguettes, croissants, Danish pastry, doughnuts, puff rolls, pies and cakes. The ISBs receives these products in frozen form, which are ready to bake after thawing under ambient conditions. The bakery has small freezer to store these frozen products. Each of these products have different baking time-temperature requirement therefore two to three baking ovens with pre-set programs are used for baking. Baking of products is usually performed in rotations to fill the shelf with each kind of products. The space available to perform baking and related preparations is limited. Use of rolling racks was observed. The rolling racks were used to put the number of trays with frozen products to thaw or cool the baked products, cf. Figure 9.

The WB and ISB sectors do not seem to compete with each other. ISBs are flourishing on increasing consumer demand for 'freshly' baked croissants and other products. A store depending on its size has the wrapped as well as the 'freshly' baked croissants. Wrapped croissants are placed on the shelf with other packaged product categories like bread, biscuits and wafers. Whereas 'freshly' baked croissants are placed with other 'freshly' baked products like Danish pastry, doughnuts, puff rolls, pies and cakes in a special section inside the stores. The difference was also observed in the shelf space given for product display in these two sectors. 'Freshly' baked croissants always get a limited shelf space, as they have to share the space with other 'freshly' baked products. On the other hand, wrapped croissants have whole shelf available for display, cf. Figure 10.

Figure 8: In-store bakery 'Euphorim bakery' in Tesco Extra stores, London, UK. The front view- where 'freshly' baked products are displayed. (Photo by the author)

Figure 9: Inside view of the In-store bakery 'Euphorim bakery' in Tesco Extra stores, London, UK. Rolling racks are used to put the frozen product for thawing or for cooling baked products. (Photo by the author)

The need and challenges faced by ISBs are unique to their nature of operation. The need to have one of each kind of bakery product on the shelf before store opens for the day provides only a small time window for bakers to perform baking, filling, packaging and other related operations. Baking is often performed in small quantity and frequently to provide 'fresh' baked products. The operational efficiency is low compared to the high-speed commercial production. The packaging consideration requires shelf-ready packaging differentiating graphics to increase products shelf presence. The need of lower inventory level demands universal packaging design to suit all products packaging need. This restricts the packaging innovation, as often the product sizes are non-uniform resulting in oversized packages.

Managing in-store food wastage is another area of challenge as most of the products have short-life (one day) compared to that of WBs products (5-7 days). In Tesco stores alone 41% of the waste has been reported (Little 2015). The ISBs have adopted increased activity of bake-off i.e. using frozen pre-prove dough or part-baked dough instead of making the dough using raw ingredients. Mainly due to expensive energy and raw materials (flour, dairy, butter, cocoa, etc.) driving cost reduction and rising concern to bakery waste reduction amongst the retailers.

(A)

(B)

Figure 10: Display shelf for croissants in Tesco Extra stores, London, UK. (A) 'Freshly' baked croissants sharing shelf space with other-baked products. (B) Wrapped croissants displayed on whole shelf space. (Photo by the author)

3.1.2 Packaging Forms and Materials

This section presents information collected during market visit on croissants packaging forms and materials. Packaging tends are discussed in the end of the section. Table 3 provides a summary of different forms and materials used by the Wrapped and the In-store bakeries in the 5 stores visited during market visit.

Table 3: Packaging forms and materials used in croissant packaging. (By author)

Stores	In-store bakery product	Wrapped bakery product
Tesco	OPP tray rPET tray Paperboard box tray	PP film + rPET tray
ASDA	rPET tray	PP film + rPET tray
Sainsbury's	OPP tray rPET tray	PP film + rPET tray
Morrisons	OPP tray rPET tray	PP film + rPET tray PP film + recycle paperboard tray
Waitrose	Laminated paper bag Bottom gusseted bag rPET tray	PP film + recycle paperboard tray
ALDI	Gusset paper bag with perforated plastic film	PP film + rPET tray
LIDL	Gusseted paper bag with perforated plastic film	Metalized film (OPET/PET/PE/Alu/PE)

3.1.2.1 Packaging Forms

Packaging scenario of 'freshly' baked products is changing. Usually sold open in woven baskets the products are now packed either in a flexible form or a semirigid form. *Flexible form* can be deformed with little force and generally can be returned to original shape after deformation, e.g. bags and pouches. *Semirigid form* can be deformed with moderate force and may or may not return to original shape, e.g. Paperboard box, plastic thermoform trays (McKeen 2013). Croissants are light and fragile products that need protection against any mechanical or physical damage during filling, handling or transport. Therefore, a semirigid form is most suitable form to provide the required protection to product. Also, it is a most convenient form used by In-store bakeries.

Use of semirigid form in combination with flexible form is common within wrapped bakeries sector. The croissants and other baked products are packed into a tray and wrapped with a flexible film on a packaging machine. These trays are designed with cavities to hold individual pieces, which provide additional protection during transport. Figure 11 shows different forms used for croissants packaging by the wrapped bakeries and the In-store bakeries.

3.1.2.2 Packaging Materials

Commonly used material for croissants packaging are *polyethylene terephthalate* (PET), *polypropylene* (PP), *polyethylene* (PE), *aluminum* (Alu), *ethylene vinyl alcohol* (EVOH), *paper* and *paperboard*.

Polyethylene terephthalate (PET) is the material most commonly recommended and approved material by major food retailers (Par-Pak 2015). It can be easily thermoformed into semirigid forms (trays or boxes) that provide adequate protection to product. It offers design flexibility to have different packaging forms as discussed in section above. Its transparency offers product visibility, which is a key parameter for product's visual appreciation before purchase. PET could be used as oriented PET (OPET) that has better barrier to moisture due to structural orientation (McKeen 2013).

Polypropylene (PP) can be used either in uniaxial oriented (OPP), or biaxial oriented (BOPP) form. OPP is oriented uniaxial in machine direction and BOPP is stretched in both machine and transverse direction. The results of orientation are increased stiffness, enhanced clarity, improved oil and grease resistance, and enhanced barrier properties to water vapor and oxygen. OPP is about three times stiffer and stronger than low-density polyethylene film (Calafut 1998).

Polyethylene (PE) is commonly used in bread packaging. Common forms of PE used in bakery application are low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE). LDPE allows good optics and printability. Bread and other wrapped bakery products are usually packaged in LDPE bag of 1 to 1.5 mm thickness in which the end is twisted and sealed with a strip of adhesive tape or twisted wires. PE is also used as a sealant layer in multilayer film structures.

Figure 11: Forms of packaging used for croissants. (A) Semirigid plastic tray with flexible film. (B) Semirigid paperboard tray with flexible film. (C) Semirigid paperboard box. (D) Semirigid Plastic box. (E) Multilayer flexible film for single serve croissant. (F) Flexible film with paper support for single serve croissant. (Photo by the author)

Aluminum (Alu) is used in combination with materials above-mentioned and paper to form a multilayer structure. Its used isn't commonly observed for croissant packaging except for chocolate filled croissants sold at LIDL stores. Aluminum is used when a product requires barrier values of less than 0.04 g /(100 in^2 day) for water vapor transmission rate or < 0.05 cm^3 /(100 in^2 day) for oxygen transmission rate (Butler and Morris 2013). Table 4 lists some of the other multilayer structure used in bakery application.

Table 4: Multilayer structure for bakery application. Adapted from (Butler and Morris 2013)

Structure	Layers (%)	Thickness (µ)
LLDPE/PP/LLDPE	10/80/10	30-60
Paper/PE/Alu/PE	40/12/9/35	20-23
PET/Alu/PET	12/9/75	-
EVOH/PP	20/80	30-60

Ethylene vinyl alcohol (EVOH) use as multilayer film is very useful when high oxygen-barrier properties and odor resistance are required. It can effectively retain fragrances and preserve the aroma of the contents within the package. Marketing effectively uses its high transparency and luster, which improve package appearance by providing excellent sparkle. Other commonly exploited use is due to resistance to oil and organic solvent, printability and antistatic properties.

Paper is the widely used material in bakery application by the In-store bakeries. It is used in combination with perforated plastic films where the holes enable diffusion of water vapor out from the package offering an ease to pack 'hot/warm' product. To enhance the functionality and water barrier property of paper it is coated with PE.

Paperboard can be easily printed, embossed, creased, cut, folded and glued (Andersson 2008). For these reasons, the design of innovative packages considers the use of paperboard. Another advantage is that they occupy less storage space in collapsed state compared to semirigid plastic trays or boxes. The surfaces of paper are coated with mineral pigments on the external side or on both sides. The thickness of a folding boxboard varies 300 to 600 micron (Andersson 2008).

3.1.3 Packaging Machine

Machinability is important factor in material selection and design consideration. Croissants packaged in semirigid tray and wrapped with flexible film are packed on a horizontal form-fill-seal system (FFS). Figure 12 presents a sequential operation of packaging croissant in a horizontal FFS machine. The film is drawn from reel and formed into horizontal tube around the product with continuous seal underneath formed by heater blocks and crimping rolls. Then, rotary heaters make the crimped end seals and cut-off produces individual packs. At times gas flushing is used in the packs, especially for premium category products. It prevents the mechanical damage to product and allows vertical stacking on shelf.

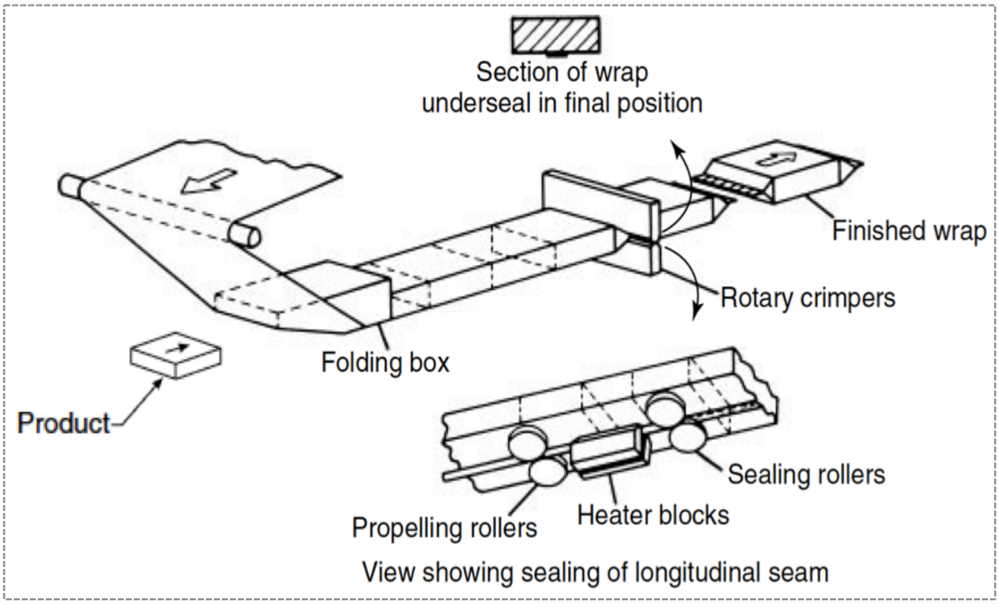


Figure 12: Horizontal form-fill-seal machine. Adapted from (Brennan and Day 2012).

3.1.4 Packaging Trends

The continued move towards sustainability in the UK is channelizing focus on recycle, reduce and reuse of packaging materials. An increase use of recycled-PET (rPET) for direct food contact surface is observed. The recycled tray has good clarity and gloss as APET. It is available in one of two formats. Format 1, co-extruded multi-layer sheet of 50% super clean recycled PET post-consumer waste and 30% post-industrial sandwich between 20% prime PET resin. Format 2, mono-layered blend consisting of a mix of food-approved super clean post-consumer recycled PET, post-industrial regrinds and prime virgin PET resin, (Par-Pak 2015). The postconsumer content is only from reputable sources that have approval for direct food contact use.

3.2 Packaging Prototype Development and Feedback

The UK market study provided a key insight for packaging design consideration to make a shelf-ready airtight pack for In-store bakery products. Compared to WBs it was observed that the ISBs packaging differs not only in form and material but also in pack sealing and shelf life.

The croissants packaging from ISBs lack in airlock sealing compared to the packaging of WBs. Also, the ISBs croissants packed in semirigid plastic tray and paperboard box tray has shelf life of one-day compared to WBs croissants with 5 to 7 days shelf life. The reason for such a short life for ISBs product was the firming of product due to moisture loss. Another reason hypothesized for shorter shelf life was lack of an airtight pack seal. So, if the pack has airlock seal just like a flexible film wrapped and sealed to a plastic tray the shelf life could be extended. But constraints associated with adopting this forms was need for a new packaging line that suits not only croissants packaging but also other baked products packaging. Thus, the author developed prototypes. Need for filling, handling and sealing ease during in-store bakery operations was taken into consideration.

The option found most suitable for a shelf-ready airtight pack was using resealing closures. These resealing closures are commonly used in packaging of cookies, nuts and pet foods. The UK based company Zip-Pak® provided the resealing closures. Flextrus Groups, Sweden, provided the flexible materials. Two prototypes were developed each with bottom gusset and high performance LDPE/HDPE resealing closure and self-mating, audible LDPE resealing closures respectively. The designs of the closures can be referred in Figure 6. The closures were heat sealed to the packaging material using electric band sealer. Prototype 1 was made using PE film with product window, cf. Figure 13 and Prototype 2 used Paper/ PE/Alu/PE flexible film, the bag was designed with a handle, cf. Figure 14.

Figure 13: Prototype 1-Bottom gusseted PE bag with LDPE/HDPE material, high performance resealing closure from Zip-Pak®. (Photo by the author)

(A) (B)

Figure 14: Prototype 2. (A) Bottom gusseted Paper/ PE/Alu/PE bag with handle. (B) The self-mating, audible LDPE resealing closure from Zip-Pak®. (Photo by the author)

3.2.1 Prototype Feedback and Conclusion

The feedback on prototypes was received from the experts group at Lantmännen Unibake, UK. The group consisted of the Innovation director, the category manager, and the product developer. Table 5 provides brief summary on comparative evaluation of both prototypes with semirigid plastic tray and paperboard box tray from marketing perspective and Table 6 from in-store bakery perspective.

Table 5: Comparative evaluation of prototypes with current packaging forms used in the UK market -Marketing perspective.

Prototype 1and 2	Semirigid plastic tray and Paperboard box
Easy to open, to close with resealing closures.	Hard to open and close for consumers.
Very easy to carry handle to load pouches for display and for consumers to pick.	No handle support.
Slim design profile takes up less space on the display counters, and consumer waste bin.	Occupies more space.
Branding and marketing communications possibility.	Requires additional support, e.g. paper sleeves.

Table 6: Positives and negative feedback on prototypes- In-store bakery perspective.

Positives	Negatives
+ Audible and intuitive sealing ease	- May reduce the current operational efficiency due to more time required for opening the bag, filling the product and sealing compared to the time required for packing in semirigid plastic tray.
+ Option to use PET/ rPET tray inside resealable bag or just the bag.	- Product susceptible to damage during handling and transport.
+ Can be used for other products, e.g. cookies, etc.	

Packaging design is an important consideration. A semirigid design form is required to provide adequate protection to the product during handling and storage. Any change in design with respect to the current design form, especially semi rigid plastic box tray, will result in reduced operational efficiency of the in-store bakery operator. The choice of using resealable pack design is a trade-off between marketing and in-store bakery requirements. It was therefore decided not to use the resealable closure for experiments.

3.3 Summary

The findings of market visit laid the foundation to define product, packaging, marketing and in-store bakery requirements. Material selection process got easier. Consequently it was easier to define requirement to the packaging material suppliers to source the materials for investigation. Feedback received on prototype highlighted the influence of packaging design on in-store bakery operations. Therefore, re-closure option for an airlock seal is not taken for further studies. The collected information helped in experiment designing process. It was decided to conduct product analysis for 48-hour storage time. Materials currently used in the market by In-store bakeries were also included in the study. A pack size with two-croissant unit was decided for use.

