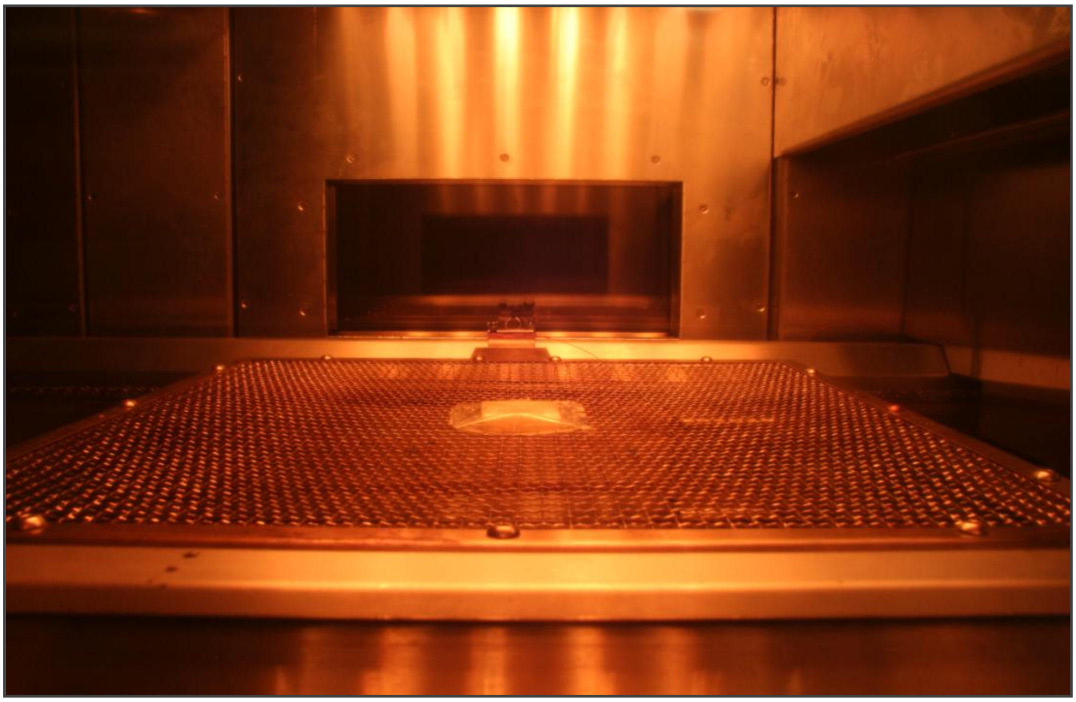

Selection of packaging material suitable for infrared heating of food

Master of Science Thesis in the Master Degree Programme, Materials and Nanotechnology

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Cover:
A piece of bread inside a plastic pouch is exposed for IR heating.

Abstract

Today there is a large industrial interest in infrared (IR) heating of packaged foods. The requirements on these types of packaging materials are that they need to be transparent and heat resistant. The IR treatment of packaged food can reduce the number of microorganisms and also increase storage time without using preservatives.

Infrared light belongs to the electromagnetic spectra and the IR wavelengths can be divided into three groups; short-IR (0.7 µm-2 µm), medium-IR (2 µm-4 µm) and long-IR radiation (4 µm-1 mm). In this study only short-IR radiation has been used and it has also the highest intensity of the three groups. The advantages with IR heating compared to ordinary convection heating are faster heating, higher efficiency, less energy required and a more uniform heating.

All the incident energy that hits the object will be reflected, absorbed or transmitted. Since as much energy as possible should be absorbed of the food product, it is important that the packaging material transmit as much energy as possible, i.e. the packaging material should have a high transmittance and a low absorbance and reflectance. The most common packaging materials for foods are metal, glass, paperboard and plastics, but it is only plastics that fulfil the requirements of high transparency and low absorption. In this study twelve different packaging materials were tested and they consist of different varieties of the polymers polyethylene (PE), polyamide (PA), polypropylene (PP), polyethylene terephthalate (PET) and barriers of ethylene vinyl alcohol (EVOH).

To find a method that could be used to evaluate the twelve different materials, it was necessary to first evaluate the heating conditions of the IR oven and then do tests with a black body. The black body was made of two copper plates that were painted black and had a thermocouple in between, which measure the temperature in the centre of the black body. A black body absorb all incident energy and do not reflect or transmit anything. Because of this, the black body could be used as a reference since the tested materials will be either on top of the black body or shaped as a pouch around the black body.

The tested materials were evaluated with respect to their transmittance, reflectance and changes in tensile strength. The three best suited materials as a packaging material for IR heating were chosen for further tests with bread, to see how the materials behave in contact with food. To study the changes of the IR treated bread with a plastic film on top, the water activity and the weight of the bread was measured before and after IR treatment. A plastic film on top of the bread did not influence the heating time significantly and the water activity and weight of the bread changes less with a plastic film on top of the bred during heating compared to an IR treated bread without a film on top.

Sammanfattning

Idag finns det ett stort intresse av att kunna värma paketerad mat genom infraröd (IR) strålning och kravet på ett paketeringsmaterial för detta användningsområde är att det måste vara transparent och värmetåligt. Genom att IR behandla paketerat livsmedel kan mängden mikrobiella bakterier på livsmedlet minskas samt att hållbarhetstiden kan förlängas utan användning av konserveringsmedel.

IR strålning tillhör det elektromagnetiska spektrumet och våglängderna på IR strålning kan delas in i tre olika kategorier; kortvågig IR (0.7 µm-2 µm), medelvågig IR (2 µm-4 µm) och långvågig IR (4 µm-1 mm). I denna studie har endast kortvågig IR strålning använts och det är även den typ som är den mest intensiva av de tre olika IR vågorna. Fördelarna med att värma livsmedel med IR strålning istället för i en traditionell ugn är att uppvärmningen går snabbare, mer effektiv process, mindre energiåtgång och det blir en mer jämnare värmning.

Av den totala energin som når ytan på ett objekt kommer energin att reflekteras, absorberas eller transmitteras. Då så mycket som möjligt av energin ska nå livsmedlet är det viktigt att förpackningsmaterialet släpper igenom så mycket energi som möjligt, dvs. förpackningsmaterialet behöver ha en hög transmittans samt låg absorption och reflektants. De vanligast förekommande förpackningsmaterial för livsmedel består av metall, glas, kartong eller plast men det är bara plast som uppfyller kravet på hög transmittans och låg absorption. I studien användes tolv olika förpackningsmaterial för livsmedel som bestod av olika varianter av polymererna polyeten (PE), polyamid (PA), polypropylen (PP) och polyetentereftalat (PET) samt även barriärer av etylen vinyl alkohol (EVOH).

För att ta fram en metod som kunde användas för utvärdering av de tolv olika materialen var det nödvändigt att först granska IR ugnens värmningsförhållanden och sedan göra tester med en så kallad svart kropp. Den svarta kroppen bestod av två stycken svartmålade kopparplattor med ett termoelement emellan som mäter temperaturen i mitten av den svarta kroppen. En svart kropp absorberar all infallande energi och reflekterar eller transmitterar ingen energi, därför kunde den svarta kroppen användas som referens då de testade materialen lades antingen på den svarta kroppen eller som en påse runt den svarta kroppen.

De testade materialen utvärderades i transmittans, reflektants och skillnad i dragstyrka och de tre bästa materialen, lämpliga som förpackningsmaterial för IR värmning, valdes ut för fortsatta tester med bröd för att se hur materialen betedde sig vid kontakt med livsmedel. För att studera förändringarna i det bröd som IR behandlats med en plastfilm över sig, mättes vattenaktiviteten och vikten på brödet före och efter IR värmning. En plastfilm över brödet under IR värmning påverkade inte värmningstiden speciellt mycket och vattenaktiviteten hos brödet förändrades mindre när en plastfilm låg över brödet, jämfört med ett IR behandlat bröd utan plastfilm.

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Finally I would like to thank all my friends and family that have supported me during those weeks I have been working with my master thesis. Thank you all.

Content

Glossary

Absorption: A process where gas, liquid or energy is taken up by another substance.

Acetal: An organic chemical compound and a functional group with the formula RCH(OR′)(OR″), where R, R′ and R″ are different chemical groups. Acetal is used in chemical synthesis to prevent undesirable reactions (Nationalencyklopeden 2010).

Amorphous: An amorphous material has no shape e.g. areas in polymers where no regular structural pattern (such as crystallinity) occurs.

Black body: A body that absorbs all incident energy and do not reflect or transmit anything. The emissivity of a black body is equal to 1.

Bulk polymer: The easiest and most common polymers belong to this group of polymers e.g. PE and PP.

Copolymer: A polymer formed from a number of monomers. A copolymer is a polymer with properties from two or more separated polymers.

Crystals: A very organized and regular group of atoms that forms crystals within a material. The degree of crystallinity influences hardness, density, transparency etc.

Electromagnetic spectrum: The electromagnetic spectrum is the range of all possible frequencies from the electromagnetic radiation. The spectrum extends from long, low frequent radio waves to short and high frequent gamma rays.

Emissivity (ε): A body’s ability to emit electromagnetic radiation (heat or light). A black body have the highest possible emissivity ($\varepsilon=1$).

Engineering polymer: Polymers with properties that compete with properties of metals. Better properties than bulk polymers but not as good as advanced polymers.

EVOH: Ethylene vinyl alcohol. A copolymer between ethylene and vinyl alcohol and this combination is commonly used as a barrier.

Glass transition temperature (T_g): T_g is where a material goes from a glass-like to a rubber-like material or vice verse, i.e. hardness and stiffness changes significantly.

Grey body: A body that is not totally black. A grey body does not absorb as much energy as a black body and the emissivity for a grey body is between 0 and 1.

Infrared (IR): Infrared light consists of waves between 0.7 µm and 1 mm and is placed next to the visible light in the electromagnetic spectra.

Melting temperature (T_m): Melt temperature (T_m) or melting point. T_m is the temperature at which a material changes from a solid to a liquid or in the other way.

Microwave: Longer waves than IR waves and also lower frequency. Microwaves are between 1 mm to 1 m.

Modulus: The slope of the stress-strain curve in the elastic region.

PA: Polyamide or nylon is a polymer which consists of amide bonds.

PE: Polyethylene belongs to the bulk polymer and is one of the easiest processing polymers.

PET: Polyethylene terephthalate, the most common of the thermoplastic polyesters.

Polyester: A class of polymers consisting of ester bonds.

Polyolefin: Plastics that contains only carbons and hydrogen. PE and PP belongs to this group.

PP: Polypropylene belongs to the bulk polymers. PP has higher strength and stiffness than PE.

PVdC: Polyvinyldiene chloride. A polymer derived from vinyldiene chloride and is common used as a moisture barrier.

Radiation: Heat transport through waves.

Reflectance: That part of the incident light or energy that scatters back from the object.

Semi crystalline: A material that has both amorphous parts and crystalline parts.

Specific heat capacity (C_P): The specific heat indicates how much heat that is needed to change the temperature of a material.

Tensile strength: A measure of the force needed to pull a material apart.

Thermocouple: A connection between two different metal plates that generate a voltage when the temperature is changing. Thermocouples are used as temperature sensors for measurements.

Thermoplastic: A polymer that become softer and melts during heating. Because of this thermoplastics can be re-melted and recycled.

Thermoset: A thermoset is a polymer that just can be moulded once by heat and if heated again, it will start to degrade.

Transparency: The ability of a material to let light or energy to pass through the material.

Ultraviolet (UV): Ultraviolet light consists of waves between 10 nm and 400 nm and is placed next to the visible light. UV-light has a higher frequency than IR-light. The sun consist of e.g. UV which makes polymers degrade faster.

Water activity (a_w): a_w is the moisture pressure above the food material divided by the moisture pressure above pure water i.e. $a_w=P/P_0$.

1 Introduction and objective of work

Heating of packed foods by infrared (IR) radiation has large industrial interest. IR is a rapid heating method allowing for example surface decontamination of packed foods without affecting food quality. One of the most important properties on a package material for this application is that the packaging material has to allow the transmission of IR radiation to the product without reducing the amount of energy transmitted to the food product.

Today there is a lack of information about how the optical properties of different packaging materials affect the IR radiation, and consequently the amount of energy absorbed by the food. By knowing how a material behaves during IR heating it can help to select material for IR treatment of packed foods. The IR treatment of package food can reduce the amount of microbiological growth and also increase storage time without using preservatives.

1.1 Objective

The aim with the project is to evaluate the effect of selected packaging materials on IR heating and select the most suitable packaging materials for food products. The work will only focus on already existing packaging materials for food products.

Expected results are to evaluate the heating conditions in an IR oven and find a methodology to assess packaging material for IR heating and evaluate the performance of different packaging material regarding IR heating.

2 Literature review

The literature review is divided into two main parts. The first part (chapter 2.1-2.2) consists of information about the IR technology. The second part (chapter 2.3-2.6) consists of information about packaging material, their properties and behaviour in contact with heat and food products and also how to evaluate their mechanical properties.

2.1 Infrared (IR)

Infrared light is a type of electromagnetic waves with a wavelength between 0.7 µm and 1 mm and is placed next to the visible light in the electromagnetic spectra (see figure 2.1). The IR wavelengths can be divided into three parts (Richardson 2001), (Krishnamurthy, et al. 2008);

- Short waves or near-infrared (NIR), wavelengths between 0.7 µm and 2 µm.
- Medium waves or mid-infrared (MIR), wavelengths between 2 µm and 4 µm.
- Long waves or far-infrared (FIR), wavelengths between 4 µm and 1 mm.

Short IR waves have the highest frequency of the three different IR waves and it also appears at higher temperatures (above 1000 °C). Medium IR waves have a lower frequency than short IR and therefore also a lower temperature and long IR waves have even lower frequency and working at temperatures below 400 °C. Long IR waves are the main heat transfer mechanism in ordinary ovens and most food components absorb radiative energy in that wavelength area (Krishnamurthy, et al. 2008). A new technique in food processing is to use short IR waves in applications like drying, baking, frying and surface decontamination of foods.

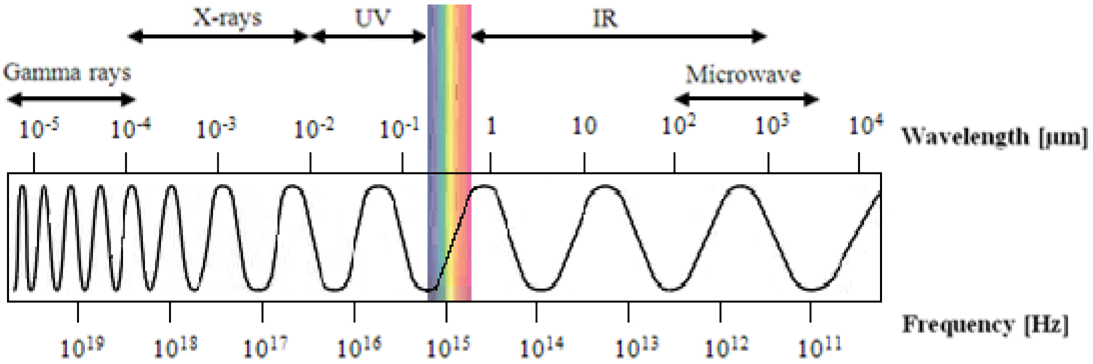


Figure 2.1*. Electromagnetic wave spectrum. Infrared waves are in between the visible spectra and microwaves.*

2.1.1 Infrared heating

There are many advantages with IR heating compare to convection heating methods. One of the main reasons to use IR heating is that it can reduce both processing time and manufacturing costs. This mostly because the oven does not heat the surrounding air so the heat is only absorbed by the product. The heating time is reduced and also the energy consumption and consequently the processing costs. Other advantages and some disadvantages with IR heating are listed on the next page (Richardson 2001), (Staack 2008), (Krishnamurthy, et al. 2008).

Advantages:

- High thermal efficiency.
- Fast heating rate.
- Uniform drying temperature.
- Uniform heating.
- High degree of process control.

Disadvantages:

- Low penetration power.
- Prolonged exposure of biological materials may cause fracturing.

IR heating has many application areas in industries, for example in the car industry or in the paper processing, where drying is a common technique (Richardson 2001). Today, IR heating is introduced more and more in the food processing industry and the main reason to heat food products is to extend their shelf life or to enhance the taste of the food (Krishnamurthy, et al. 2008).

The absorbed amount of IR radiation at a product is dependent on many factors. Some of them are (Ircon Drying Systems 2001);

- The distance between the IR source and the exposed object, a shorter distance gives a faster heat transfer.

- The colour of the object. The darker the object is, the more radiation it will absorb e.g. a black body absorb as much radiation that is possible for a certain situation. At the same time a colourless material will transmit almost all radiation.

- The angle that the IR radiation hits the object. The fastest heat transfer is when the IR radiation hits the object perpendicular.

- The thickness of the object. It takes longer time to heat a thick object compared to a thin, but a thick material will keep the heat for a longer time. A too thin object will transmit some of the radiation.

- A large surface area which is exposed to IR radiation will have a higher heat transfer than a smaller surface area.

2.1.2 Optical properties

When IR waves hits an object the incident waves will be reflected, absorbed or transmitted (see figure 2.2). The reflection of IR radiation depends on the surface structure and properties of the surface material. A metal reflect more radiation than e.g. paper. The roughness and smoothness of the surface will also affect the reflection.

The transmission depends on the thickness of the material. A thicker material gives a lower transmission. Also the colour of the material affects the amount of transmitted energy. A black body will not reflect or transmit any radiation while a transparent material transmits almost all incident radiation.

The degree of heating in the material depends on the absorption, the more absorption, the more heating. Also, the higher temperature, the shorter waves and this will cause a deeper penetration of the material. The heat transfer can be calculated by Stefan-Boltzmann's law (see chapter 2.1.4.1).

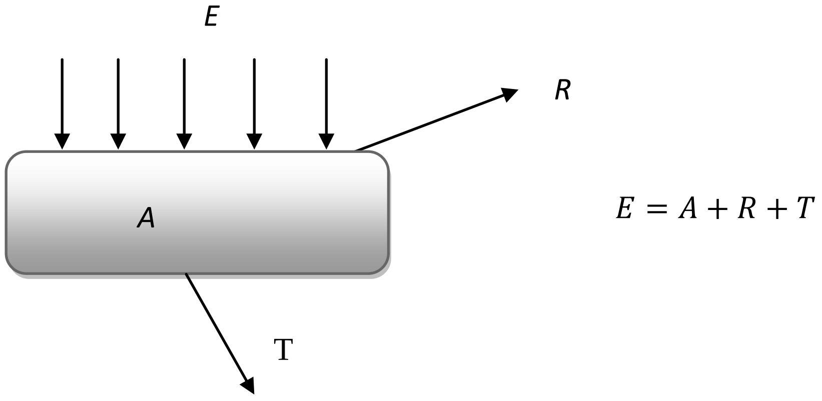


Figure 2.2. *The total energy (E) that hits the product is either reflected (R), absorbed (A) or transmitted (T).*

When the IR waves hits a molecule in the object, vibration and rotation on the molecules starts and transform the radiation into heat. The fundamental vibrations that occur are stretching and bending (see figure 2.3). Stretching means that the distance between the atoms in a molecule increases and decreases and bending means that the atoms move. This movement in the molecules will be transformed into heat (Richardson 2001).