4 Methodology

This chapter outlines approach to investigate the impact of various packaging materials on the shelf life of baked croissants. The study is empirical in nature and combines both quantitative and qualitative measures. The experimental design, materials investigated metrics for evaluation and experimental procedure are discussed in this chapter. Results from in-lab experiments are reported in the chapter 5.

4.1 The Experiment Design

Goal**: Identify a packaging material that is most suitable for extending the shelf life of baked croissants. The investigation should help us understand the interaction between the product, the packaging material and the atmosphere.**

Design

This study undertakes an empirical approach to investigate the impact of various packaging materials on the shelf life of baked croissants. Baked but unpacked croissants will be used as the reference (the *controlled group*) to compare and discuss the observations on baked and packed croissants (the *variable group*). The variable in the experiment is the packaging material.

An over view on experiment design is presented in Figure 15. Croissants will be baked following standard process and then packed in different packaging materials and stored under ambient conditions for 48 hrs. The impact of packaging material on the shelf life of croissant will be estimated through measurements of various quantitative and qualitative parameters at intervals of 1 h, 6 h, 12 h, 24 h and 48 h. The quantitative measures are: *moisture content* and *water activity*. Qualitative measures are: *texture analysis* and *sensory evaluation*. Comparison will be drawn between not only the control and the variable group, but also among packaging materials using analysis of variance methods. A material will be considered significantly different from the other for $p < 0.05$, which suggests that the probability of observing the differences is less than 0.05. For this reason, samples will be drawn from 4 croissants at all observation stages and for each of the measure. The mean scores for the measures will be used for discussion purpose.

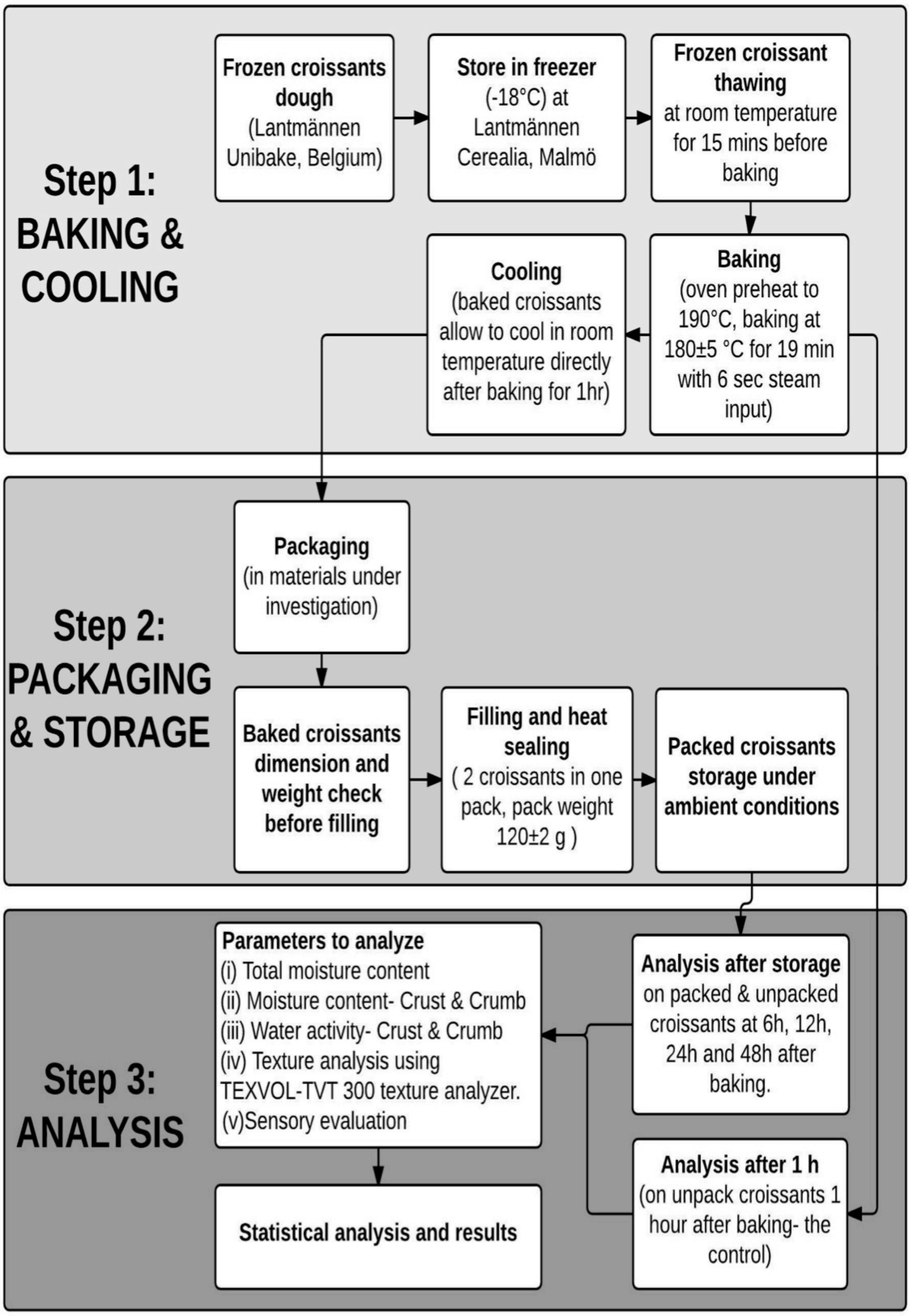


Figure 15: Experiment Design- the baking, packaging, storage and analysis of unpacked and packed croissants. This design is followed to investigate 10 packaging materials. The material analysis was performed in groups, viz. first group with 3 materials, second group with 3 materials and third group with 4 materials. (By the author)

4.2 Material

Two key components of the in-lab experiments are the product (croissants) and the packaging materials. Frozen, pre-proved, all-butter croissant (Premium Straight-70 g) was obtained from Lantmännen Unibake, Belgium. Ten commercially available packaging materials were obtained from packaging material suppliers located in the Sweden and UK. These materials had water vapor transmission rates varying in the range from 0 to 20 g m^{-2} day^{-1} (38 °C, 90% RH). Table 7 provides information on the ten materials investigated in this study. Basis the description given in Table 7 the materials can also be described in three groups: monolayer materials, multilayer flexible film and paper base multilayer flexible film. The In-store bakeries in the UK market currently use material 1 and 8.

Table 7: Packaging material description

Material	WVP*	Description	Source
Material 1	Very high	Monolayer semirigid PET box tray	Par-Pak®, UK
Material 2	Moderate	Monolayer perforated plastic film	Flextrus Helmstad AB, Sweden
Material 3	High	Monolayer flexible plastic film with resealing closure	Amcor, UK
Material 4	Moderate	Multilayer film with oriented PET polymer	Flextrus Group AB, Lund, Sweden
Material 5	Moderate	Multilayer film with oriented PET/EVOH polymer	Flextrus Group AB, Lund, Sweden
Material 6	Low	Multilayer film with oriented PP/EVOH polymer	Flextrus Group AB, Lund, Sweden
Material 7	Very high	Multilayer Paper/PET polymer film	Flextrus Group AB, Lund, Sweden
Material 8	Very high	Multilayer Paper/PE box tray	Bensongroup, UK
Material 9	Moderate	Multilayer Paper/PP polymer film	Flextrus Group AB, Lund, Sweden
Material 10	Zero#	Multilayer Paper/ Aluminum film	Flextrus Group AB, Lund, Sweden

*Water vapor permeability. The literature reference used for this classification is mentioned in the Appendix 8.4.
As per the definition containing aluminum.

4.2.1 Permeability of Materials

The details provided by packaging material supplier were not sufficient for accurate material characterization. Also, description of properties of complex materials (laminates) used for baked pastries packaging is not explicit in the literature references used in the study. The ASTM standard methods for measurements could not be used, as humidity control chamber was not available at the baking facility. Due to these limitations the estimation of material permeability or water vapor transmission rates used for discussion is based on the permeability values of the type of polymer used in manufacturing of the material.

4.3 Evaluation metrics

The quantitative parameters evaluated to understand the moisture migration phenomenon in croissants were *moisture content* and *water activity*. The crispness and firmness of croissants (qualitative parameters) were evaluated using *texture analysis* and *sensory evaluation* techniques.

4.3.1 Moisture Content

Sartorius MA 30 infrared moisture analyzer is used to quantify the total moisture content in croissants. The moisture content of the crust (3 g sample) and the crumb (5 g) samples is used. Determination is carried out in duplicate at 160 °C for 6 minutes.

4.3.2 Water Activity

Water activity of 0.5 g crust sample and 1.0 g crumb samples is measured. It is determined as the RH of the air in equilibrium with the parts of the samples in a sealed measuring chamber using a chilled-mirror dew point technique at 23 °C (Aqua Lab CX-2, Decagon Devices, Pullman Wash., U.S.A.). Representative samples of crust and crumb was taken from four different croissants. The device is checked for offset using standard verification standards of 13.3 M LiCl (a_w 0.250 ±0.003), 6 M NaCl (a_w 0.760 ±0.003). The device was let to warm up for 15 minutes, and initial readings with distilled water (a_w 1.000 ± .003.) were made. Mean of two observations is taken as final water activity value.

4.3.3 Crispness and Firmness

Use of instrumental texture analysis tests as an indication of the sensory texture is common in biscuits and bread. However, there is no scientific consensus about the test and probe types that can be correlated with the sensory texture of pastries. Croissants are analyzed on TEXVOL-TVT 300 texture analyzer (Perten Instruments, Sweden). The test method used is received from company. A Warner-Bratzler shear blade with guillotine probe is use to cut the croissant, with test speed of 2 mm/s. The cut is performed perpendicularly to the main axis of the croissant until 90% compression. The small peaks/irregularities on force-time curve obtain on TVT texture analyzer are a result of crispness of the product. The firmness value in joules (*J*) is obtained from the total area under the force-time curve. Statistical differences in mechanical properties between samples at different hours are determined by a one-way Analysis of Variance and a Tukey-Honestly significant difference (HSD) test at 5% significance level.

4.3.4 Sensory Measures

The magnitude estimation technique is use to determine the crispness intensity and overall textural attributes. Due to resource constraint the author, who received the training by R&D professionals at Lantmännen Unibake, Belgium performed the sensory evaluation using ratio scales. The results will be used as an indication of difference. For each attribute a positive value is assigned if perceived as defined in Table 8. Adaptation and fatigue are issues of consideration in this type of sensory evaluation. Suitable palate recovery period between product trials is given.

The standard test method for sensory evaluation is received from the company. The score evaluation is based on the bipolar magnitude estimation of sensory attributes (ASTM E 1697-05). The scale with ‘ratio’ properties is used. Ratio scales have a particular application in the sensory analysis technique of magnitude estimation, in which comparative measurement are made using numerical ratios, so there is no a priori requirement to set any limits to the ends of the scale (Lawless and Heymann 1999). The preliminary baking trials (not discussed here) and market samples were used to define the sensory attributes and corresponding reference. The standard score of product acceptability at >65 % score is also received from the company.

Table 8: Definition and references for sensory attributes of the croissants. (By the author)

Nr.	Sensory attribute	Definition	Reference
1	Aspect	The ‘first impression’	Croissants 1 h after baking
2	Color	Intensity of golden brown color, light or dark.	Intensity of golden brown color
3	Shine	Relative dullness	Croissants 1 h after baking
4	Layering	Distinct layers accentuating flakiness	Croissants 1 h after baking
5	Stand	Sunken bottom and uneven color	Croissants 1 h after baking
6	Crispness	Noise of food during mastication	High: Breakfast cereal (crisp). Low: Fresh breadcrumb
7	Crumb color	Absence of dough color or yellow spot	Croissants 1 h after baking
8	Crumb structure and softness	Refers to open/close air pockets. Softness refers to soft or hard crumb when pressed with fingertips.	Refer Appendix 8.2
9	Mouthfeel	Dry/ Doughy/ Moist and buttery.	Croissants 1 h after baking

4.4 Procedure

4.4.1 Baking and Quality of Croissants

Baking trials are performed to standardize baking time-temperature parameters. Different values for baking temperature, steam input and number of croissants were tried. Frozen croissants were place on oven trays lined with greaseproof paper (3×4 croissants per tray). They were allowed to thaw in room temperature of 23±1 °C for 15 min, Figure 16(Left). The thawed croissants were then baked in a convection rotating rack oven (Revent-626) at 180±5 °C for 19 minutes with steam input for 6 seconds, Figure 16(Right).

After baking the croissants were let to cool for an hour at room temperature. The croissants were then packed in different packaging materials and stored under ambient conditions, 23±1 °C and 40±8 % relative humidity (RH). Observations on various measures were obtained at 1 h, 6 h, 12 h, 24 h and 48 h after baking.

Figure 16: (Left) Frozen croissants lined on oven tray. (Right) Baked croissants, 180 °C for 19 minutes. (Photo by the author)

The dimensions (length and width) of all the baked croissants were measured using a color scale (cf. Figure 17). The color scale is used to check if the dimensions of baked croissants match the standards identified by the Lantmännen Unibake, Belgium. Croissants that fit into the orange color scale were accepted for further investigation, while croissants that fit only in the green color scale were rejected. The height (mm) was measured using a digital height gauge (Limit, Sweden), cf. Figure 18.

Figure 17: Color scale (mm) developed for the measurement of croissants length and width. Croissant fitting into orange color scale is accepted. Croissant is rejected if it fits only in green color scale, as is smaller in size. (Photo by the author)

Figure 18: Digital height-gauge used to measure the croissant height. (Photo by the author)

4.4.2 Packaging of Croissant

All packaging materials, except Material 1, 3, and 8, were received as film. The film was formed into a pouch with two-side heat-sealing using an electric band sealer. The dimension of each pouch is presented in Table 9. In each pack two units of croissants were packed. The total pack weight was 120±2 g. Care was taken to not damage the croissant crust while sealing. Packed croissants were placed on rolling racks along with the unpacked croissants. Figure 19 is the pictorial presentation of the ten packaging materials used in the study.

Table 9: Package dimensions

Materials	Pack dimensions* (mm)
Material 1	230 x 170 x 80
Material 8	220 x 140 x 55
Material 3	300 x 200
Material 2, 4, 5, 6, 7, 9	300 x 230

*Length x Width x Height


Material 1


Material 2


Material 4


Material 5


Material 6


Material 7


Material 8


Material 9


Material 10


Material 3

Figure 19: Ten commercially available packaging materials selected for investigation studies. (Photo by the author)

5 Results and Discussion

This chapter presents and discusses the observations made during the lab experiments that were outlined in section 4.3. Frozen croissants were first allowed to thaw and then baked. After 1 hour of cooling under ambient conditions they were packed into packaging materials under investigation. Samples were stored at room temperature of 23±1 °C and 40±8 % relative humidity (RH) and analyzed at 1 h, 6 h, 12 h, 24 h and 48 h after baking. With regard to the evaluation metric, measures for the values of *total moisture content*, *water activity*, *firmness* and *sensory score* were taken for both unpacked croissants and packed croissants. The unpacked croissants one hour after baking, is the *control* and corresponding measurements were used as reference for analyzing the observations on the packaged croissants. The *moisture content* and *water activity* of croissant's crust and crumb were also recorded in order to be able to do a fine-grained analysis. The process of baking frozen croissants and analysis was carried out in groups of three, three and four for the ten different packaging materials investigated in this study.

5.1 Quality and Baking of Frozen Croissants

For the study at hand, frozen croissants produced in Lantmännen Unibake Belgium facility were delivered to the Lantmännen lab facility in Malmö, Sweden, where the experiments were performed. The quality of frozen croissants received for these experiments was not found to be the same as those used for outlining the methodology for this study (see Section 4.4.1). The parameters in the experimental methodology were identified during the baking trials of croissants. The croissants received in Malmö were observed with surface wrinkles after thawing under ambient conditions for 15 minutes, shown in cf. Figure 20(A). This defect was not observed in the earlier received samples for baking trials, cf. Figure 20(B). The main reason identified for the difference is that frozen croissants were not packed in Styrofoam box with dry ice. This may have exposed samples to temperature variations causing some thawing and re-frosting during transport in refrigerated truck (-18 °C).

This defect in frozen croissants resulted in changes in the thawing time and baking parameters. Frozen croissants are thawed for 30 minutes (instead of 15 minutes as outlined earlier) under ambient conditions and then baked at 185 °C for 19 minutes with steam input of 8 seconds (instead of 6 sec). After 1 hour of cooling the baked croissants were evaluated for sensorial acceptability. After scoring the product for nine parameters outlined in the section 4.3.4 an overall score of 93% was obtained. The defined standard for sensorial acceptability is a score >65%. Thus, product was accepted for further studies. However, differences were observed in the structure of the croissants' crumb. For the frozen samples used in this study the crumb was more open, cf. Figure 21(A), compared to the earlier samples, Figure 21(B). All observations reported in this study were made on the frozen samples with wrinkles [Figure 20(A)].

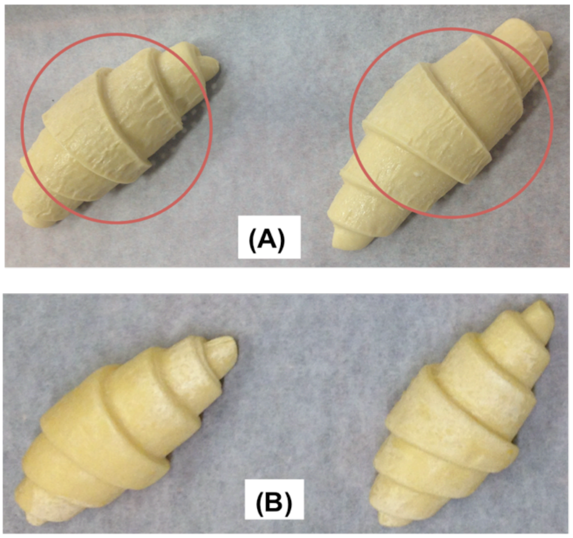


Figure 20: Quality defect in frozen croissants after thawing at room temperature for 15 min. Top/ (A)- Wrinkles on surface. Bottom/ (B)- No wrinkles on surface. All the experiments reported here were performed on (A). (Photo by the author)

(A)

(B)

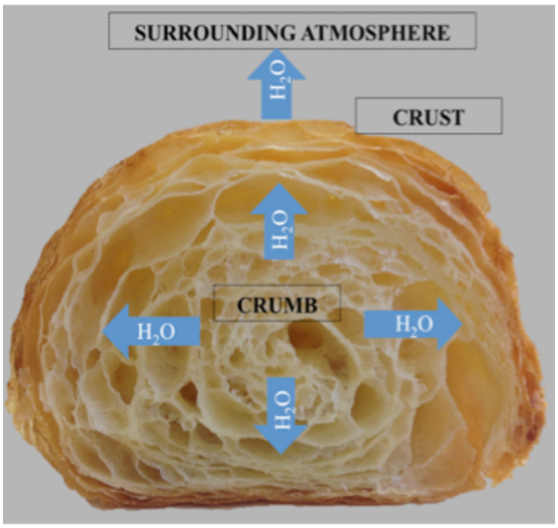
Figure 21: Crumb structure of baked croissants. Top/(A)- Frozen croissants that had surface wrinkles after thawing. Bottom/ (B)- Frozen croissants that had no surface wrinkles after thawing. (Photo by the author)

5.2 Observations on Unpacked Croissants

To assess the impact of packaging materials on croissants storage life, it is necessary to first look at the changes in quantitative and qualitative measures that occur in unpacked croissant during storage. These measures are then used as a reference to evaluate packed croissants. This section reports the changes in the moisture content, water activity, texture and sensorial parameters of unpacked croissants during the storage period of 1 h to 48 h, at 40±8 % RH and 23±1 °C.

5.2.1 Changes in Quantitative Measures

The changes in quantitative measures observed in croissants during storage are related to *moisture migration* phenomenon between the crumb, crust and the surrounding atmosphere. This phenomenon is illustrated in Figure 22. Earlier studies conducted by Lantmännen Unibake report that directly after baking the water activity (a_w) of crust is as low as 0.1. However, the water activity quickly increases from 0.1 to 0.6 during the first hour of cooling at room temperature. This increase in water activity of crust is due to moisture migration from crumb to the crust. The crust impedes the moisture loss to the surrounding atmosphere. But the migration phenomenon occurs until thermodynamic equilibrium is achieved.



Water migration:

- From crumb to crust as a_w Crust is < a_w Crumb
- From crust to the atmosphere as a_w Crust is > RH_{atm}

Water activity:

- a_w Crust = 0.59
- a_w Crumb = 0.94
- RH_{atm} = 40±8 %

Figure 22: Cross section of croissant showing directions of moisture migration during storage. The direction of moisture migration is indicated by arrows and explained in the table. The water activity values (a_w) for crust and crumb corresponds to 1 hour after baking. (Photo by the author)

Figure 23 illustrates the impact of moisture migration in croissant's moisture content and water activity. The *total moisture content* of croissant increases between 1 h to 12 h and then decreases between 12 h to 48 h of storage. Similar results on total moisture content were observed in case of bread rolls stored at 40% RH (Hirte et al. 2010). The initial decrease in moisture content between 1 h to 6 h is not significant ($p > 0.05$). However, significant differences ($p < 0.05$) were observed between 6 h and 12 h storage. Same difference was observed between 12 h and 24 h storage. The change is non-significant between 24 h to 48 h storage as well (refer to Appendix 8.5).

The increase in the total moisture content during first 12 h of storage is due to significant moisture gained by the crust. An estimated 40% increase in the moisture content of the crust is observed at 12 h. Interestingly; it can be observed in Figure 23 that the moisture gain in crust is not directly proportional to the moisture loss in crumb. To get a better understanding of this it is important to look at the *water activity* values of the crust and the crumb. The water activity values of crumb are not significantly different during first 12 h storage, but a significant difference ($p < 0.05$) in the water activity of the crust is observed. In a separate preliminary experiment (results not shown) samples were taken at 1 h, 2 h, 4 h, 6 h, 8 h, 10 h and 12 h and it was observed that the changes related to water activity already start to occur between 4 h to 6 h. Thus it can be said that during the first 12 h storage the increase in croissants' moisture content is due to changes in water activity of the crust and moisture gain by crust.

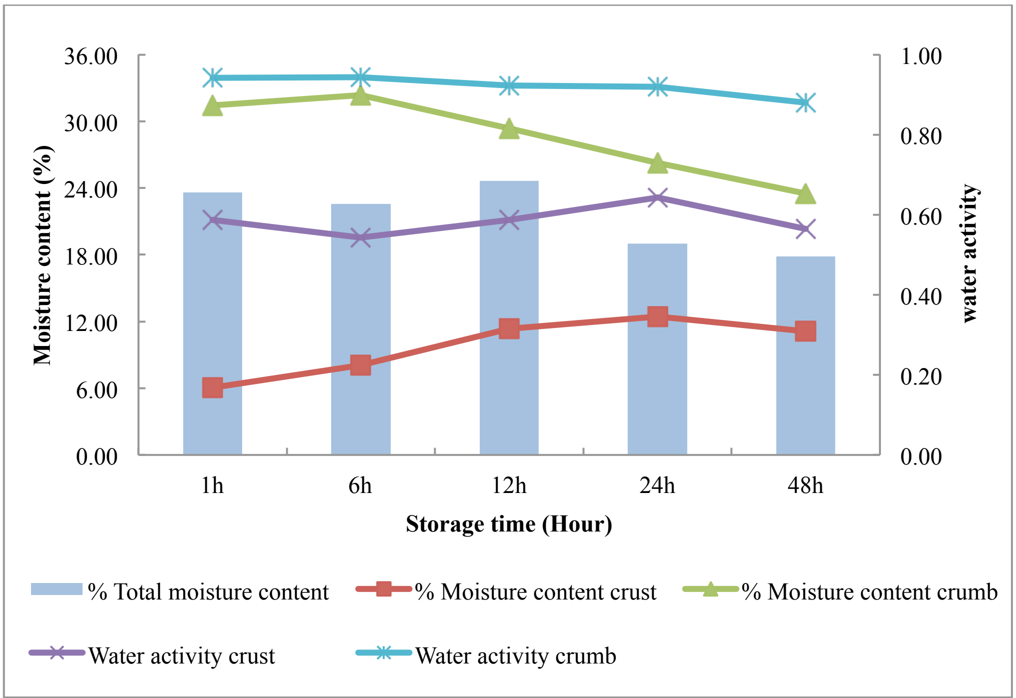


Figure 23: Change in moisture content and water activity of unpacked croissants during 48 hour storage at 40±8 % RH and 23±1 °C. Mean value of two observations. (Appendix 8.5)

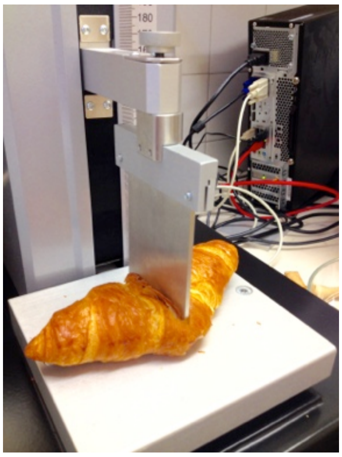
The significant decrease in croissant moisture content in following 12 h storage i.e. between 12 h to 24 h is due to loss in crumb moisture content. An estimated loss 10% is crumb moisture content is observed at 12 h storage. A significant difference ($p<0.05$) is also observed in the crumb water activity at 12 h storage. It is also observed that in the 1 h to 12 h storage if crust has gained 3 g water then the crumb has lost equivalent amount of water in 12 h to 48 h. This is explained by the lower water permeability of crust causing migrated water from crumb to accumulate in the crust and not allow to leave immediately to the surrounding atmosphere (Hirte et al. 2010).

5.2.2 Changes in Qualitative Measures

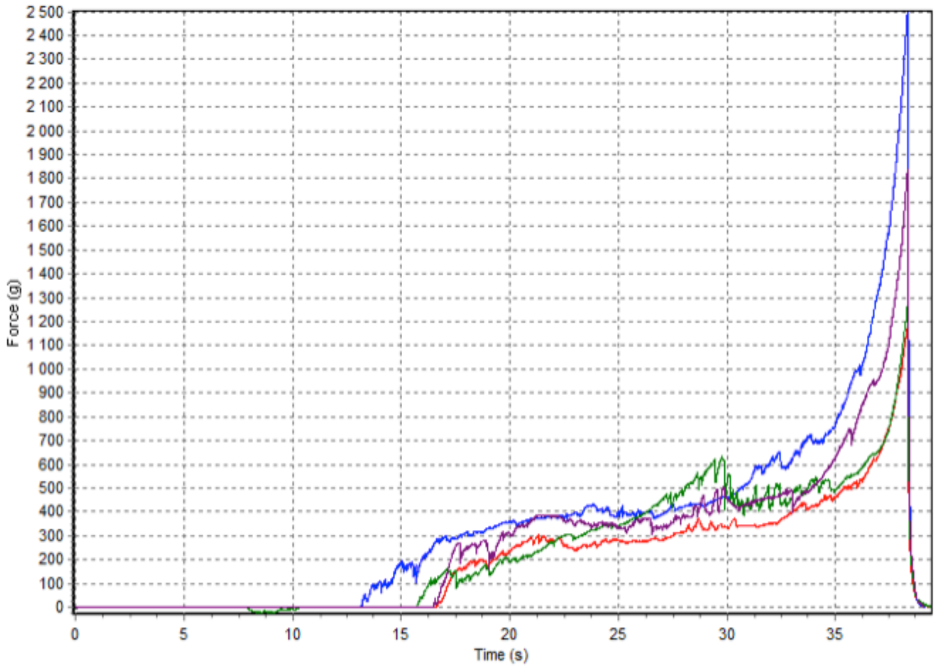
The changes in qualitative measures of croissants are related to changes in its *crispness*, *firmness* and *overall sensorial acceptance*. Crispness of croissants is determined using TVT texture analyzer. The small peaks/irregularities on force-time curve obtain on TVT texture analyzer are a result of crispness of the product. This is illustrated in Figure 24. However, the graph is a mere representation. It doesn't give an absolute value that signifies any statistical variation within and between the measured samples.

Crispness was also scored as a parameter during sensory evaluation. Directly after baking the crust of the croissants was very crispy and dry. But due to moisture migration to the crust during storage crispness is lost. The sensorial evaluation shows that the product crispness is preserved only up to 12 h storage (score 69%) as during this time the crust gained moisture (a gain of 11%). This observation corroborated with the loss in crispness of toasted rusk rolls at moisture content between 10–11% (Primo-Martín et al., 2009). But when we look at to the force-time graph for corresponding 12 h storage it shows an increase number of smaller peaks. This increase peaks can be false interpret as product being crispier then previous storage time. Perhaps acoustic measurements coupled with the instrument would give better results (Roudaut et al. 1998).

Firmness is another parameter that can be determined from the same force-time curve on TVT texture analyzer. It is expressed as the energy to deform the croissant 90 %. The firmness value in gram is obtained from the total area under the force-time curve, cf. Figure 24. These values were converted to joules (J). The impact of change in total moisture content between 12 h to 24 h is also observed on the croissant firmness. The firmness value at 12 h is almost twice the initial value [cf. Figure 25(A)]. Similar observation is also recorded in the *overall sensory score*, as shown in Figure 25(B). It is noticed that the organoleptic acceptability of unpack croissant is preserved to a satisfactory degree (score > 69%) only up to 12 h storage. The corresponding total moisture content is 25% and crust water activity is 0.59. After 12 h storage there is a sharp decline in product acceptability.

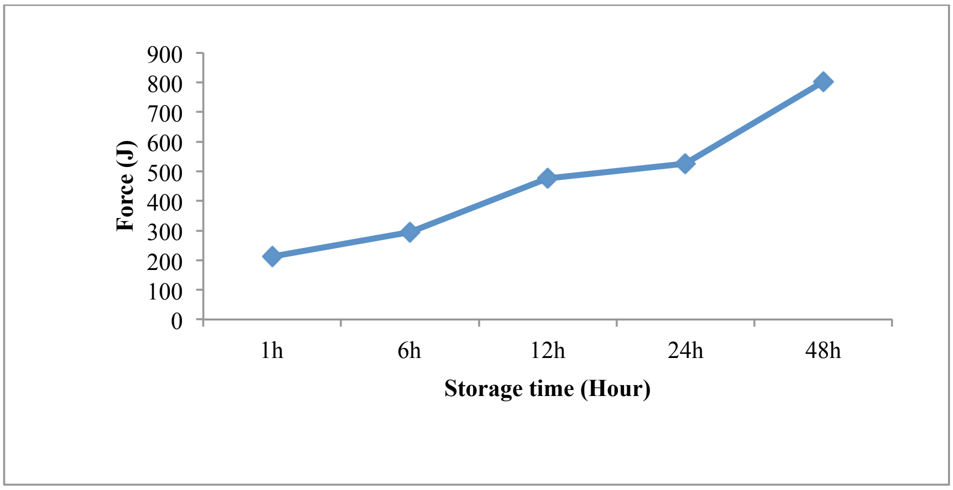


(A)

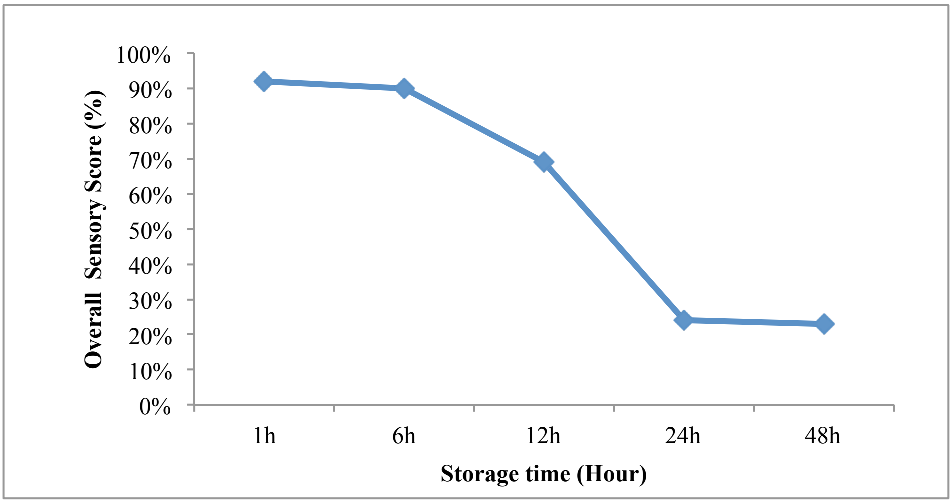


(B)

Figure 24: (A) TVT-Texture analyzer-Warner-Bratzler shear blade to cut the croissant for measuring crispness and firmness. (B) Force-time curve obtain on TVT-texture analyzer for unpack 1 h croissants. Small peaks/irregularities on curve are a result of the crispness of the sample. Total area under the curve gives product firmness value. Different lines on curve are for four observations taken on four unpack 1 h croissants. 'X' axis represents compression time measured in seconds and 'Y' axis represents measured force in gram. (Photo by the author)



(A)



(B)

Figure 25: Unpacked croissants (A) Firmness (expressed as the energy to deform the croissant 90 %) during 48 h storage (Joule). Mean value of four observations. (B) Overall sensory evaluation score (percentage). More than 65% score is acceptable.