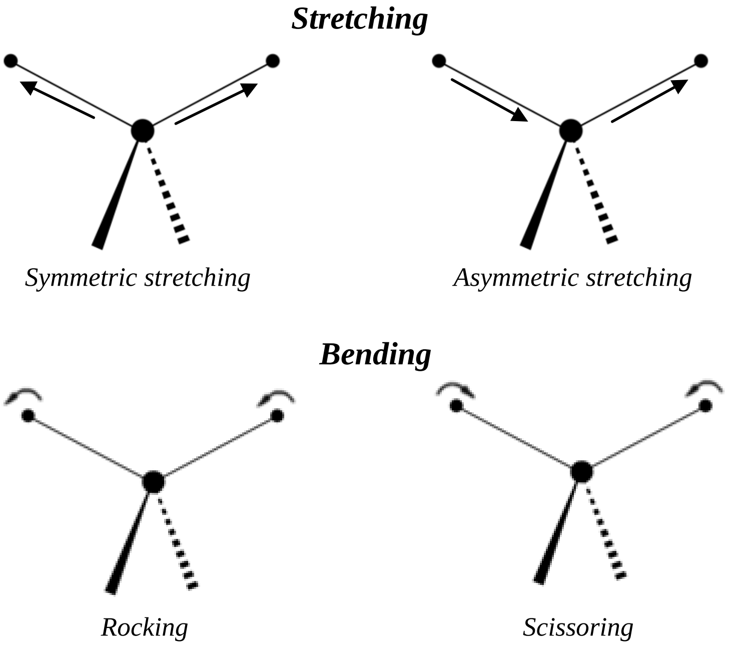


Figure 2.3. *The figure shows how the molecules vibrate when IR waves hits them.*

2.1.3 Black body

A perfectly black body is an object that absorbs all incident electromagnetic radiation and do not reflect anything i.e. the emissivity is equal to the absorption ($\varepsilon = 1$). The radiation leaving the black body is only dependent on the properties of the black body itself. There is only one parameter that affects the radiation leaving the black body and it is the temperature of the body and every temperature have their own wavelength (see figure 2.4).

A body which does not absorb all incident radiation is called a grey body. A grey body has a lower emissivity than a black body and the emissivity is dependent on the frequency of the radiation, temperature and direction (Staack 2008).

2.1.4 Basic laws of black body radiation

2.1.4.1 Stefan-Boltzmann's law

The energy that radiates from a body can be described with the Stefan-Boltzmann law (equation 2.1).

$$q = \varepsilon\sigma A T^4 \qquad \text{(Equation 2.1)}$$

Where q is the energy that radiates from a body [W], ε is the emissivity, σ is Stefan-Boltzmann constant (σ = 5.6704·10^{-8} W/m^{2}K^4) (Mohr, Taylor and Newell 2007), A is the surface area [m^2] and T is the temperature in Kelvin. The emissivity for a black body is equal to 1 and for a grey body; the emissivity is between 0 and 1 (Staack 2008), (Richardson 2001).

2.1.4.2 Planck's law

The maximum intensity that can be produced by a black body is shown in figure 2.4. The curves in figure 2.4 show the maximum possible radiation that can be absorbed by a body at temperatures ranging from 200 K to 6000 K. The maximum intensity that a body can produce can be calculated by Planck's law (equation 2.2).

$$I_{\lambda,b}(\lambda,T) = \frac{2hc_0^2}{\lambda^5(\exp\left(\frac{hc_0}{\lambda kT}\right)-1)} \qquad \text{(Equation 2.2)}$$

Where I is the intensity [A], h is Planck's constant (h = 6.63·10^{-34} m^2 kg/s), c_0 is the speed of light in vacuum [m/s], λ is the wavelength [m], k is the Boltzmann constant (k = 1.381·10^{-23} J/K) (Mohr, Taylor and Newell 2007) and T is temperature in Kelvin (Staack 2008), (Richardson 2001).

2.1.4.3 Wien's displacement law

The spectral distribution has a maximum point which gives the wavelength, λ_{max}, and is dependent on the temperature. Wien's displacement law (equation 2.3) describes how the wavelength is shifted dependent on the temperature. Lower temperatures give longer wavelength and also a lower intensity (Staack 2008).

$$b = \lambda_{max} T \qquad \text{(Equation 2.3)}$$

Where λ_{max} is the maximum wavelength [m], T is the absolute temperature of the black body [K] and b is Wien's displacement constant ($b = 2.898 \cdot 10^{-3}$ m K) (Mohr, Taylor and Newell 2007).

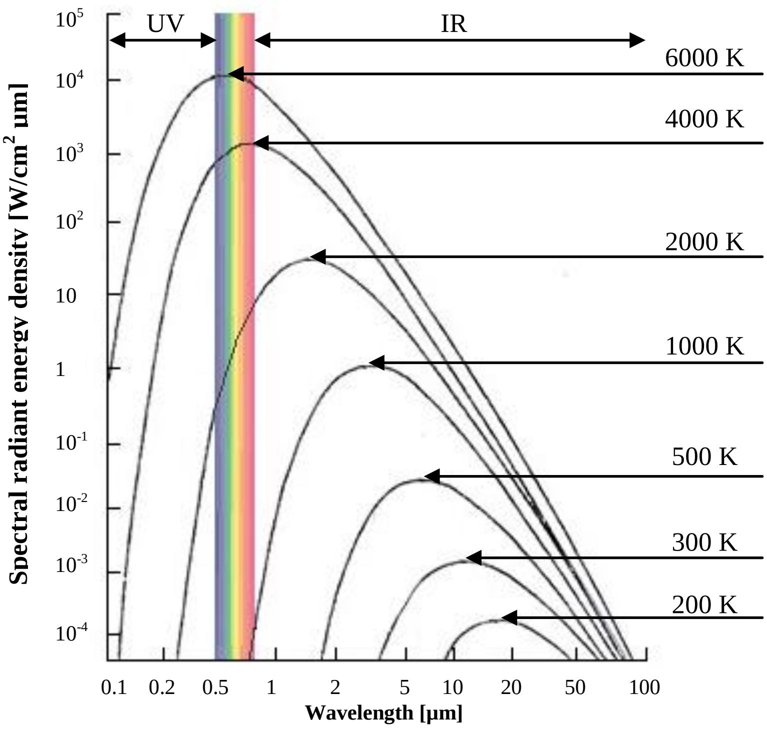


Figure 2.4. *A black body spectrum for objects at different temperatures.*

2.2 Heat transfer

Heat can be transferred from one object to another object in three different ways; conduction, convection or radiation. Figure 2.5 shows the three different cases.

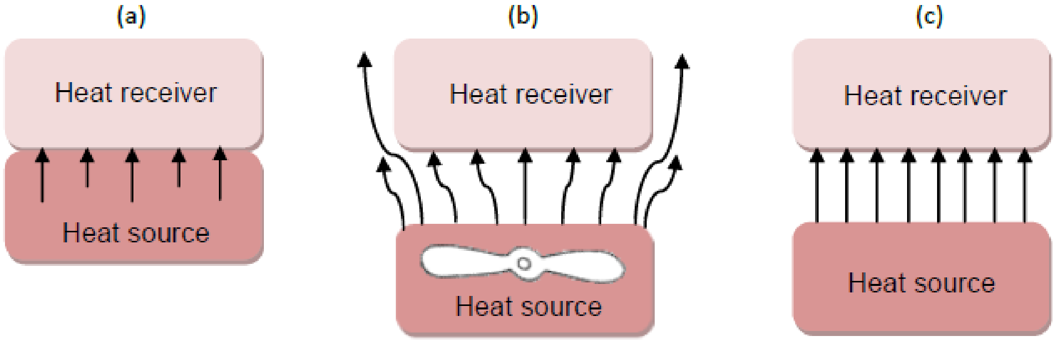


Figure 2.5. *Three different ways of heat transfer through (a) conduction, (b) convection and (c) radiation.*

2.2.1 Conduction

Conduction occurs mostly in solid elements but can also happen in thin fluids of gas or liquids. With conduction, heat is transferred and distributed by atoms vibrating against other atoms or by electrons moving from one atom to another, within a substance. There is a direct contact between the heat source and the heat receiver. The driving force in conduction is the temperature difference between the colder part of the body and the warmer part. Conduction is affected by the element's specific heat capacity, dimensions and temperature difference (see figure 2.5a) (Svenska AB Philips, Ljusavdelningen 1974). The heat transfer by conduction can be calculated with equation 2.5.

$$q_x = -kA\frac{dT}{dx} \qquad \text{(Equation 2.5)}$$

Where q_x is the rate of heat flow in the direction of heat transfer by conduction [W], k is the thermal conductivity [W/m°C] and A is the area [m^2]. dT and dx is the difference in temperature [°C] and length [m] (Singh and Heldman 2009).

2.2.2 Convection

Convective heat transfer occurs if there is a liquid or gas that can transfer heat from one body to another. There are two different types of convection – *free convection* or *forced convection*. Free convection occurs if there are any temperature differences or density differences. The liquid or gas wants to equalize the difference and if there is a temperature difference, heat starts to move from the warmer body to the cooler body (see figure 2.5b). Forced convection occurs if there is a fan or a pump which force the liquid or gas to move in a certain direction (Svenska AB Philips, Ljusavdelningen 1974). The heat transfer from convection can be calculated with equation 2.6.

$$q = hA(T_s - T_\infty) \qquad \text{(Equation 2.6)}$$

Where q is the heat transfer from convection [W], h is the convective heat transfer coefficient [W/m^2°C], A is the area [m^2] and T is the temperature [°C] either at the surface (T_s) or in the surroundings (T_∞) (Singh and Heldman 2009).

2.2.3 Radiation

Heat transfer can occur through heat radiation by electromagnetic waves. A hot body transport energy to a colder body. When the electromagnetic waves hit the colder body it is absorbed by the body and the radiation is converted into heat. This phenomenon happen in solids, liquids and gases but the more transparent the body is, the less efficient is it as a heat receiver. The heat transfer through radiation is dependent on the temperature difference between the radiation source and heat receiver, absorption properties, emission properties, dimensions of the bodies and also how the bodies are related to each other (see figure 2.5c) (Svenska AB Philips, Ljusavdelningen 1974). The heat transfer from radiation can be calculated by equation 2.7.

$$q = \sigma\epsilon A T_A^4 \qquad \text{(Equation 2.7)}$$

Where q is the rate of heat radiation [W], σ is the Stefan Boltzmann constant (see chapter 2.1.4.1), ε is the emissivity, A is the area [m^2] and T_A is the surface temperature in Kelvin (Singh and Heldman 2009).

2.3 Packaging material

The Codex Alimentarius Commission defined in 1985 the functions of a food package as ”*Food is packaged to preserve its quality and freshness, add appeal to consumers and to facilitate storage and distribution”*. A packaging material therefore needs at least four primary functions to fulfil the definition of a packaging material: containment, protection, convenience and communication (Robertson 2006).

Different food products have different demands on the packaging material. Some foods are sensitive to e.g. moisture, oxygen, light or microbial growth and therefore there is no general packaging solution. The packaging has to act as a barrier to protect the food and preserve its colour, flavour or aroma and the packaging plays an important role in the preservation of the shelf life of the food (Man and Jones 1994).

2.3.1 Different types of packaging materials

There are many different types of packaging materials suitable for food products and all of them have special properties. The four most common groups of packaging material for food is paperboard or cardboard, glass containers, metal cans or plastic packaging.

2.3.1.1 Paperboard

Paper and paperboard as a food packaging material is widely used and can be found in all the main categories of food such as dry food, frozen food, liquid food, fast food, fresh food etc. There are many different types of paper and they vary in e.g. appearance and strength mostly dependent on which type of fibre that is used and also how the fibres are processed.

Paper and paperboard packaging is used over a wide temperature range, from frozen food to heating in a microwave oven or a conventional radiant heat oven and to resist these temperature differences (ca -20 to 200 °C) and also to resist different compound in the food product such as oils and water or other environmental compounds such as UV light, oxygen etc., the paperboard need to be laminated. The laminates can be some kind of metal e.g. aluminium or different kind of plastic laminates to get better properties of the packaging material.

Another property with paper and paperboard as a packaging material is that it has a low environmental impact in the main raw material. Paper can also be coloured very easily, which is suitable when convey important information to the customers (Coles, McDowell and Kirwan 2003).

2.3.1.2 Glass

Glass containers in food packaging are used for both liquid and solid food products and the most common shape for this is bottles, which have narrow necks, and jars, which have wide openings. Examples of food packaged in glass containers are spices, baby foods, dairy products, carbonated drinks, jams and marmalades.

Some properties with glass containers as a packaging material are for example transparency, heat processable, microwaveable, environmental benefits etc. There are also some drawbacks with glass containers, for example glass are very brittle and heavy compared to plastic material, warehousing and distribution costs and glass is an elastic material with a higher thermal conductivity than plastic (The Engineering Toolbox 2010) and will therefore absorb some of the energy (Coles, McDowell and Kirwan 2003), which not is preferred in this study.

2.3.1.3 Metal cans

Metal cans are used for packaging both liquid and solid food products e.g. carbonated soda, fish, tomato purée and fruits. The main reason with metal cans as a food packaging material is to preserve and protect the product, resist chemical actions and withstand external environmental conditions.

The most common metals used for food containers are steel and aluminium which are both relatively low-cost materials that are non-toxic, capable of being hard worked and recyclable. Both steel- and aluminium- based packaging materials can be re-melted without any loss of quality during the re-melting process. To prevent corrosion the inside surface could be coated and this will also prevent the food product to interact with the metal.

Most filled metal containers can be heat processed to provide a shelf life of 2-3 years or more. Because of the heat processing, when the food is inside the metal can, no growth of microorganism occur. Therefore, it is not necessary to add preservatives. However, some chemical reactions can occur in the sealed container during storage like loss of colour and flavour. There are especially three factors that affect the shelf life of food packaged in metal cans and it is the sensory quality, nutritional stability and interactions with the container (Coles, McDowell and Kirwan 2003).

2.3.1.4 Plastics

Plastic as a packaging material for food products is widely used and the many properties of plastic materials make it suitable for almost all types of food. Some of the advantages with using plastic materials are that it is easy to process, easy to make special shapes or structures, it is cost effective, light weighted and they provide choices in transparency, colour, heat resistance etc. Plastic materials are a mixture of polymers and additives and depending on what type of additive and polymer used, plastics can have many different properties for example it can have a wide temperature range from deep frozen food processing and storing to reheating a packaged food product in a microwave or a conventional oven (Strong 2006).

The main reasons why plastic materials are used as a packaging material for food products is that plastic materials protect the food from spoilage, do not interact with the food, light weighted and they are available in a wide range of shapes, structures and designs (Coles, McDowell and Kirwan 2003).

A plastic material can either be a thermoplastic or a thermoset. Most plastic materials are thermoplastics which mean that they become softer and melt during heating. Because of this, thermoplastics can be re-melted and recycled. A thermoset material can just be moulded once by heat and if heated again, it will start to degrade. There are some environmental benefits with plastic as a packaging material such as the light weight of plastic which for example decrease the transports, compared to other packaging alternatives. A drawback with plastic materials is that they are made from oil, which not is a renewable resource. To make the view of plastic materials more sustainable they try to get good biodegradable plastic materials and today it is possible to use bio based plastic materials (Strong 2006).

2.3.2 Materials used in plastic packaging for food products

In this chapter, some of the most common materials in food packaging will be described. The main properties for the materials listed below are that they are all more or less transparent and they also more or less heat resistant, which are the requirements for the materials tested in this study.

2.3.2.1 Polyethylene (PE)

Polyethylene is the simplest of all polymers and has the molecular formula as in figure 2.7. The properties of PE are:

- High stiffness and strength.
- Resistant to water and solvents – good when PE is used for applications such as chemical reaction pipes, where the inertness of the container is critical. Bad when inks, paints or other solvents based materials are used to decorate PE.
- Low melting point – easier to process but the application area is limited due to a lower temperature range.
- Inexpensive – easy manufacturing, low energy required and large amount can be produced at the same time.
- Excellent electrical resistance – good insulator due to no electrical charge transfer.
- Thermal resistance – good thermal insulator and do not transfer heat.

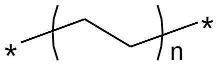


***Figure 2.7.** The repeating unit of polyethylene.*

PE can exist in many different shapes depending on the structure of the polymer chains and the structure also affects the properties of PE. The most common are low-density PE (LDPE) and high-density PE (HDPE).

LDPE is an amorphous polymer with both long and short branches. The long branches make the polymers to pack more densely and therefore also a lower density than HDPE. LDPE is an amorphous material with few crystals. The glass transition temperature (T_g) is -40 °C or lower and the melting temperature (T_m) is between 80-115 °C (CHEMnetBASE 2010) and it also has the lowest melting point of all types of PE, which make LDPE easiest to process. LDPE is flexible, have high impact toughness and a stress crack resistance.

HDPE is more linear than LDPE and has only few short branches. Due to the branching HDPE is crystalline and have a higher melting point (135 °C) and a lower glass transition temperature (-100 – -140 °C) (CHEMnetBASE 2010). HDPE have a higher strength and stiffness than LDPE but it is also more brittle.

There are a wide range of applications of PE e.g. trash bags, toys, pipes, electrical wire coating, package films and containers (Strong 2006).

2.3.2.2 Polypropylene (PP)

Polypropylene belongs to the bulk polymers and the molecular formula for PP is shown in figure 2.8. Some of the properties of PP are listed below:

- Resists stress cracking – more resistant than PE.
- Stronger and stiffer than HDPE – PE is a first choice in many applications but for applications where higher strength and stiffness is required, PP is used.
- Resistant to water and solvents – similar as PE but more sensitive to UV and oxidative degradation than PE.
- Higher T_g (-20 °C) and T_m (160-175 °C) (CHEMnetBASE 2010) than PE – generally higher processing temperature, which increase the amount of energy required in the manufacturing.
- Low cost.