From aforementioned observations on the quantitative and qualitative measures of unpacked croissants for 1 h, 6 h, 12 h, 24 h and 48 h, it is noted that significant differences in measurements only show up in recordings during the 6 h to 12 h storage and 12 h to 24 h. Therefore in the rest of this Chapter reports and discuss changes occurring in packaged croissant between 6 h to 12 h and 12 h to 24 h. The detailed observations are reported in the Appendix 8. Based on the observations on the unpacked croissants, it can be hypothesized that *a packaging material in which the aforementioned changes are not significant between 12 h to 24 h storage would be the most suitable material to extend product shelf life.*

5.3 Observations on Packaged Croissants

Ten different commercially available packaging materials, identified in section 4.2 of Chapter 4 were investigated in this study. The water vapor transmission rates of these materials are shown in Figure 26. The values are either obtained from literature reference (Appendix 8.4) or provided by the packaging material suppliers. In this section first the observations on the materials 1 and 8 are presented, as these are currently used in the UK market by In-store bakeries (ISBs) for packaging. Following this are the observations on the remaining of the materials.

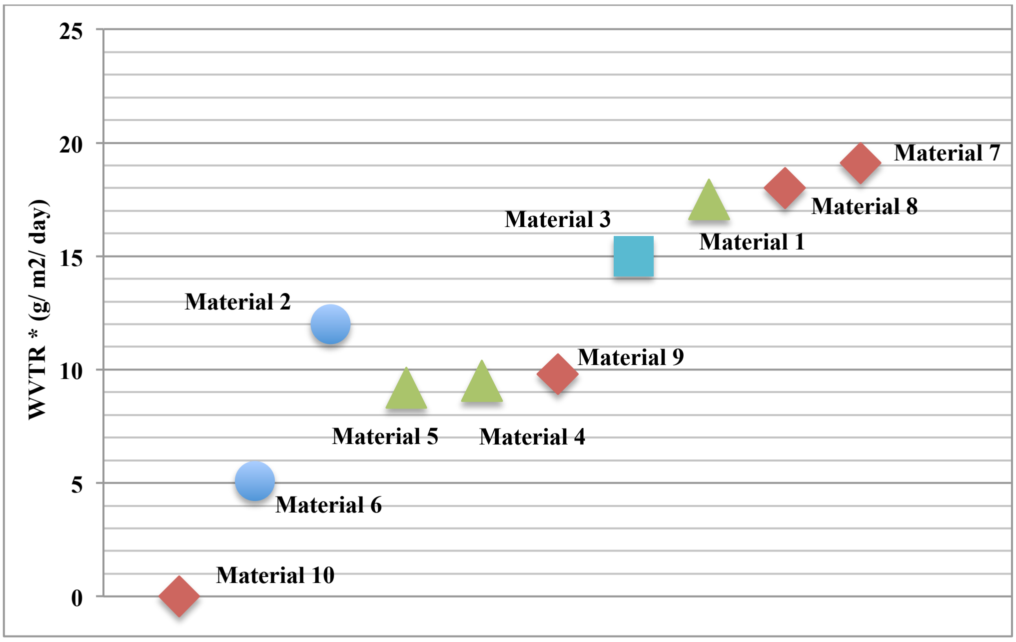


Figure 26: Water vapor transmission rate (WVTR) values of ten packaging materials investigated in the study.

5.3.1 Materials Currently Used in the UK Market

5.3.1.1 Material 1 and Material 8

The In-store bakeries in the UK currently (when this study was conducted) use Material 1 (Semirigid PET box tray) and Material 8 (Paper/PE box tray) to pack 'freshly' baked croissants. Figure 27 provides a sample illustration of baked croissants packed in these materials. Both the trays do not have airlock seal. The calculated surface area to volume ratio was similar even though the design appears different (Appendix 8.8). This mitigates the influence of packaging design on observations and results.

Figure 27: Croissants packed in Material 1 (Left) and Material 8 (right) that are currently used by In-store bakeries in the UK. (Photo by the author)

The total moisture content and water activity of crust in these two materials as well as the unpacked croissants (the control) are presented in Figure 28. The changes observed in Material 1 and 8 similar to changes in the unpacked croissants during 48 h storage. However, these changes were slowed down due to packaging. Significance difference was observed between Material 1 and Material 8 ($p<0.05$). This difference is as expected because PET polymer has lower water vapor permeability compared to coated paper (Appendix 8.4). This observation corroborated with plastic film being more effective to limit the moisture loss from an intermediate moisture food-sponge cake compared to coated paper (Dury-Brun et al. 2006). Furthermore, the changes observed in Material 8 are not significantly different from unpacked croissants. While the two materials preserve slightly higher moisture content in the packed croissants than the unpacked croissants, the significant drop in moisture content over 12 h period indicates the limitation of the materials as suitable for storage over 12 h.

Similar observations were noted for the firmness values and sensorial acceptability. Product firmness increases during storage, cf. Figure 29. Consequently the sensorial acceptability reduces during storage, cf. Figure 30. As with the moisture content and water activity, changes on these scales occur at relatively slower rate in Material 1 compared to Material 8. The reason for higher sensorial acceptability of croissants in Material 1 is due to the moist mouthfeel and softer crumb. Thus, moisture loss in crumb and a firm product is obtained when packed in paper/PE box tray.

Interestingly, it is observed that Material 1 and Material 8 with very-high water vapor transmission rates, 18-20 g m^{-2} day^{-1} (38 °C, 90% RH) are not suitable for croissants packaging to extend the shelf life.

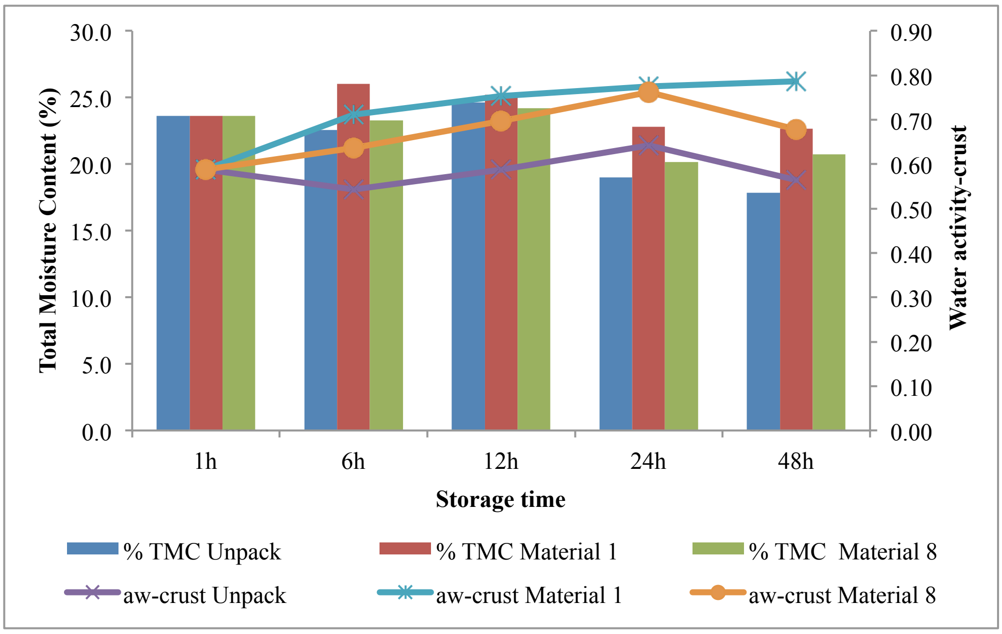


Figure 28: Total moisture content (%) and water activity (aw) values for croissants packed Material 1 and 8 during 48 h storage in comparison with unpacked croissants. No significant difference ((p>0.05) between Material 8 and unpacked croissants. Significant difference (p<0.05) observed between packed croissants in Material 1 and Material 8.

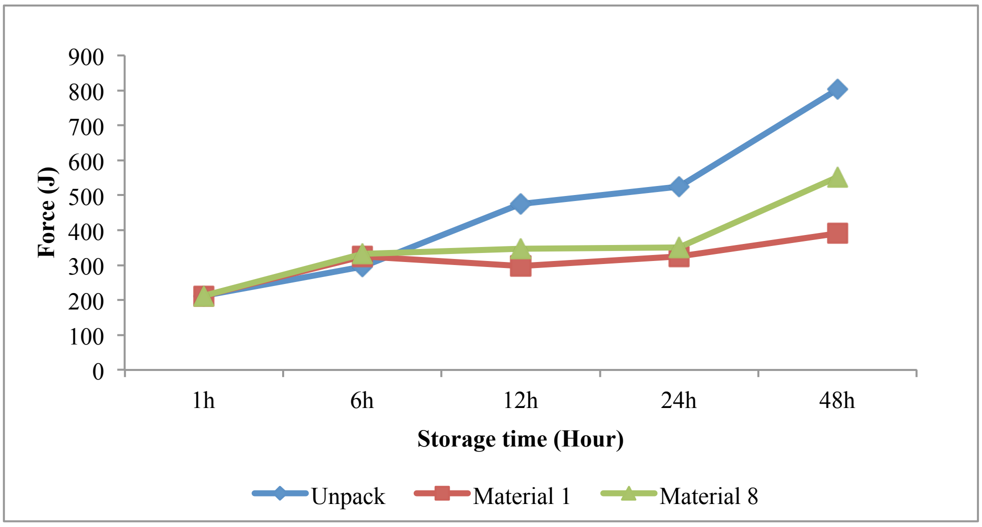


Figure 29: Packed croissants firmness- Material 1 and 8 in comparison with unpacked croissants. Significant difference (p<0.05) observed in the firmness at 24 h storage. Packed croissants in Material 8 observed to be less firm then that in Material 1.

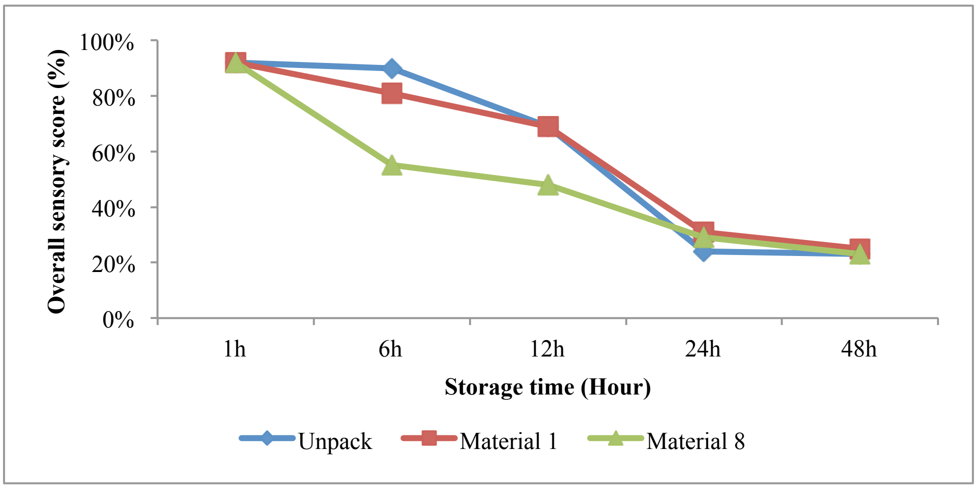


Figure 30: Overall sensory score for packed croissants in Material 1 and 8 in comparison with unpacked croissants. Higher score for Material 1 when compared to Material 8 at 6 h and 12 h because croissants were perceived with moist mouthfeel and softer crumb. Croissants packed in Material 8 had dry mouthfeel and firm crumb.

5.3.2 Materials Not Currently Used in the UK Market

5.3.2.1 Material 9 and 10

In comparison to the Material 1 and 8, when the croissants are packed in a material with zero permeability to water vapor, e.g. Material 10 (multilayer paper/ aluminum film), significant increase in total moisture content and water activity of crust is observed in first 12 h storage, Figure 31. An estimated gain of 12% is observed in first 12 h of storage. The water activity (a_w) of crumb does not show significant difference until 24 h storage. This is explained by the barrier offered by presence of aluminum layer in the film that does not allow water exchange with the surrounding atmosphere causing a high RH inside the package (Robertson 2011b).

The firmness of the product did not show sudden changes as seen in the case of unpacked croissants, cf. Figure 32. The organoleptic acceptability showed sharp decrease, from 92% score to 52% score at 6 h due to loss in crust crispness, cf. Figure 33. The loss in the crispness is due to softening of crust by the plasticization effect of water migrated from crumb to crust and redistribution in package headspace (Cauvain and Young 2008; Robertson 2011b). Similar changes were observed in Material 9 even though the material WVTR is not zero (Appendix 8.9). An explicit explanation to observed similarity couldn't be provided due to limited information on the materials. However, one probable reason could be the influence of the ambient RH conditions on material behavior. Material 10 composition does not allow moisture exchange with the surrounding atmosphere but Material 9 can allow the moisture influx through packaging surface from the surrounding atmosphere (as explained in the section 2.4.2). It can be thus concluded that materials with zero WVTR is also not suitable for croissants packaging.