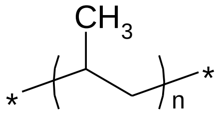
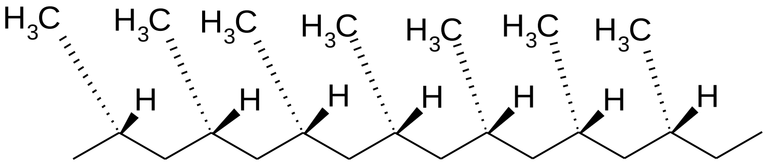
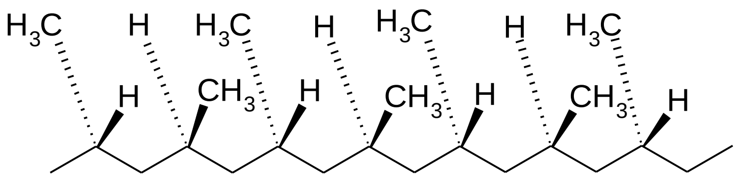


Figure 2.8. *The repeating unit of polypropylene.*

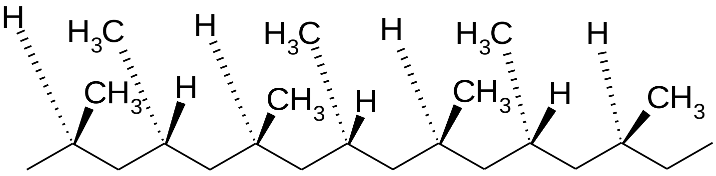
PP can exist in three different structures (stereoisomers); isotactic, syndiotactic or atactic. The different structures (see figure 2.9) gives the polymer different properties and the main property that differ the three structures is that isotactic PP can pack into crystals and the other two cannot due to the large methyl group. Isotactic PP is rigid and strong and is therefore the only PP of commercial importance. Application area for PP is e.g. microwave containers and utility fibres (Strong 2006).



a) Isotactic



b) Syndiotactic



c) Atactic

Figure 2.9. *Three different structures of polypropylene.*

2.3.2.3 Polyethylene terephthalate (PET)

PET is an engineering thermoplastic that belongs to the polyester group. The repeating unit for the most common thermoplastic polyester is shown in figure 2.10. Some properties of PET are listed below:

- Tensile strength and use temperature comparable to nylon (PA) and acetal.
- Excellent mechanical properties – due to orientation effects, the molecules are oriented in one direction and become very strong in that direction.
- Transparent – the size of the crystals are not large enough to interfere with visible light and cause scattering.
- Low moisture absorptivity.

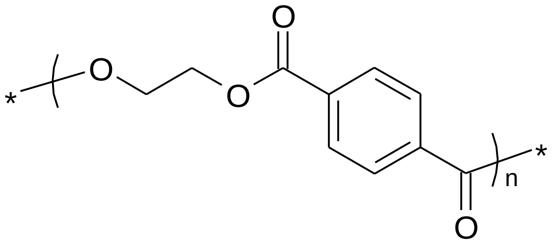


Figure 2.10. *The repeating unit of polyethylene terephthalate.*

PET is a semi crystalline polymer with high T_g (67-125 °C) and T_m (max 280 °C) (CHEMnetBASE 2010). Because of PET is an engineering polymer, its application area is where the requirements are higher than the bulk polymers can perform. The applications for PET are for example soft-drink containers, high performance films such as magnetic tape and electric insulation, fibres used in textile applications e.g. sleeping bags and winter coats (Strong 2006).

2.3.2.4 Polyamide (PA)

Polyamide or nylon belongs to the engineering thermoplastics and has the largest number of applications of all engineering polymers. The repeating unit of PA can be seen in figure 2.11. Due to the hydrogen bonds in the nylon molecule, the movement is restricted of the molecule relative to each other. This will facilitates the close packaging of nylon molecules and the polymer will have a high crystallinity. This will give the properties of nylon, which are listed below:

- High strength and stiffness.
- Good toughness.
- Low gas and vapour permeability.
- Good fatigue life.
- High temperature processing.
- Slightly water absorbent.

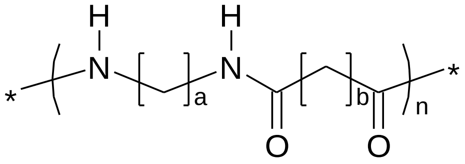


Figure 2.11. *The repeating unit of polyamide.*

There are many different types of nylon and the difference between them depends on the number of carbons in the molecular segments between the amide groups. Because of this, T_g and T_m for nylon vary depending on which molecule used. Applications for nylon can be found in fibres (for e.g. tents, carpets, ropes and hosiery), gears, impellers, bearings, cocking bags, zippers etc. (Strong 2006).

2.3.2.5 Ethylene Vinyl Alcohol (EVOH)

EVOH is a copolymer between ethylene and vinyl alcohol and this combination is commonly used in food applications where it acts as a barrier, primarily as an oxygen barrier. The glass transition temperature and melting temperature for EVOH depends on the content of ethylene and vinyl alcohol for example T_m increase with increasing vinyl alcohol content and decrease with increasing ethylene content and T_g decrease with increasing content of ethylene. At a low concentration of vinyl alcohol, T_m for EVOH is similar as for LDPE. At a content of 59 mol % ethylene T_m is 159 °C and T_g is 31 °C

(CHEMnetBASE 2010). The mechanical properties are dependent on the ratio of ethylene and vinyl content e.g. water absorption, presence of plasticisers and preparation conditions. The hardness of the copolymer increases as the vinyl alcohol content increase (CHEMnetBASE 2010).

2.4 Important mechanical properties of packaging materials

To evaluate the mechanical properties of a material, different tests can be made. These tests are interesting to perform to see if there are any changes before and after the material are exposed to IR radiation. The test used in this study is tensile test.

2.4.1 Tensile test

In a tensile test, or drag test, the materials tested are exposed for a load that drag the material apart until it break. Figure 2.12 shows how a typical stress-strain curve for a plastic material could look like.

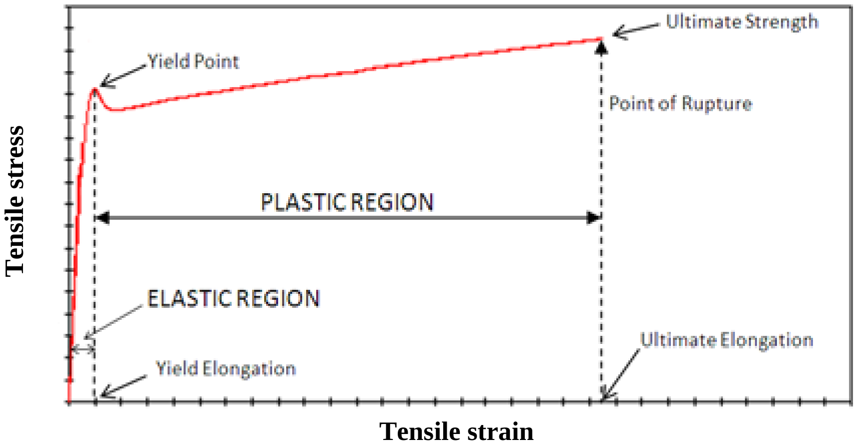


Figure 2.12. *Stress-strain behaviour for a polymeric material.*

In the elastic region the stress-strain curve is almost linear and the slope is called Young's modulus. A large modulus means that the material can resist deformation strongly and a larger modulus also means a stiffer material. In this region the material will recover to its original shape when the stress is removed. When the curve reach the yield point or elastic limit, the deformation of the material become partially non-recoverable and the area beyond the yield point is called the plastic region. After the yield point there is a reduction in stress because of the thinning of the test sample, this is called necking and it is now the polymers start to arrange themselves in the tensile direction. When the maximum strain of the material is reached there will be a break or a rupture. A higher strain until rupture indicates a soft material while a low value indicates a brittle material (Strong 2006).

2.5 Heat treatment of packed foods

Heat treatment of packaged food has been used for some time and there are some different methods used and also the packaging material differs for the different methods.

For ordinary heat treatment of packaged food, the rate of heat penetration will depend on e.g. the container material (heat penetrates tinned iron walls in a can faster than glass) and the size and shape of the container. One of the most common materials for ordinary heat treatment is metal cans and for example fish can be canned, pasteurized and then refrigerated until use. Baked products such as cakes can be baked in open top cans with plastic re-closable lids. The cake is baked in the can and just before it is fully baked, it is removed from the oven, and the can is closed and then returned to the oven to destroy moulds or yeast in the cake.

An alternative of packaging material for heat treatment is a heat-sterilized pouch. The pouch is made of flexible laminates such as polyamide, polyester, polyolefin or aluminum foil. When the pouch is filled and sealed, it can be sterilized and become microbiologically stable.

Another method that uses packaged food is when cooking food under vacuum. The food is placed in sealed and evacuated heat stable pouch or thermoformed tray, so that the flavor, aroma and nutrient quality of the food will be as similar to fresh food as possible. Ready-to-eat foods and microwavable convenience foods are prepared by this technique (Paine and Paine 1992).

There have been tests made on different packaging materials suitable for microwave heating and the most common materials for microwave heating are polyester such as PET, polypropylene (PP) laminates with a barrier layer of ethylene-vinyl alcohol (EVOH), polyethylene (PE) and polyvinyldiene chloride (PVdC). Some of these polymers are described in chapter 2.3.2 (Ozen and Floros 2001).

2.6 Selection of packaging for IR heating

There is no known literature about how infrared heating affect different packaging materials suitable for food products and the selection of a suitable packaging material in this study will be based on:

- Already existing packaging materials for food products.
- The transparency of the materials.
- The heat resistance of the materials. The materials need to be heat resistance to at least 100 °C.
- Changes in mechanical properties of the materials. There should be as few changes as possible in the mechanical properties and the mechanical properties will be evaluated with a tensile test.
- To fulfill these requirements the material need to be plastic.

3 Materials and methodological considerations

3.1 Materials

The materials tested were all plastic transparent materials and common used as a food packaging material. The materials were selected based on their transparency and heat resistance. The table below shows the material used and their suppliers.