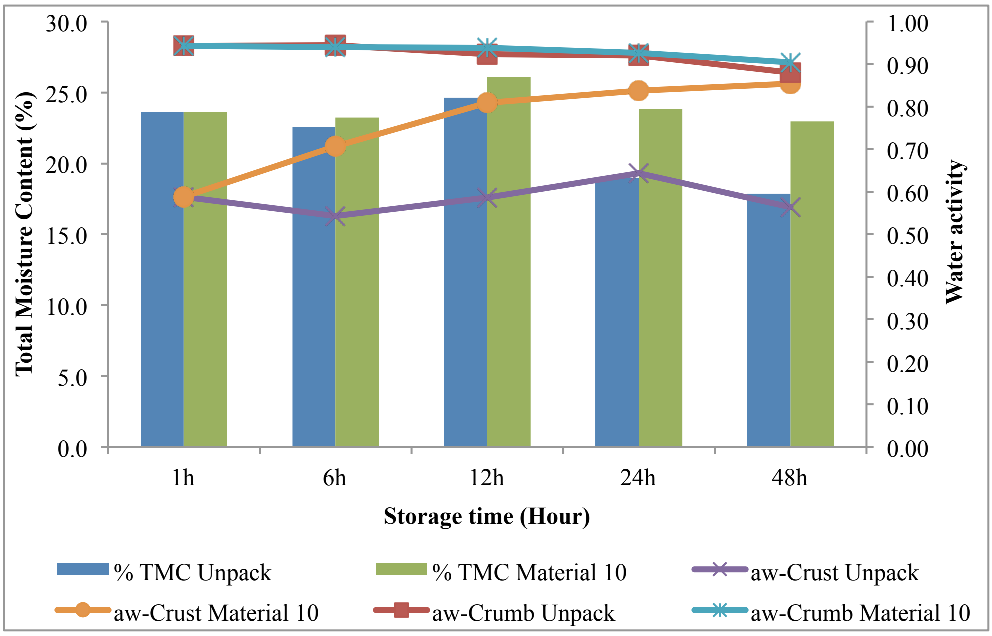


Figure 31: Total moisture content (% TMC) and water activity (aw) of crust and crumb for croissants packed in Material 10 during 48 h storage compared with unpacked croissants. Significant changes observed at 6 h and 12 h storage due to high RH inside the package. (Appendix 8.9)

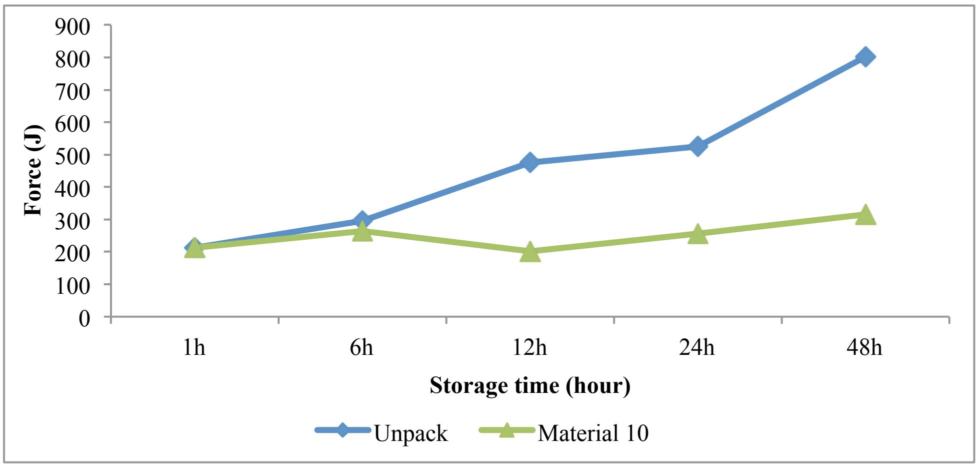


Figure 32: Firmness value in Joule for croissants packed in Material 10 compared to unpacked croissants during 48 h storage.

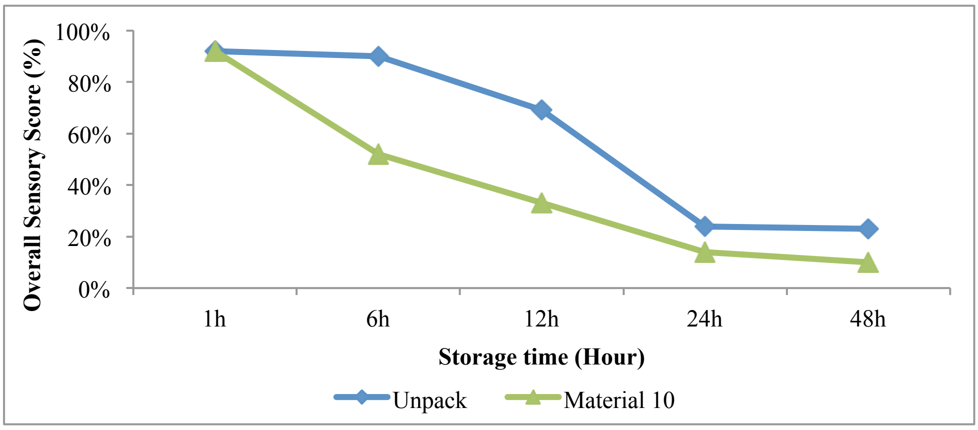


Figure 33: Overall sensory score for croissants packed in Material 10 compared to unpacked croissants during 48 h storage. Significant decrease in product acceptability at 6 h storage, <52% score, due to loss in crispness.

5.3.2.2 Material 3, 6 and 7

From the observations on material with zero and very high WVTR we can conclude that for other materials with low to moderate WVTR (cf. Figure 26 and Table 7) the critical water activity value of crust would be in the range of 0.59 to 0.81 and critical value of moisture content would be less than 25±1% during 12 h storage. This would be true under the assumption that there is no interaction between the material and permeating water.

The rest of the packaging materials were screened for the aforementioned critical values. And it was found that amongst the rest eight materials Material 3, 6 and 7 do not follow stated critical values range during 12 h to 24 h storage. In other words, the shelf life of croissants packed in this material was limited to 12 h as observed in the case of Material 1 and 8. Information regarding changes in quantitative and qualitative measures for croissants packed in Material 3, 6 and 7 can be found in Appendix 8.10.

On the other hand, only three materials were found to follow the stated critical value range during 12 h to 24 h storage. These are Material 2, Material 4 and Material 5 that are discussed in detail in the next section.

5.3.2.3 Material 2, 4 and 5

Material 2, 4 and 5 were observed to have critical total moisture content (%) value of <25±1% during 12 h – 24 h storage, cf. Figure 34. Significant difference ($p>0.05$) observed for Material 5 at 12 h storage. No significant difference observed between

Material 2 and 4 at 12 h storage. Material 2 shows significant difference at 24 h storage compared to Material 4 and 5.

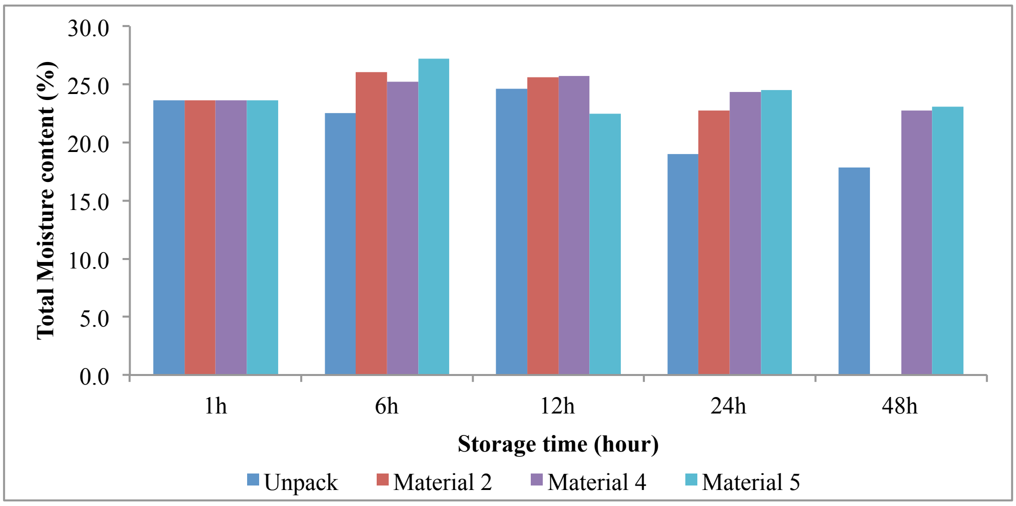


Figure 34: Selection of Material 2, 4 and 5 basis critical total moisture content (%) value of <25±1% during 12 h – 24 h storage. Significant difference (p>0.05) observed for Material 5 at 12 h storage. No significant difference observed between Material 2 and 4 at 12 h storage. Material 2 shows significant difference at 24 h storage compared to Material 4 and 5. Material 2 observations for 48 h were not taken.

The critical water activity value of crust observed in these materials was in the range of 0.59-0.81 during 12 h – 24 h storage, cf. Figure 35. The change in water activity of crust during 12 h storage is found to be lowest in Material 2 ($a_w = 0.1$), Material 5 ($a_w = 0.14$), Material 4 ($a_w = 0.18$), respectively. The difference in the water vapor permeability of these materials, Material 2 > Material 4 > Material 5, explains this difference. It is interesting to observe such difference between material 4 and 5 that are derived from the similar oriented PET polymer. The difference could be result of amorphous or crystalline sites in polymer film as a result of machine orientation or presence of hygroscopic film layer, such as EVOH. Material 2 has holes of 100μ diameter (with 22 mm spacing) that allows some water to escape to the surrounding atmosphere causing least change in crust water activity.

The changes observed in water activity of the crumb are relatively slower compared to changes in water activity of crust, cf. Figure 36. The change in water activity of crumb becomes significant only after 12 h storage. Packed croissants showed less changes compared to unpacked croissants during storage. The observations indicated in the graph for 1 h storage corresponds to unpacked croissants (the control) so when used to compare the 6 h observation for Material 2, high variation is observed. But this could result from variations in baking and not using the same batch for 1 h and 6 h observation.

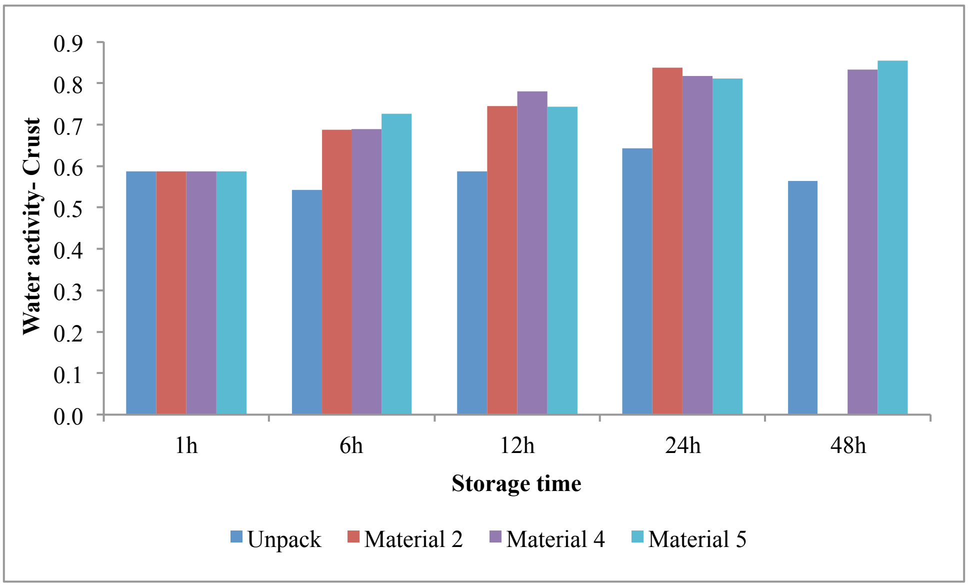


Figure 35: Selection of material 2, 4 and 5 basis critical water activity value of crust in range of 0.59-0.81 during 12 h – 24 h storage. Significant difference ($p<0.05$) observed in Material 4 at 12 h storage. No significant difference observed in Material 2 and 5 ($p>0.05$).

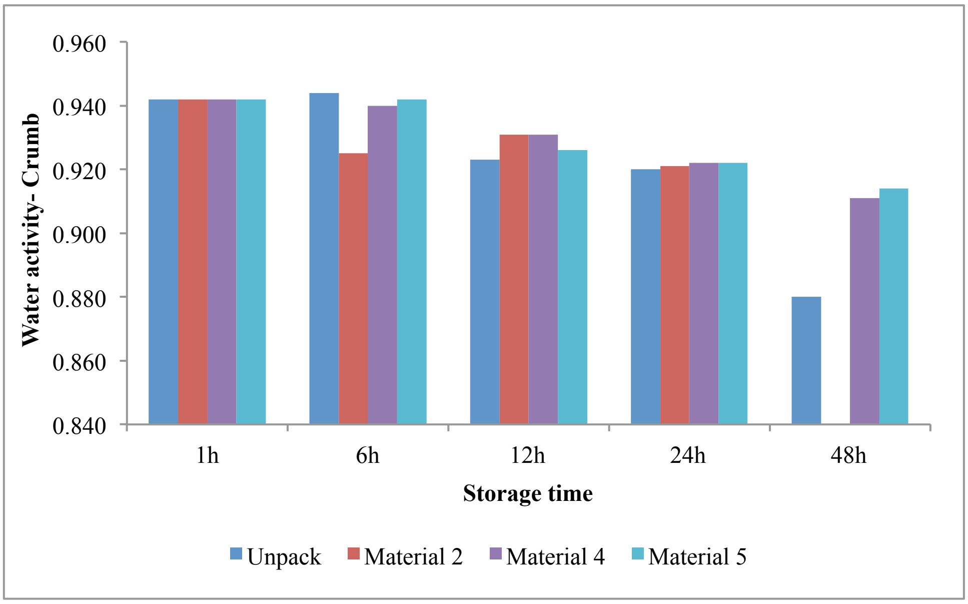


Figure 36: Water activity of crumb during 48 h storage. Unpacked croissants vs. packed croissants in Material 2, 4 and 5. Significant difference observed in Material 5 at 12 h storage. No significant difference observed between Material 2 and 4. Material 2 observations for 48 h were not taken.

The changes observed in moisture content of crust were minimum for Material 2, cf. Figure 37. Further, an estimated 15% increase in the moisture content of the crust is observed in these three materials compared to 40 % increase observed for unpacked croissants at 12 h storage. The crumb also showed least changes for 12 h and 24 h storage, cf. Figure 38. The loss in moisture content of crumb during 12 h storage was half the percentage loss observed in unpacked croissants.

The croissants behavior in Material 2, 4 and 5 indicates that the rate of water transport to the crust, the rate of water uptake by the crust and subsequent loss to the environment was slowed down in these three materials. However, to compare the rate of exchange knowledge on moisture migration phenomenon occurring at the material barrier surface is also required. This was not scoped in the designed experiments.

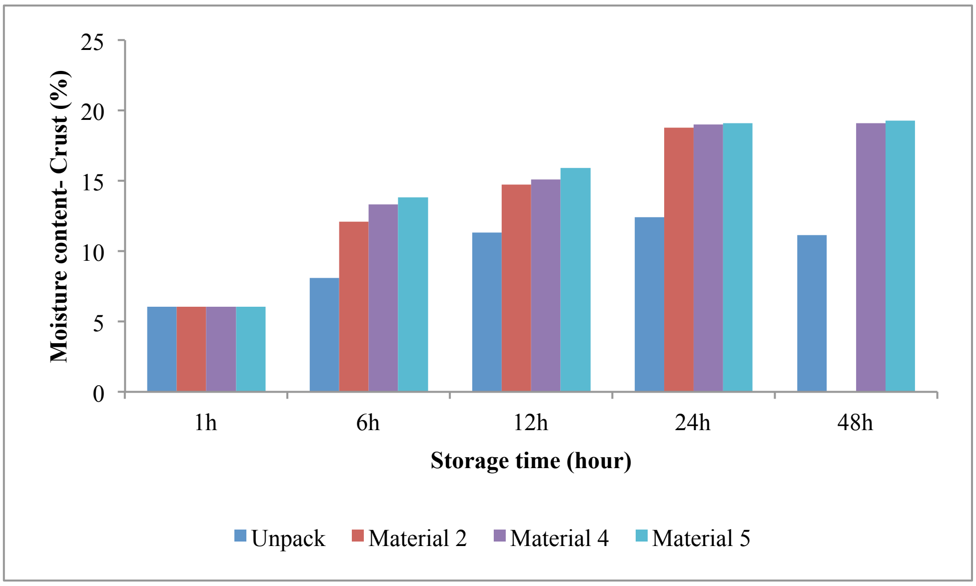


Figure 37: Moisture content of crust during 48 h storage. Unpacked croissants vs. packed croissants in Material 2, 4 and 5. Significant difference ($p<0.05$) observed in Material 2 at 12 h storage. No significant difference observed in Material 4 and 5 ($p>0.05$).

The impact of minimum changes in moisture content and water activity values during storage was observed in product firmness, cf. Figure 39. The firmness values were low for packed croissants compared to unpacked croissants. A lower value indicates that the crumb is moist and soft. In other words the crumb was able to retain sufficient moisture at 24 h storage in these materials. The moisture retained in the crumb at 24 h storage was higher in Material 2> Material 4> Material 5.

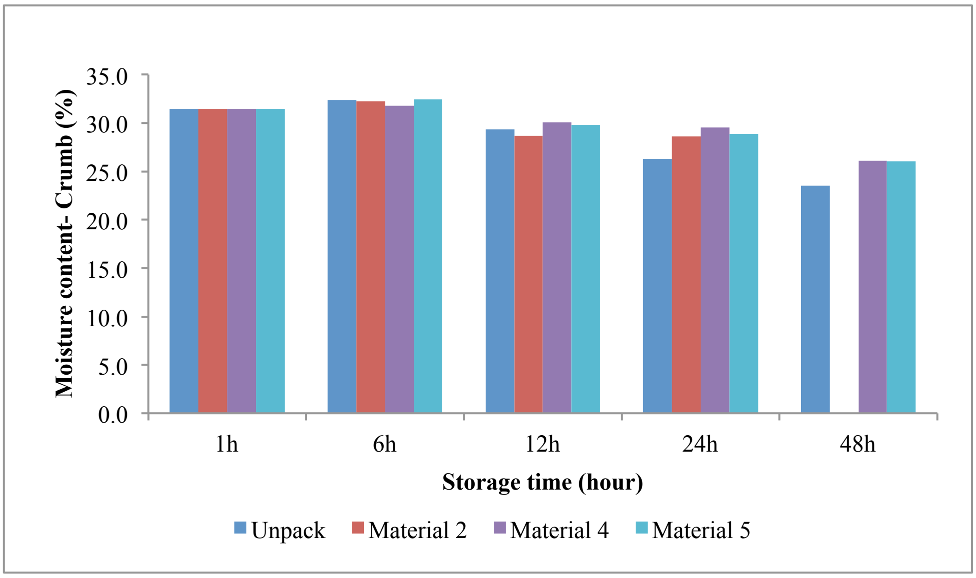


Figure 38: Moisture content of crumb during 48 h storage- unpacked croissants vs. packed croissants in Material 2, 4 and 5. At 24 h moisture retained by crumb was higher in Material 2> Material 4> Material 5. Material 2 observations for 48 h were not taken.

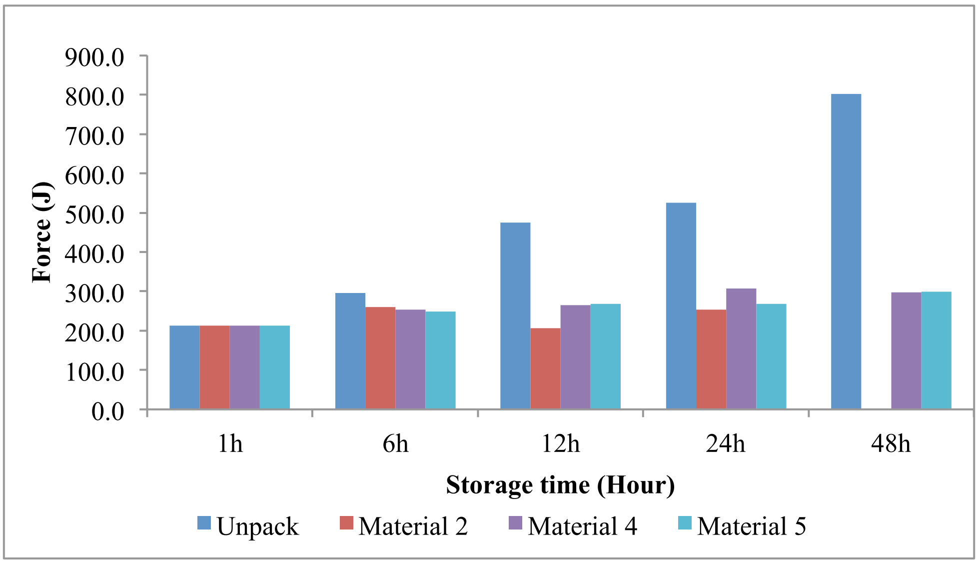


Figure 39: Packed croissants firmness in Material 2, 4 and 5 vs. unpacked croissants. Material 2 showed slower increase in firmness during 24 h storage. This indicates that at 24 h crumb has retained sufficient moisture. This difference can be attributed to nature of Material 2- a perforated plastic polymer compared to non-perforated PET base Material 4 and 5.

To confirm the sensorial acceptability of the product, sensory scores were also compared. While the crispness was lost during 12 h storage in all the packed croissants the product was perceived with moist mouthfeel. Significant difference between acceptability of product in Material 4 during 12 h to 24 h storage is noticed, Figure 40. The difference perceived is due to dry mouthfeel and firm crumb in other two materials. When compared to unpack croissants (the control) higher acceptability is obtained, as the crumb was still moist.

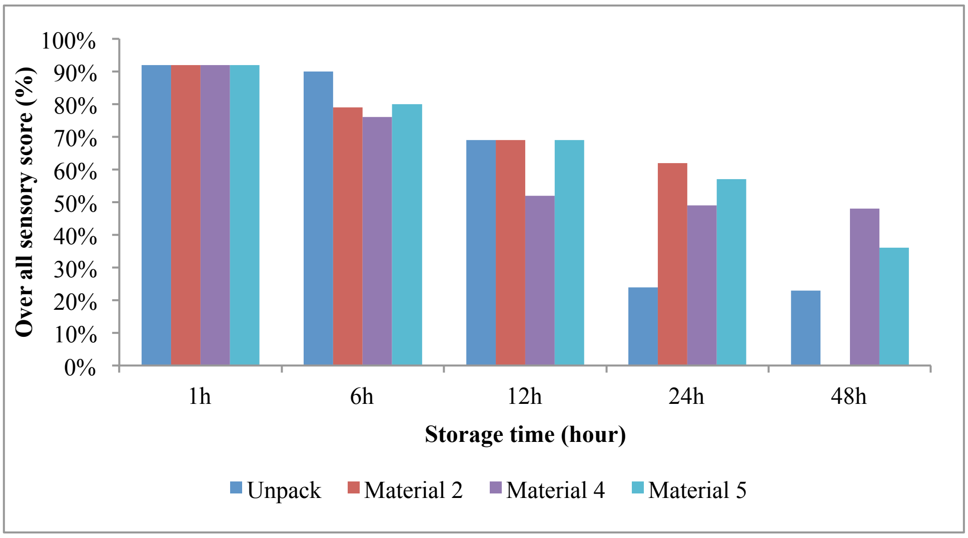


Figure 40: Overall sensory score of packed croissants in Material 2, 4 and 5 vs. unpacked croissants. >65% acceptability between 12 h - 24 h storage. Product acceptability higher in Material 2 and 5 at 24 h storage due to perceived moist mouthfeel. The crispness of packed croissants was however lost at 6 h storage.

It was also observed that changes in croissant behavior in these materials were slower compared to croissants in Material 1 and 8. The product behavior in these materials further indicates that may be lack of an airlock seal in Material 1 and 8 packaging design might have influenced the moisture loss from product. Thereby limiting croissants shelf life to 12 h. So, if Material 1 and 8 were to have airlock seal, the changes in product behavior could be slowed down with Material 1 over Material 8. However, the product behavior in Material 2 and 5 indicates that a control rate of moisture loss is required from the product in order to extend the shelf life. It can be concluded here that packaging materials with moderate MVTR, 9.2-9.5 g m^{-2} day^{-1} (38 °C, 90% RH) are the most suitable for croissant packaging. This material could be a monolayer or a multilayer film structure.

5.4 Summary

Ten packaging materials were investigated in this study (section 4.2 of Chapter 4). The WVTR values of these materials were in the range of 0 to 20 g m^{-2} day^{-1} (38 °C, 90% RH). When croissants are packed the rate of moisture migration from crumb to the crust and subsequently to the surrounding atmosphere are slowed down. The slowed moisture migration is further influenced by the packaging material composition and its water vapor barrier property.

It was observed that the product behavior during storage is acceptable in monolayer films and multilayer flexible film compared to the paper based multilayer flexible film. Packaging materials with very high or high WVTR are not suitable for croissants packaging. Similar results are for the materials with low or zero WVTR. Packaging materials with moderate WVTR are found most suitable to obtain a product with soft crumb during 24 h storage.

6 Conclusions and Future Work Recommendations

In the empirical studies conducted in this work following conclusions have been drawn:

i. Use of critical moisture content and water activity value of product is useful to judge the performance of barrier materials. These values give the information on moisture transfer and related changes in crispness, firmness and sensory parameters of the product.

ii. The crispness measure using force-time curve on texture analysis is not a good indicator for acceptable or unacceptable crispness when comparing different samples.

iii. Evaluation of product sensorial acceptability is very important. The main sensory parameters influenced when croissants were packed are- crispness, firmness and mouthfeel.

iv. The product crispness is not preserved during storage when it is packed. But softness of crumb is preserved for 24 h.

v. The three suitable materials identified for shelf life extension of croissants are: monolayer *oriented-polypropylene* film with perforations (WVTR of 10-14 g m^{-2} day^{-1}) and multilayer *oriented- polyethylene terephthalate* film with or without *ethylene vinyl alcohol* polymer (WVTR of 9.2-9.5 g m^{-2} day^{-1}).

vi. The organoleptic shelf life of croissants is limited to 12 h when packed in materials currently used in the UK, i.e. Material 1 and Material 8. Further it can be concluded that materials with very-high WVTR of 18-20 g m^{-2} day^{-1} are not suitable packaging material for shelf life extension of croissants.

vii. The croissants behavior in Material 2, 4 and 5 indicates that the rate of water transport to the crust, the rate of water uptake by the crust and subsequent loss to the environment was slowed down in these three materials. Therefore, it is possible to retain softness in the crumb up to 24-hour storage.

viii. The primary function of a packaging for croissants and related pastry product is to provide a controlled rate of moisture transfer between the product and it's surrounding.

It can be thus concluded that rate of moisture migration phenomenon in croissant can be slowed down by using material with optimal water vapor permeability. An optimal packaging material is the one that would guarantee the crumb softness but allow enough water loss in the crust to keep some crispness.

This study shows that approach to problems concerning moisture migration in the product requires understanding of the differences in the water activity. If an optimal packaging material is required for a new product or product with a formulation change the first could be to obtain the product moisture sorption isotherm. This will give the products critical values of moisture content and water activity. These critical values should be also tested via simple sensory evaluation technique.

As for further study, it can be an objective and future work to evaluate product behavior in customized monolayer-packaging material with optimal number of holes and hole size. It is recommended to include packaging design as a factor in investigation and consideration to get consumer feedback or a larger group of subjects for conducting product sensorial evaluation.

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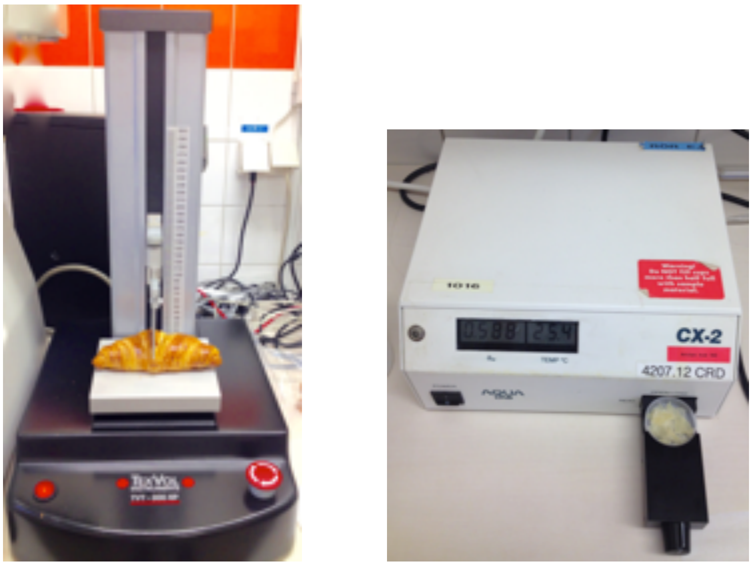
8 Appendix

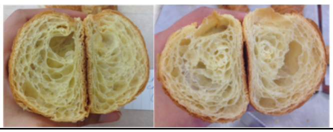
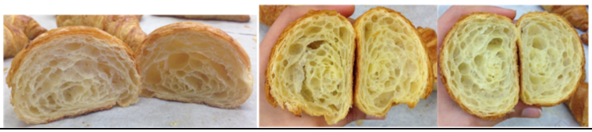
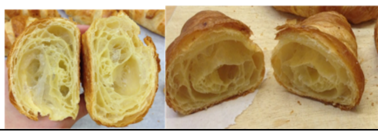
8.1 Baking Oven, Texture Analyzer and Water Activity Meter

(Left)- Convection rotating rack oven (Revent, 626) for croissants baking. (Right) packed and unpacked croissants on rolling racks for storage



(Right) TVT Texture Analyzer (Perten Instruments, Sweden). (Left) Aqua Lab CX-2, Decagon Devices, Pullman Wash., U.S.A for water activity measurement.

8.2 Crumb Structure Score Card

SCORING SCALE	DESCRIPTION
-3	Smallest air pockets, evenly distributed, most dense crumb structure 
-2	Smaller air pockets, unevenly distributed, a denser crumb structure. 
-1	Small air pockets, unevenly distributed, a dense crumb structure. 
0(Standard)	Fairly sized air pockets, evenly distributed, neither open nor dense crumb structure. 
+1	Big air pockets, unevenly distributed, an open crumb structure. 
+2	Bigger air pockets, unevenly distributed, an open crumb structure 
+3	Biggest air pockets, uneven distribution, an open crumb structure 

8.3 Questionnaire

Used to identify and define product and packaging needs.

Product assessment questionnaire

i. Physical state of product- size, shape, weight, density?
ii. General nature of product- Perishable? Fragile?
iii. How can it be damaged? By crushing? By temperature changes? By moisture and relative humidity changes? By oxygen? By odors? By light? By Spoilage? By incompatibility with materials?
iv. How can the package be unsatisfactory? Insufficient barrier? No proper sealing? Transfer odors or flavors to product? Stains easily?

The distribution requirement

i. What happens to the package on its journey to the consumer?
ii. Probable storage conditions?
iii. Duration of storage on shelf/ transport?
iv. The importance of minimum cube (volume) in relation to transport cost?
v. Form of handling equipment?

The marketing requirement (4P's)

i. What is the competition? Packages size? Quantities sold? Price bracket? What are the selling points?
ii. Where is it sold? Self-service? Supermarket? Hypermarket?
iii. Target consumer segment
iv. Consumer Shopping behavior
v. Why does it need packaging? Existing packaging positives and negative?
vi. Packaging convenience and use? Easy opening? Re-closure? Window or completely enclosed? After use? Disposable?
vii. Design requirement? Regulatory requirement? Any limitations?

Packaging material selection and machinery considerations

i. Defining requirements to supplier? Production methods? Cost? Specifications? Sourcing?

ii. Defining marketing needs and product characteristics

iii. Properties of packaging materials?

iv. Search for initial concepts? What must the package achieve? Pros and cons?

Packaging design requirement

i. Existing design review? New design or redesign?

ii. Addressing which consumer requirements? Size? Appearance? Usage instruction?

iii. Shelf size? Estimated display life? Position of display? No. of shelves? Degree of branding necessary?

iv. Cost limitations?