Table 3.1. *All the materials that were tested in this study, their thickness and supplier.*

Material	**Thickness [µm]**	**Supplier**
PA/PE	100	Kontikigroup AB, Täby (Sweden)
OPA/PE	120	Amcor Flexibles, Täby (Sweden)
PE/PA/PE	320	Amcor Flexibles, Täby (Sweden)
PET	62	Kontikigroup AB, Täby (Sweden)
PP	30	Kontikigroup AB, Täby (Sweden)
PP/EVOH/PP/PE	300	Kontikigroup AB, Täby (Sweden)
PP/EVOH/PP	700	Kontikigroup AB, Täby (Sweden)
OPET/APET (Eco Lite)	48	Flextrus AB, Lund (Sweden)
OPP//PELD-EVOH-PELLD (Ecotop 3)	47	Flextrus AB, Lund (Sweden)
OPP/PELD-EVOH-PELLD (Ecotop 2)	60	Flextrus AB, Lund (Sweden)
OPET//PELD-EVOH-PELLD (Ecobar 2)	52	Flextrus AB, Lund (Sweden)
OPET//PE-EVOH-PELLD (Ecobar 3)	37	Flextrus AB, Lund (Sweden)

Table 3.2. *The name of all polymers included in this study.*

Polymer	Name
PA	Polyamide
OPA	Oriented polyamide
PE	Polyethylene
PELD	Also LDPE, Low density polyethylene
PELLD	Also LLDPE, Linear low density polyethylene
PET	Polyethylene terephthalate
OPET	Oriented polyethylene terephthalate
APET	Amorphous polyethylene terephthalate
PP	Polypropylene
OPP	Oriented polypropylene
EVOH	Ethylene Vinyl Alcohol

3.2 Equipment

The equipments needed to perform the tests are described in the following chapters.

3.2.1 IR treatment chamber

The equipment used for IR heating is an IR oven (Ircon Drying Systems AB, Värnersborg, Sweden) with two different sections (see figure 3.1). One of the sections has short IR-waves and the other section has medium IR-waves. The IR oven should simulate a tunnel and the plate going into the oven is 60×60 cm and inside the oven it moves back and forth over an area of 20 cm. The IR lamps that are used have an emissivity maximum at 1.2 µm for short IR waves and 2.7 µm for medium IR waves (Ircon Drying Systems 2001). There are three different heating zones for each section, upper heating, lower heating and heating from the sides. For this study only short IR waves and only upper heating was used.

Figure 3.1. *The IR oven at SIK. The section to the right has short IR waves and the section to the left has medium IR waves.*

3.2.2 Black body

The black body used for all temperature measurements was made of two copper plates with the dimensions 5×5×0.6 cm, and a thermocouple between the two plates, which measured the temperature in the centre of the black body (see figure 3.2). The copper plates were painted black and to get the best result of the tests the black body need to be repainted after some time of measuring. To avoid heat transfer by conduction from the grid of the IR oven to the black body, the black body had two thin metal legs, which were fixed to around 5 cm from the grid (see figure 3.3). The specific heat of the copper plates is 385 Ws/kg°C (Mörtstedt and Hellsten 1999).

The thermocouple (copper-constantan) inside the black body was connected to a memory logger (Hioki 8420-01/8421-01 MEMORY HiLOGGER) which registered the temperature in the centre of the black body every second. The logged values can afterwards be transferred to Microsoft Excel for further work.

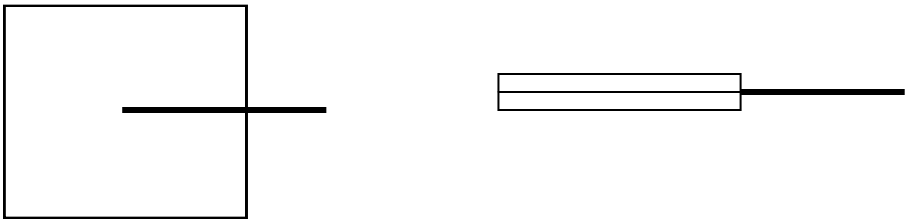


Figure 3.2. *A schematic picture of the black body setup. Two copper plates with a thermocouple in between the two plates.*

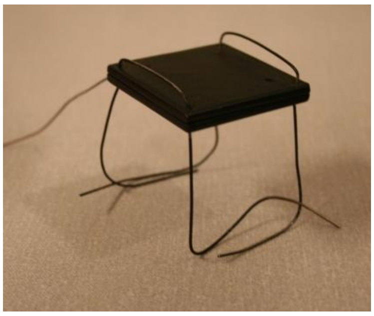


Figure 3.3. *The black body setup with legs rises the black body around 5 cm from the grid. The black body is connected to the memory logger with a thermocouple.*

3.2.3 Mechanical properties

To estimate the change in mechanical properties for the plastic films a tensile test was performed using an Instron Universal Testing 5542 (see figure 3.4). The system was connected to a computer and the software Bluehill 2.6 controlled the measurements. A standard test method for tensile properties of thin plastic sheeting (International, ASTM 2000) was followed.

Figure 3.4. *Tensile tests were performed on an Instron Universal Testing 5542 in a climate room holding 23 °C and RH 50%.*

3.2.4 Water activity

The final test was made on food and to evaluate the changes between untreated and IR treated food, the water activity of the food was measured before and after IR heating of the food. The water activity was measured with Decagons AquaLab Series 3, see figure 3.5.

Figure 3.5. *The equipment for measure water activity.*

3.3 Experimental setup

To find a method that works for testing plastic materials, different tests on a black body were made to evaluate the distance between IR source and the black body, location of the black body on the grid, intensity of the oven and also how much the preheating of the oven will affect the results. The methods used to evaluate this are described below.

3.3.1 Placement in the oven

Tests on a black body at different locations in the oven were made to obtain the best location on the grid and also to see how much different locations can affect the results. The area of the grid going into the oven is 60×60 cm and a black body were placed at 25 different locations on the grid, see figure 3.6. For this test the black body was exposed to IR radiation with an IR intensity of 100 %. The distance between the IR source and the black body was set to 50 cm and the temperature was measured in the black body every second with a memory logger. MatLab was used to get a good view over the heat distribution in the oven.

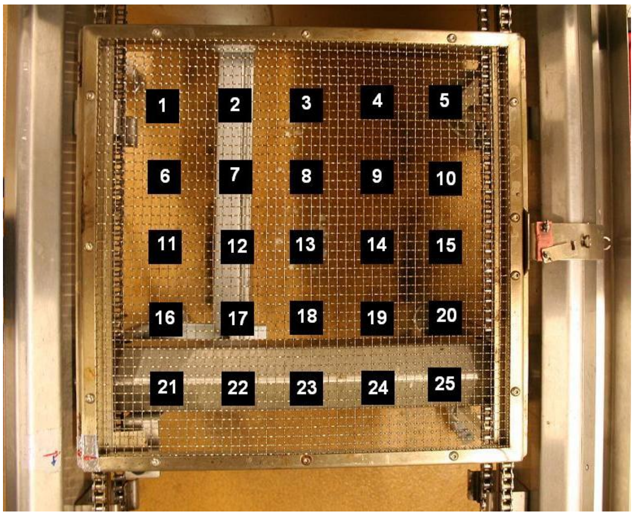


Figure 3.6. *The black body (5×5 cm) where placed at 25 different locations in the IR oven and with ca 5 cm between every measure point.*

3.3.2 Distance between IR lamps and material

The smaller the distance is between the IR source and the object gives a faster heat transfer. At the same time, the bigger the distance is between the IR source and the object, the more uniform heating of the object. To see how much the heat transfer differ for different distances some test were made on a black body. For these tests the black body was placed in the middle of the grid, position number 13 in figure 3.5. The distances tested where between 15 cm and 55 cm with 5 cm difference between every test. The IR oven had an IR intensity of 100 % and the temperature of the black body was measured every second with a memory logger.

3.3.3 Intensity

To study how the intensity affects the heating of the black body, tests at a certain distances and time were done with IR intensities varying from 1, 25, 50, 75 and 100 % for short IR waves. For this test the distance was fixed to 50 cm, the exposure time was 90 seconds and the black body were placed in the middle of the grid (position 13 in figure 3.5). The temperature of the black body was measured every second with a memory logger.

3.3.4 Effect of the oven walls

The walls in the oven are made of stainless steel and can therefore absorb the IR radiation. During IR heating, the walls in the oven will get warmer and emit IR and this could affect the results if the first measurements are performed in an unheated oven and after a while, the measurements are performed in a heated oven. To see how much this affect the results, tests was made on a black body placed in the centre of the grid (position 13 in figure 3.5) with a distance of 50 cm to the IR source and with an IR intensity of 100 % for 90 seconds. The black body was heated from a temperature of 30 °C in an unheated oven and then another test was done where the temperature was measured from a temperature of 30 °C in a preheated oven, for the same heating time and with the same IR intensity as in the earlier test.

3.4 Measurement of IR transmittance in materials

The tests made on the plastic films where performed in two different ways. Chapter 3.4.1 describes the test when the plastic film was put on top of the black body while chapter 3.4.2 describes the test when the black body was inside a sealed pouch.

3.4.1 Measurements on a black body with a thin film

A thin film was placed around the black body (see figure 3.7) and exposed for IR radiation at a distance of 50 cm between the IR source and the material. From the results from chapter 3.3, the time can be calculated for how long time the black body need to be in the oven to reach over 100 °C, from a starting temperature of 50 °C. The materials were exposed for IR radiation at four different intensities of short wave IR; 25 %, 50 %, 75 % and 100 %. The temperature was measured every second, in the centre of the black body, with a memory logger and three tests were made at each level of intensity to get a mean value.