8.4 Permeability Characteristic of Materials

Polymer Name	Thickness (μ)	Basis weight ($g\ m^{-2}$)	WVP* ($g\ m^{-2}\ day^{-1}$)	Literature Reference
Coated Paper	-	300	528[a]	(Dury-Brun et al. 2006)
Kraft paper	-	200	426[b]	-
Paperboard	400	242	246 ± 26	-
Coated Paperborad (25% Clay)	-	200	89	(Andersson 2008)
PET	25	-	15-20	(Galić et al. 2009) (Butler and Morris 2013) (Coles et al. 2003)
Biaxially oriented PET	25	-	18.6	(Fereydoon and Ebnesajjad 2013)
OPET	25	-	18 (20 °C)	(Galić et al. 2009)
Aluminum	25		0	(Coles et al. 2003)
EVOH copolymer	25	-	24-120	-
PP (cast)	25	-	10-12	(Coles et al. 2003) (Butler and Morris 2013)
OPP	25	-	5-7	(Coles et al. 2003)
BOPP	25	-	5.9	(Fereydoon and Ebnesajjad 2013)
EVOH	25	-	60	(Galić et al. 2009); (Butler and Morris 2013)
EVOH	25	-	1000	(Coles et al. 2003)
PE (cast)	25	-	15	(Galić et al. 2009)

* *Water vapor permeability measured at 38 °C/ 90% RH*
[a] *at 25 °C/ 50% RH*
[b] *at 23 °C/ 50% RH*

8.5 Total Moisture Content (%TMC), Moisture Content (MC) and Water Activity (a_w) of Unpacked Croissants

	% TMC$^{\$}$	% MC crust$^{\$}$	% MC crumb$^{\$}$	a_w-crust$^{\$}$	a_w-crumb$^{\$}$
1h	23.6±0.7 ^{b}	6.0±0.1 ^{a}	31.4±0.6 ^{d}	0.57±0.00 ^{a}	0.94±0.004 ^{c}
6h	22.5±0.6 ^{b}	8.0±0.1 ^{b}	32.3±0.4 ^{d}	0.54±0.01 ^{c}	0.94± 0.001^{c}
12h	24.6±0.4 ^{c}	11.3±0.1 ^{c}	29.3±0.4 ^{c}	0.59±0.00 ^{b}	0.92±0.007 ^{b}
24h	18.9±0.1 ^{a}	12.4±0.1 ^{d}	26.2±0.3 ^{b}	0.64±0.05 ^{d}	0.92±0.003 ^{b}
48h	17.8±0.1 ^{a}	11.1±0.1 ^{c}	23.5±0.1 ^{a}	0.56±0.04 ^{a}	0.88±0.006 ^{a}

$^{\$}$ *mean values* ± standard deviation *of two observations*
**mean values followed by same letter are not significantly different from each other (p≤ 0.05)*

8.6 Firmness Value of Unpacked croissants

	Firmness$^{\#}$ (J)
1h	212±50 ^{a}
6h	295±69 ^{a}
12h	475±65 ^{bc}
24h	525±89 ^{c}
48h	802±136 ^{d}

$^{\#}$*mean values* ± standard deviation *of four samples*
**mean values followed by same letter are not significantly different from each other (p≤ 0.05)*

8.7 Materials Currently Used in the UK Market

a) % TMC$

	Unpack	Material 1	Material 8
1h	23.6±0.7 de		
6h	22.5±0.6 d	26.0±0.1 g	23.3±0.4 de
12h	24.6±0.4 ef	25.2±0.3 fg	24.2±0.3 ef
24h	18.9±0.1 ab	22.7±0.2 d	20.1±0.2 bc
48h	17.8±0.1 a	22.6±0.2 d	20.7±0.3 c

$ *mean values* ± standard deviation *of two observations*
**mean values followed by same letter are not significantly different from each other (p≤ 0.05)*

b) % MC crust$

	Unpack	Material 1	Material 8
1h	6.0±0.1 a		
6h	8.0±0.1 b	14.38±0.1 fgh	10.90±1.0 c
12h	11.3±0.1 cd	15.79±0.2 hi	13.23±0.8 ef
24h	12.4±0.1 de	16.19±0.3 i	14.94±0.1 i
48h	11.1±0.1 cd	15.58±0.0 hi	13.57±0.1 efg

$ *mean values* ± standard deviation *of two observations*
**mean values followed by same letter are not significantly different from each other (p≤ 0.05)*

c) % MC crumb$

	Unpack	Material 1	Material 8
1h	31.4±0.6 ef		
6h	32.3±0.4 f	31.54±0.2 ef	30.99±0.2 e
12h	29.3±0.4 d	30.82±0.1 e	31.28±0.2 ef
24h	26.2±0.3 bc	28.89±0.0 d	27.26±0.7 c
48h	23.5±0.1 a	25.14±0.2 b	23.65±0.2 a

$ *mean values* ± standard deviation *of two observations*
**mean values followed by same letter are not significantly different from each other (p≤ 0.05)*

d) aw-crust$^{\$}$

	Unpack	Material 1	Material 8
1h	0.57±0.00 [a]		
6h	0.54±0.01 [c]	0.71±0.00 [cdef]	0.63±0.01 [bc]
12h	0.59±0.00 [b]	0.75±0.00 [def]	0.69±0.00 [cde]
24h	0.64±0.05 [d]	0.77±0.00 [ef]	0.76±0.01 [def]
48h	0.56±0.04 [a]	0.78±0.01 [f]	0.67±0.01 [cd]

$^{\$}$ *mean values* ± standard deviation *of two observations*
**mean values followed by same letter are not significantly different from each other (p≤ 0.05)*

e) aw-crumb$^{\$}$

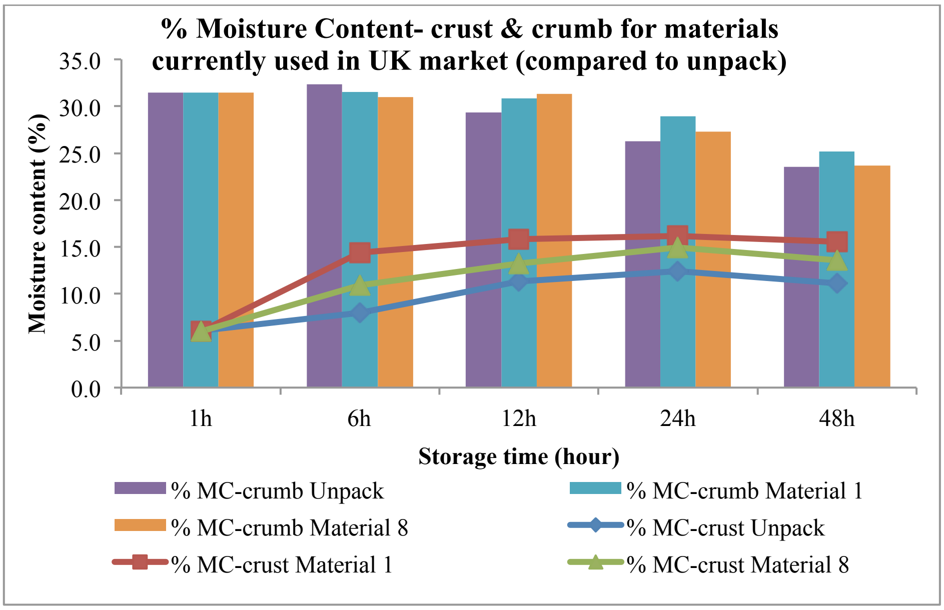
	Unpack	Material 1	Material 8
1h	0.94±0.004 [de]		
6h	0.94±0.001[e]	0.92±0.005 [bcde]	0.93±0.002 [cde]
12h	0.92±0.007 [bcd]	0.92±0.007 [bcde]	0.92±0.001 [bc]
24h	0.92±0.003 [bc]	0.91±0.006 [bc]	0.91±0.006 [b]
48h	0.88±0.006 [a]	0.89±0.006 [a]	0.88±0.001 [a]

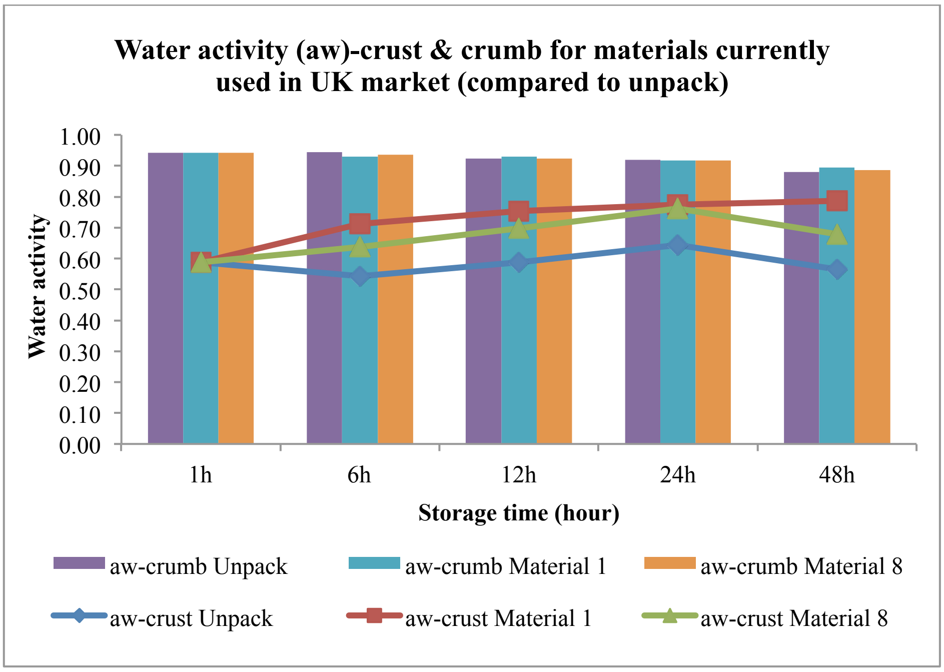
$^{\$}$ *mean values* ± standard deviation *of two observations*
**mean values followed by same letter are not significantly different from each other (p≤ 0.05)*

f) Firmness (J)$^{\#}$

	Unpack	Material 1	Material 8
1h	212±50 [a]		
6h	295±21 [ab]	324±0 [abd]	331±0 [abe]
12h	475±65 [bci]	297±0 [abc]	346±0 [abf]
24h	525±89 [cj]	324±0 [abd]	351±0 [abg]
48h	802±136 [dl]	390±0 [bch]	551±0 [ck]

$^{\#}$*mean values* ± standard deviation *of four samples*
**mean values followed by same letter are not significantly different from each other (p≤ 0.05)*


% Moisture Content- crust & crumb for materials currently used in UK market (compared to unpack)
Moisture content (%)
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
1h
6h
12h
24h
48h
Storage time (hour)
% MC-crumb Unpack
% MC-crumb Material 1
% MC-crumb Material 8
% MC-crust Unpack
% MC-crust Material 1
% MC-crust Material 8


Water activity (aw)-crust & crumb for materials currently used in UK market (compared to unpack)
Water activity
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1h
6h
12h
24h
48h
Storage time (hour)
aw-crumb Unpack
aw-crumb Material 1
aw-crumb Material 8
aw-crust Unpack
aw-crust Material 1
aw-crust Material 8

8.8 Surface Area To Volume Ratio[#] (mm)

	L	W	H	Volume (LxWxH)	Total Surface Area[*]	Total Surface Area: Volume
Material 1	230	170	80	3128000	142200	0.05
Material 8	220	140	55	1694000	101200	0.06

[#] In millimeters (mm)
[*] Total surface area= 2(LxW)+2(LxH)+2(WxH)

8.9 Materials Currently Not Used in the UK Market- Material 9 and 10

a) % TMC[$]

	Unpack	Material 9	Material 10
1h	23.6±0.7 [bcd]		
6h	22.5±0.6 [b]	24.6±0.3 [def]	23.2±0.1 [bc]
12h	24.6±0.4 [def]	25.5±0.3 [fg]	26.0±0.1 [g]
24h	18.9±0.1 [a]	24.9±0.0 [efg]	23.8±0.0 [cde]
48h	17.8±0.1 [a]	23.0±0.0 [bc]	22.9±0.0 [bc]

[$] *mean values* ± standard deviation *of two observations*
**mean values followed by same letter are not significantly different from each other ($p\leq 0.05$)*

b) % MC crust[$]

	Unpack	Material 9	Material 10
1h	6.0±0.1 [a]		
6h	8.0±0.1 [b]	12.6±0.1 [c]	12.9±0.1 [c]
12h	11.3±0.1 [c]	15.2±0.6 [d]	17.2±0.9 [e]
24h	12.4±0.1 [c]	20.0±0.0 [fg]	18.3±0.5 [ef]
48h	11.1±0.1 [c]	20.2±0.0 [g]	19.1±0.2 [fg]

[$] *mean values* ± standard deviation *of two observations*
**mean values followed by same letter are not significantly different from each other ($p\leq 0.05$)*

c) % MC crumb$^{\$}$

	Unpack	Material 9	Material 10
1h	31.4±0.6 ^{hij}		
6h	32.3±0.4 ^{j}	31.5±0.4 ^{hij}	32.1±0.3 ^{ij}
12h	29.3±0.4 ^{efg}	30.4±0.6 ^{fgh}	30.6±0.6 ^{ghi}
24h	26.2±0.3 ^{bc}	28.4±0.0 ^{de}	29.0±0.1 ^{ef}
48h	23.5±0.1 ^{a}	27.3±0.0 ^{cd}	25.2±0.3 ^{b}

$^{\$}$ *mean values* ± standard deviation *of two observations*
**mean values followed by same letter are not significantly different from each other (p≤ 0.05)*

d) aw-crust$^{\$}$

	Unpack	Material 9	Material 10
1h	0.57±0.00 ^{a}		
6h	0.54±0.01 ^{e}	0.69±0.00 ^{c}	0.70±0.01 ^{cd}
12h	0.59±0.00 ^{b}	0.78±0.00 ^{de}	0.80±0.01 ^{e}
24h	0.64±0.05 ^{d}	0.83±0.00 ^{e}	0.83±0.01 ^{e}
48h	0.56±0.04 ^{a}	0.84±0.01 ^{e}	0.85±0.01 ^{e}

$^{\$}$ *mean values* ± standard deviation *of two observations*
**mean values followed by same letter are not significantly different from each other (p≤ 0.05)*

e) aw-crumb$^{\$}$

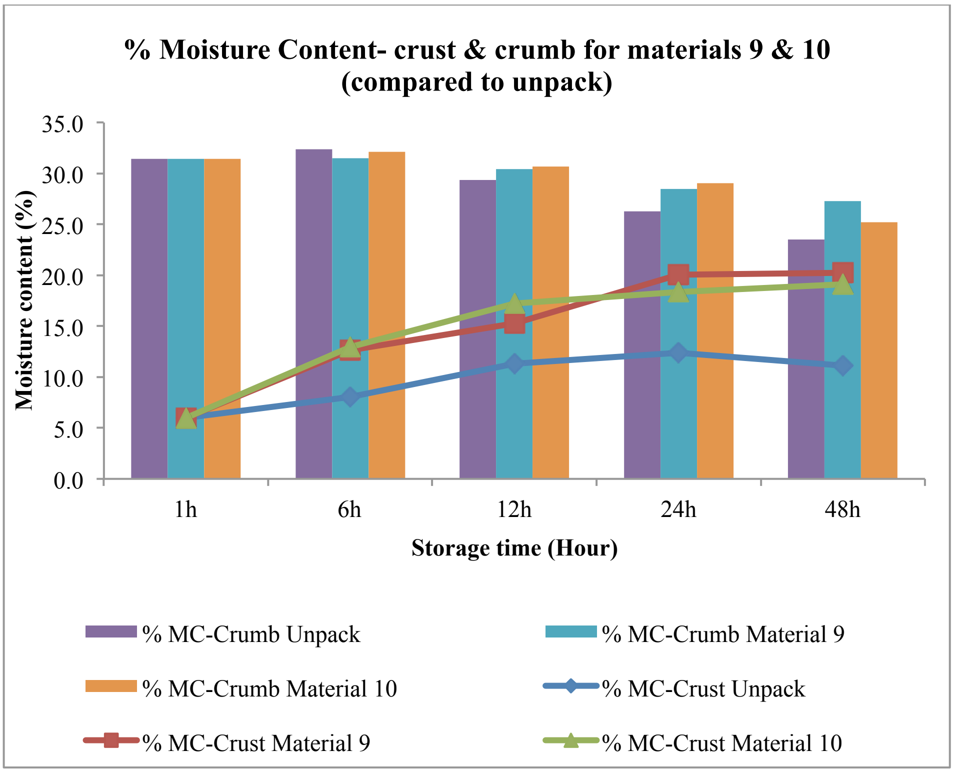
	Unpack	Material 9	Material 10
1h	0.94±0.00 ^{ef}		
6h	0.94±0.00 ^{f}	0.936±0.002 ^{cdef}	0.940±0.003 ^{def}
12h	0.92±0.00 ^{cd}	0.935±0.005 ^{cdef}	0.938±0.006 ^{cdef}
24h	0.92±0.003 ^{bc}	0.925±0.001 ^{cde}	0.926±0.001 ^{cde}
48h	0.88±0.006 ^{a}	0.885±0.005 ^{a}	0.904±0.006 ^{b}

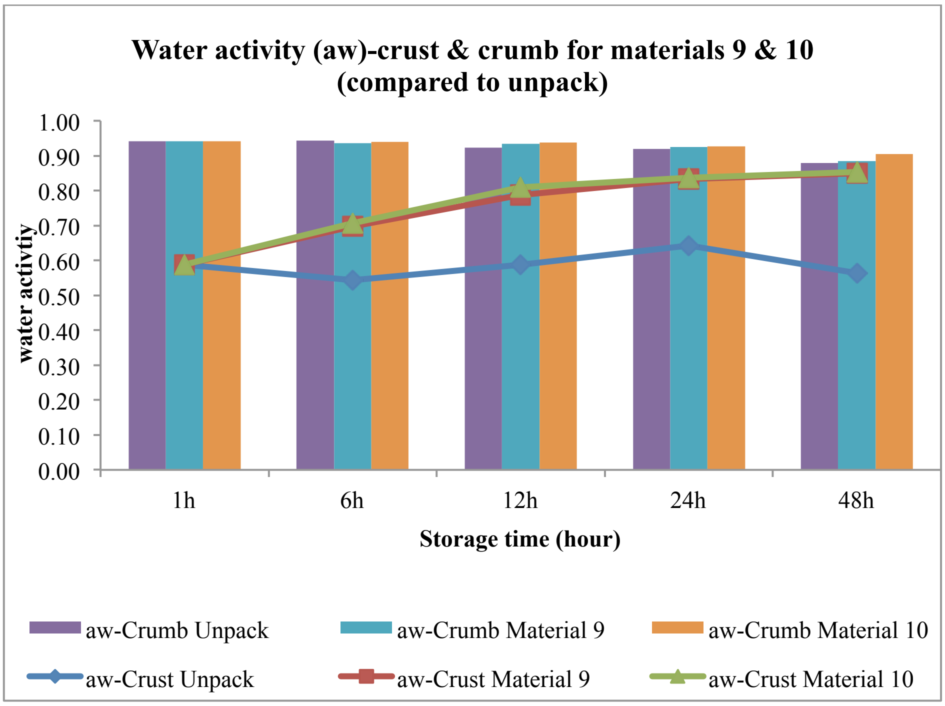
$^{\$}$ *mean values* ± standard deviation *of two observations*
**mean values followed by same letter are not significantly different from each other (p≤ 0.05)*

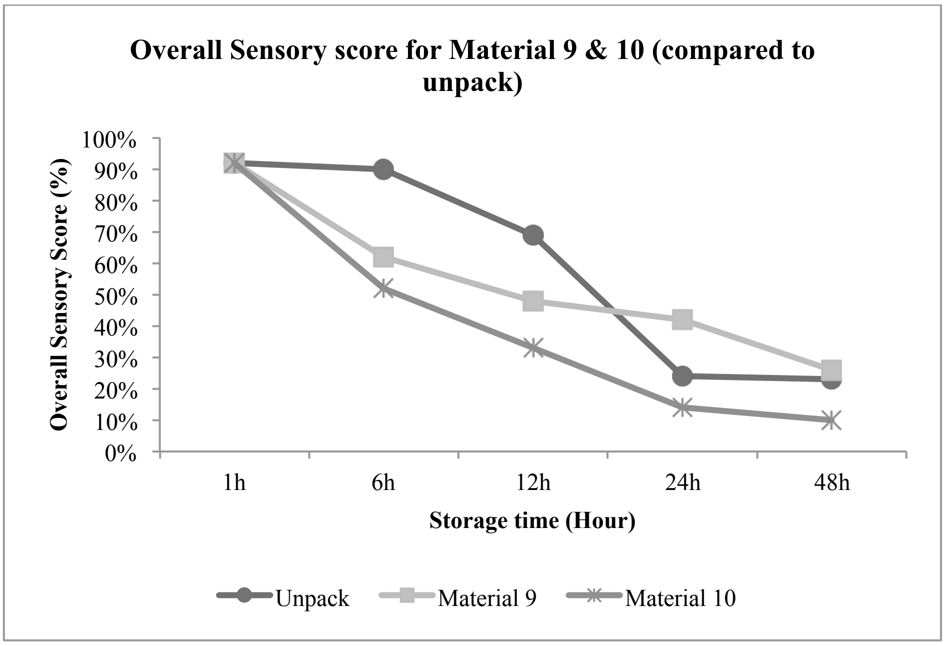
f) Firmness (J)#

	Unpack	Material 9	Material 10
1h	212±50 [a]		
6h	295±21 [ab]	266±54 [a]	264±54 [a]
12h	475±65 [bc]	233±40 [a]	201±49 [a]
24h	525±89 [c]	251±29 [a]	255±24 [a]
48h	802±136 [d]	345±38 [ab]	315±25 [a]

#*mean values* ± standard deviation *of four samples*
**mean values followed by same letter are not significantly different from each other ($p \leq 0.05$)*




Water activity (aw)-crust & crumb for materials 9 & 10 (compared to unpack)
water activtiy
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1h
6h
12h
24h
48h
Storage time (hour)
aw-Crumb Unpack
aw-Crumb Material 9
aw-Crumb Material 10
aw-Crust Unpack
aw-Crust Material 9
aw-Crust Material 10


Overall Sensory score for Material 9 & 10 (compared to unpack)
Overall Sensory Score (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1h
6h
12h
24h
48h
Storage time (Hour)
Unpack
Material 9
Material 10

8.10 Materials Currently Not Used in the UK Market- Material 2, 3, 4, 5, 6, and 7

a) % TMC

	Unpack	Material 2	Material 3
1h	23.6±0.7 ^{fgh}		
6h	22.5±0.6 ^{de}	26.0±0.0 ^{lmn}	25.5±0.2 ^{kl}
12h	24.6±0.4 ^{ijk}	25.5±0.1 ^{kl}	23.5±0.1 ^{fgh}
24h	18.9±0.1 ^{b}	22.7±0.2 ^{def}	21.9±0.0 ^{d}
48h	17.8±0.1 ^{a}		23.9±0.0 ^{ghi}

	Material 4	Material 5	Material 6	Material 7
1h				
6h	25.2±0.1 ^{jkl}	27.2±0.3 ^{o}	26.6±0.1 ^{mno}	23.5±0.1 ^{fgh}
12h	25.7±0.3 ^{lm}	22.4±0.1 ^{de}	26.8±0.0 ^{no}	26.0±0.1 ^{lmn}
24h	24.3±0.2 ^{hij}	24.5±0.0 ^{hij}	23.1±0.2 ^{efg}	21.7±0.0 ^{d}
48h	22.7±0.3 ^{def}	23.0±0.1 ^{efg}	24.4±0.1 ^{hij}	20.6±0.1 ^{c}

$^{\$}$ *mean values* ± standard deviation *of two observations*
**mean values followed by same letter are not significantly different from each other (p≤ 0.05)*

b) % MC crust$^{\$}$

	Unpack	Material 2	Material 3
1h	6.0±0.1^{a}		
6h	8.0±0.1^{b}	12.1±0.2 ^{cde}	15.3±4.1 ^{efghijk}
12h	11.3±0.1^{cd}	14.7±0.0 ^{defgij}	16.2±0.3 ^{ghijklm}
24h	12.4±0.1^{def}	18.7±0.3 ^{klmn}	15.5±0.2 ^{efghijkl}
48h	11.1±0.1^{c}		20.8±0.2 ^{n}

Table continued to next page….

	Material 4	Material 5	Material 6	Material 7
1h				
6h	13.3±1.1 cdefg	13.8±0.1 cdefgh	14.1±1.4 cdefghi	13.5±0.3 cdefg
12h	15.0± 0.1efghij	15.9±0.1 fghijklm	15.1±0.2 efghij	15.0±0.1 efghij
24h	18.9±0.3 lmn	19.0±0.1 mn	17.9±0.8 jklmn	17.3±0.0 hijklmn
48h	19.0±0.1 mn	19.2±0.1 mn	19.0±0.1 lmn	17.4±0.1 ijklmn

$ *mean values* ± standard deviation *of two observations*
**mean values followed by same letter are not significantly different from each other (p≤ 0.05)*

c) % MC crumb$

	Unpack	Material 2	Material 3
1h	31.4±0.6 d		
6h	32.3±0.4 d	32.2±0.4 k	31.4±0.3 ijk
12h	29.3±0.4 c	28.6± 0.2 efgh	28.3±0.4 defg
24h	26.2±0.3 b	28.6±0.0 efgh	28.0±0.1 cdef
48h	23.5±0.1 a		25.4±0.2 ab

	Material 4	Material 5	Material 6	Material 7
1h				
6h	31.7±0.7 jk	32.4±0.1 k	30.5±0.8 hijk	30.7±0.6 hijk
12h	30.0±0.1 fghij	29.8±0.0 fghij	30.3± 0.4ghijk	30.6±0.1 hijk
24h	29.5±0.3 efghi	28.8±0.0 efgh	28.6±1.9 efgh	27.6±0.1 cde
48h	26.0±0.1 bc	26.0±0.1 bc	25.4±0.7 ab	25.3±0.0 ab

$ *mean values* ± standard deviation *of two observations*
**mean values followed by same letter are not significantly different from each other (p≤ 0.05)*

d) aw-crust$

	Unpack	Material 2	Material 3
1h	0.58±0.03 ab		
6h	0.54±0.01 a	0.68±0.01 cde	0.66±0.01 bcd
12h	0.59±0.00 ab	0.74±0.00 efghi	0.76±0.00 fghij
24h	0.64±0.05bc	0.83±0.02 jkl	0.80±0.02 hijkl
48h	0.56±0.04 a		0.86±0.01 l

Table continued to next page….

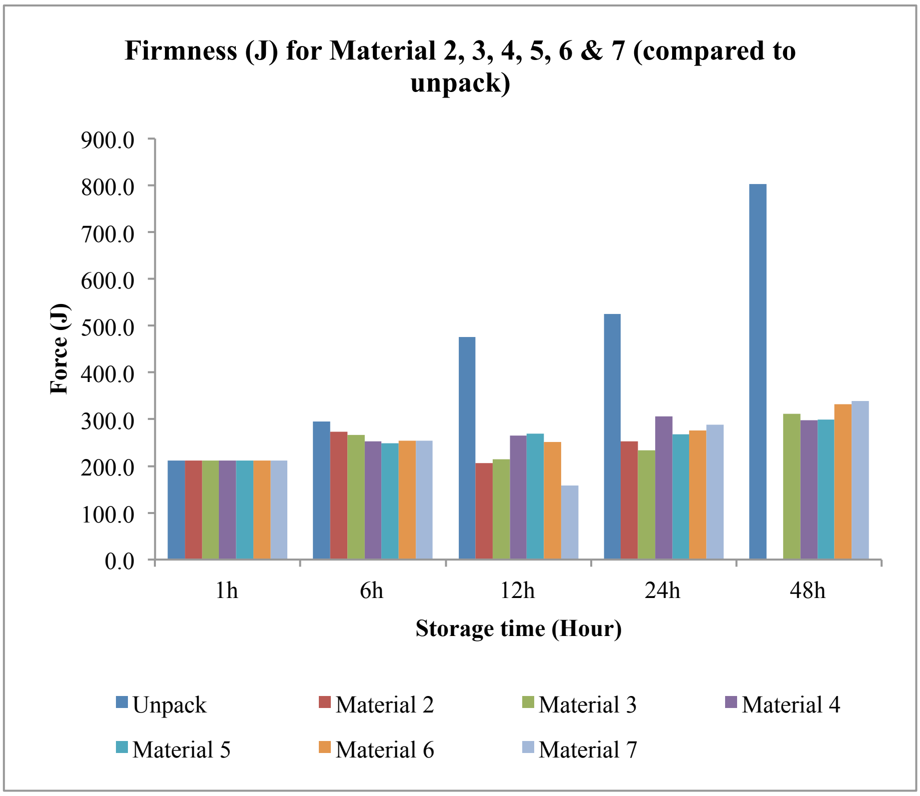
	Material 4	Material 5	Material 6	Material 7
1h				
6h	0.69±0.01 cde	0.72±0.00 defg	0.71±0.01 cdefg	0.69±0.01 cdef
12h	0.78±0.00 ghijk	0.74±0.01 efghi	0.75±0.02 efghi	0.73±0.02 defgh
24h	0.81±0.02 ijkl	0.81±0.02 hijkl	0.81±0.01 hijkl	0.83±0.01 jkl
48h	0.83±0.01 jkl	0.85±0.03 kl	0.85±0.01 l	0.81±0.00 hijkl

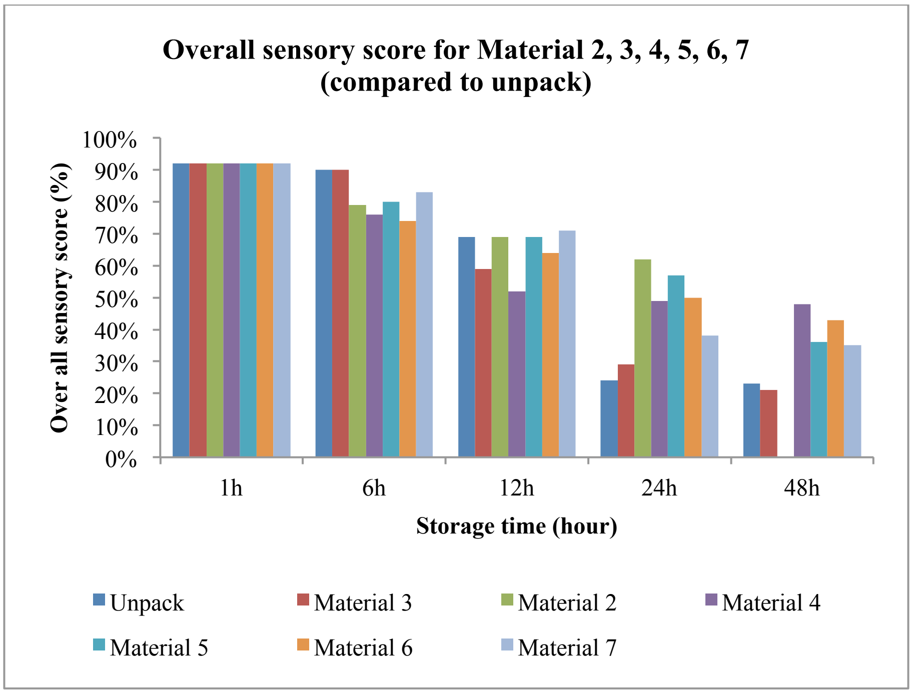
$ *mean values* ± standard deviation *of two observations*

**mean values followed by same letter are not significantly different from each other (p≤ 0.05)*

e) aw-crumb

The model was not valid as F-value= 0.975 is greater then p-value (0.05). Coefficient of Determination R^2= 49%. Therefore, comparison between materials couldn't be analyzed.




Overall sensory score for Material 2, 3, 4, 5, 6, 7
(compared to unpack)
Over all sensory score (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1h
6h
12h
24h
48h
Storage time (hour)
Unpack
Material 3
Material 2
Material 4
Material 5
Material 6
Material 7