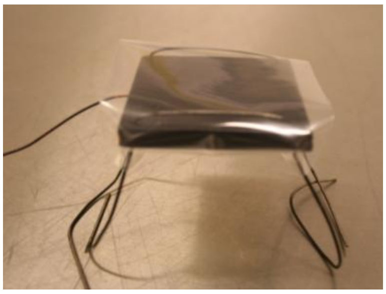


Figure 3.7. *The black body with a plastic film on top of it.*

To evaluate the transmittance of the tested materials the heat flux from the black body with a thin film *($Q_{bb+film}$)*, was divided with the heat flux from the black body without any film *(Q_{bb})* (see equation 3.3). This gives the amount of energy in percent that the plastic film transmits. The heat flux for the black body was calculated with equation 3.1 and the heat flux for the black body with a film was calculated with equation 3.2.

$$Q_{bb} = \frac{C_P m}{A} \frac{\Delta T}{\Delta t} \qquad \text{(Equation 3.1)}$$

Where Q_{bb} is the heat flux of the black body (bb) [kW/m^2], C_P is the specific heat of the black body i.e. 385 Ws/kg°C (Mörtstedt and Hellsten 1999), A is the area of the black body [m^2], ΔT is the difference in temperature [°C] and Δt is the difference in time [s].

$$Q_{bb+film} = \frac{C_P m}{A} \frac{\Delta T}{\Delta t} \qquad \text{(Equation 3.2)}$$

Where, $Q_{bb+film}$ are the heat flux for the black body with a film [kW/m^2]. The specific heat *(C_P)*, the weight *(m)* and the surface area *(A)* of the black body are the same as in equation 3.1. The difference between equation 3.1 and 3.2 are the temperature- *(ΔT)* and time difference *(Δt)*.

$$Transmittance\ [\%] = \frac{Q_{bb+film}}{Q_{bb}} \qquad \text{(Equation 3.3)}$$

Also the amount of energy that was reflected from the plastic films can be calculated by using equation 3.4.

$$Q_{film} = Q_{abs,film} + Q_{ref,film} + Q_{trans,film} \qquad \text{(Equation 3.4)}$$

Where Q_{film} is the total heat flux from the radiation that hits the film on the black body, $Q_{abs,film}$ is the heat flux that is absorbed by the film, $Q_{trans,film}$ is the heat flux that is transmitted through the thin film and $Q_{ref,film}$ is the heat flux that is reflected.

$$Q_{bb} = Q_{abs,bb} + Q_{ref,bb} + Q_{trans,bb}$$

For a black body (bb), all energy is absorbed and nothing is reflected or transmitted i.e.

$$Q_{ref,bb} + Q_{trans,bb} = 0 \ \rightarrow\ Q_{bb} = Q_{abs,bb}$$

The black body, with or without material had the same surface area and the same output power was used. This gives:

$$Q_{bb} = Q_{film}$$

$$Q_{film} = Q_{abs,film} + Q_{ref,film} + Q_{trans,film}$$

The heat absorption for plastic films can be neglected i.e.

$$Q_{film} = Q_{ref,film} + Q_{trans,film}$$

The transmitted heat flux from the film is the same as the totally heat flux for the black body with a thin film. The totally heat flux that hits the black body with a thin film, was measured from IR tests and then calculated with equation 3.2. This gives the heat flux from the reflectance of the film (equation 3.5):

$$Q_{ref,film} = Q_{film} - Q_{trans,film} = Q_{bb} - Q_{bb+film} \qquad \text{(Equation 3.5)}$$

The reflectance from the thin films can be calculated in percent of total heat flux by divide the heat flux from the reflectance of the films ($Q_{ref,film}$) with the total heat flux that hits the film (Q_{film}), see equation 3.6).

$$Reflectance\,[\%] = \frac{Q_{ref,film}}{Q_{film}} \qquad \text{(Equation 3.6)}$$

3.4.2 Measurements on a black body in a packaged environment

To see if there were any changes in the heat flux between the black body with a film on top and the black body in a package environment, the black body was placed in a sealed plastic package (see figure 3.8). The performance was the same as in chapter 3.4.1 i.e. 50 cm between the IR source and the object, temperature increase from 50 °C to 100 °C and four different intensities of short IR radiation was tested, 25 %, 50 %, 75 % and 100 %. The heat flux for the black body in a package environment was calculated in the same way as for the film on top of the black body (see equation 3.2).

Figure 3.8. *The black body inside a plastic pouch. The pouch is sealed with an impulse sealer and one small hole was made in the plastic pouch to let the water steam out because steam needs a larger volume than air.*

Also tests to see how much the size of the plastic pouch affects the results was done. This test was performed by using the same settings as earlier but different size of the pouch, where the black body was within. The sizes of the pouches tested were 1 dm^3 and 10 dm^3.

3.5 Method to measure tensile testing

To evaluate if there was any changes of mechanical properties between a treated and untreated material, a tensile test was made using an Instron Universal Testing (see chapter 3.2.3). The test was done by placing one thin plastic film between the two grips and then allowing the system to pull the film apart until it break, or the load decrease with 70 %. The system was connected to a computer and controlled by the software Bluehill 2.6, which makes it possible to measure different properties of interest e.g. tensile stress and tensile strain.

To follow the standard method *ASTM D 882-00* (International, ASTM 2000) all tests were performed in a conditioning room holding 23 ± 2 °C and a relative humidity of 50 ± 5 %. The testing device pulls the film apart until the load drops by 70 %. At least five specimens from each sample were tested and a mean value was calculated.

In Bluehill 2 it is possible to design a program with a specific method that measure different properties of interest. In this case a tensile test method was used which measured

- Tensile strain at break (%).
- Tensile stress at break (MPa).
- Modulus (MPa).
- Extension at break (mm).

3.6 Tests with bread

As a final test, the three best suited materials for IR heating was selected and then put on top of a piece of white bread (Eldorado toast). Another test was also done with one of the best plastic films shaped as a pouch around a piece of bread.

3.6.1 A plastic film on top of the bread

A piece of white bread (5.5×5.5×0.8 cm) with a film on top of it was put on top of the black body, see figure 3.9. The sample was placed in the middle of the grid with a distance of 50 cm to the IR source and an IR intensity of 100 % for 90 seconds. The temperature was measured in the centre of the black body and for one sample also in the centre of the bread.

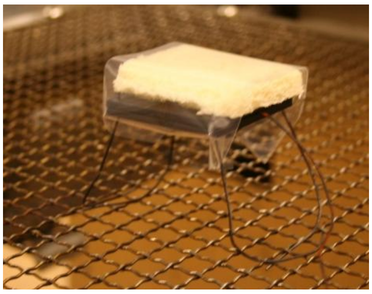


Figure 3.9. *The bread on top of the black body with a plastic film on top of the bread.*

The water activity (a_w) of the white bread was measured with AquaLab (see chapter 3.2.4) before and after IR treatment and also the weight of the bread pieces were measured before and after IR treatment. To calculate the weight loss of the bread equation 3.7 was used.

$$Weight\ loss = \frac{m_{before} - m_{after}}{m_{before}} \qquad \text{(Equation 3.7)}$$

Where *m* is the weight of the bread pieces in gram, either before the IR heating or after the IR heating.

3.6.2 A piece of bread in a pouch

A test was also made on a piece of white bread inside a plastic pouch (see figure 3.10) with a volume of 0.1 dm^3. The plastic used for this test was one of the plastic film that where best suited for IR heating. The settings and location of the sample were the same as with the bread on top of the black body. The temperature was measured every second in the centre of the bread with a thermocouple connected to a memory logger.

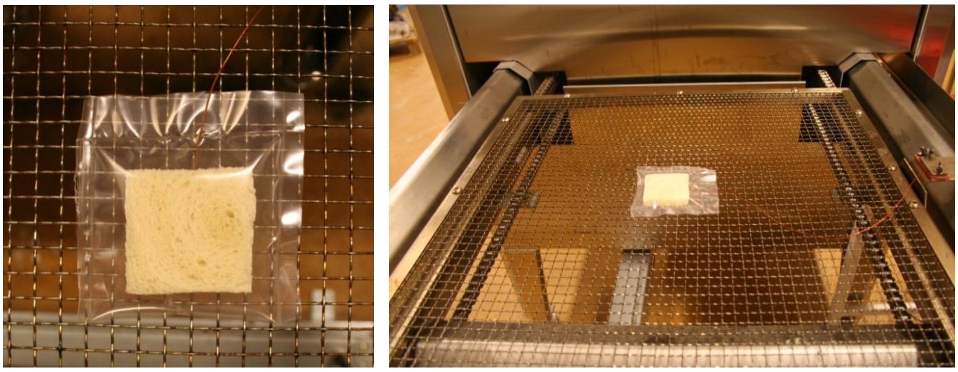


Figure 3.10. *A piece of white bread (5.5×5.5×0.8 cm) inside a plastic pouch with a volume of 0.1* dm^3*. A thermocouple connected to a memory logger measured the temperature in the centre of the bread.*

4 Results and discussion

The results can be divided into three parts. The first part is the results from the heating conditions in the IR oven (chapter 4.1 to 4.4). The second part is the results from the test with different plastic films (chapter 4.5 to 4.9) and the last part is the results from the tests with the plastic films in contact with bread (chapter 4.10).

4.1 Placement in the oven

The graph in figure 4.1 shows that it is most effective to place the object in the centre of the grid compared to the corners of the grid. This result was expected and it was also expected that it is warmer in one special direction due to the orientation of the IR lamps in the oven. These differences in heat distribution could cause an unevenly heating and it was therefore important to consider where on the grid the samples were placed and that the samples were placed on exactly the same place every time.

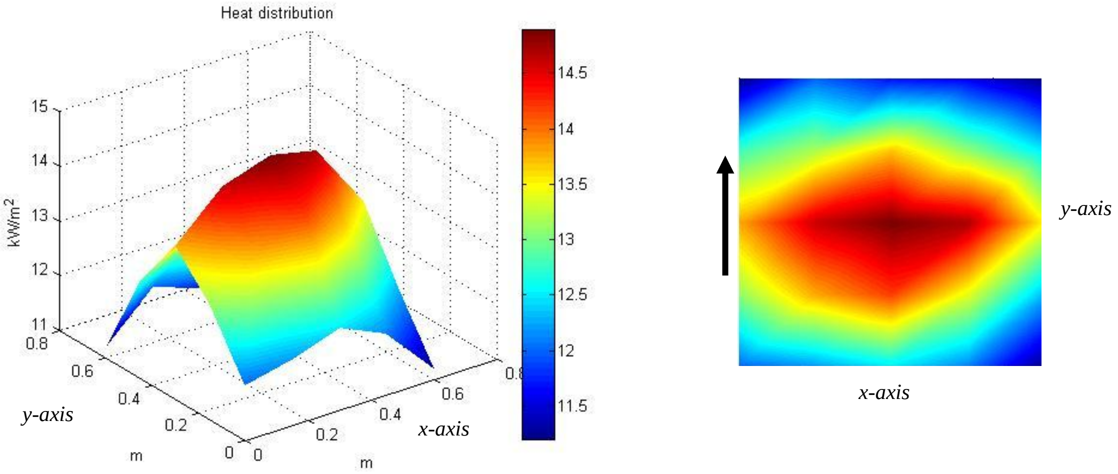


Figure 4.1. *The graph shows the different heat distributions in the IR oven. The highest heat flux is in the middle of the oven and the lowest heat fluxes are in the corners. The y-axis and x-axis are the distance on the grid. The right picture shows the heat distribution from above and the arrow shows the way the grid going into the oven.*

4.2 Distance, intensity and time

The distance between the IR source and the object, and the intensity of the IR light influence the amount of energy that reaches the black body. A higher intensity and a shorter distance gives a high process speed, which is desired due to lower production costs but at the same time the heating needs to be uniform which require a longer distance between the IR source and the object.

4.2.1 Distance between IR source and object

Figure 4.2 shows that a shorter distance between the IR source and the object gives a faster temperature increase. At the same time, a longer distance gives a more uniform heating of the object. Because of this reason the following tests was made at a longer distance, around 50 cm between IR source and object.

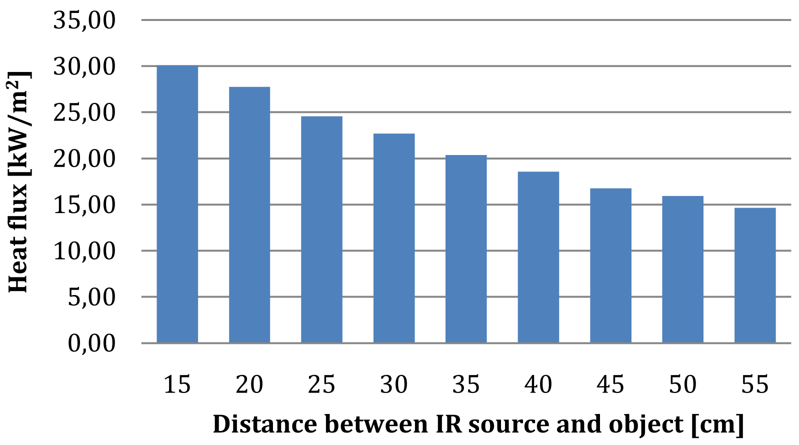


Figure 4.2. *The figure shows how the heat flux changes in the black body at different distances between the IR source and the black body.*

4.2.2 IR intensity

The result shows that a higher intensity gives a faster heating of the object. The different intensities of short IR radiation that were used for this test were 1 %, 25 %, 50 %, 75 % and 100 %. For the following tests only 25 %, 50 %, 75 % and 100 % were used because heating with 1 % IR intensity gives a too low heat flux (1.94 kW/m^2) to be interesting for this study, see figure 4.3.

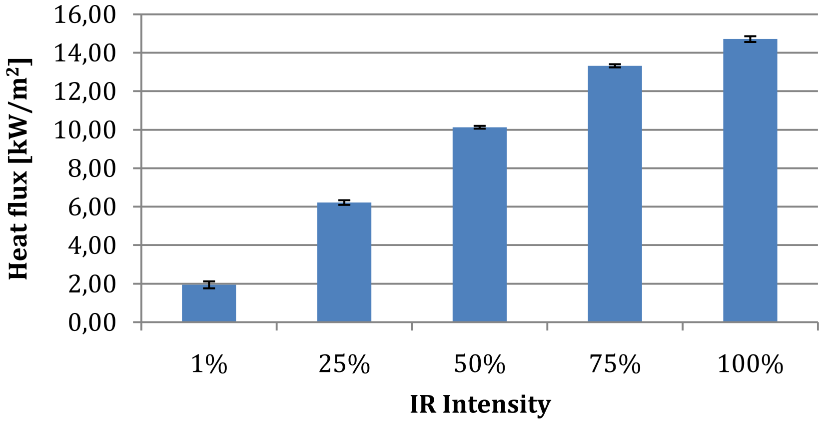


Figure 4.3. *The graph shows how the heat flux changes at different intensities.*

4.2.3 Time in oven

The materials that should be tested should have a heat resistance to at least 100 °C and therefore the time needed to reach the desired temperature have to be calculated for each intensity of interest. Figure 4.4 shows a time-temperature diagram for five different intensities of short IR waves.

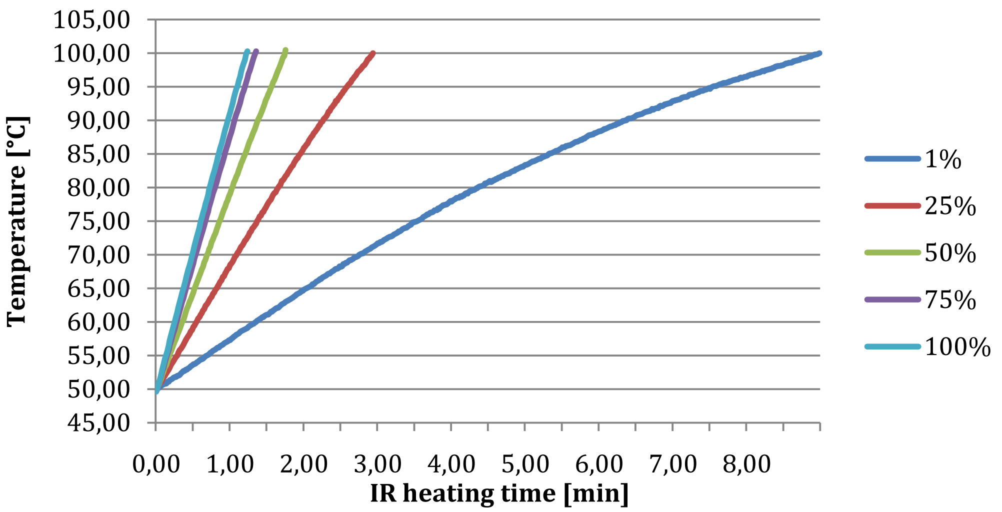


Figure 4.4. *The figure shows how the temperature and time vary at different intensities.*

The temperature increase is almost linear in the IR oven and by knowing the slope the time needed to reach 100 °C can easily be calculated from the linear equation.

The plastic films should be heat resistant to at least 100 °C and therefore the black body needed to be cooled down between every measuring. The black body was cooled to around 50 °C before next measuring and therefore the starting temperature for all tests was 50 °C and the end temperature 100 °C, so the temperature difference was always 50 °C. This gives the time needed in the oven, see table 4.1.

Table 4.1. *The slope for each of the tested intensities in figure 4.4 and the time needed in the oven to reach $\Delta T=50$ °C.*

IR Intensity	Slope	Time in oven to reach $\Delta T=50$ °C [min]
1 %	0.0920	9.06
25 %	0.2946	2.83
50 %	0.4801	1.74
75 %	0.6314	1.32
100 %	0.6971	1.20

4.3 Effect of the oven walls

The oven is made of stainless steel and depending if the oven was heated or not before the measurements start, this could affect the results. Figure 4.5 shows that there are a difference in temperature increase between a preheated oven and a cold oven.

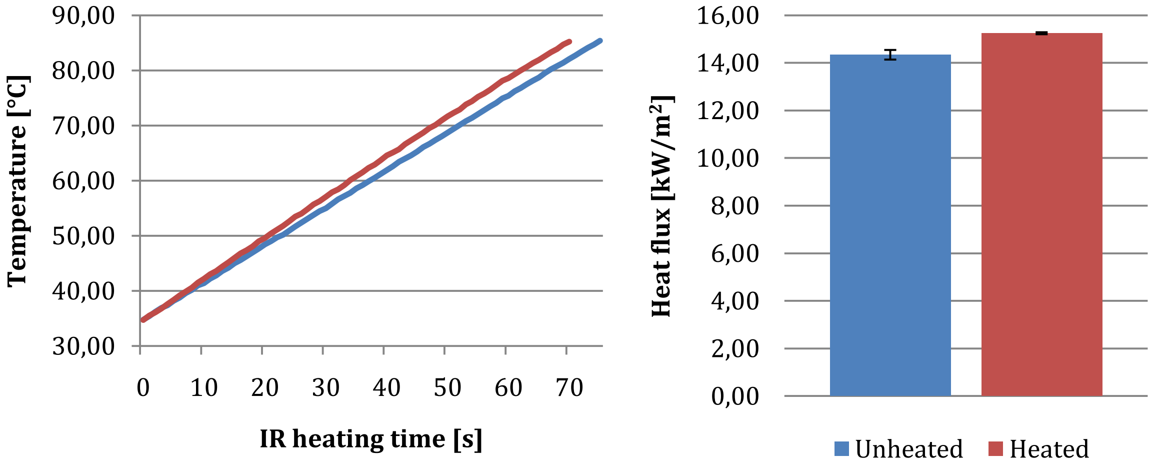


Figure 4.5. *The graph shows that there are some differences if the measurements are performed in an unheated oven or in a heated oven.*

To avoid this problem the oven was always heated up before the measurements starts and were not allowed cooling down more than a couple of minutes between the measurements.

4.4 Heat flux

The temperature was measured every second in the centre of the black body and with equation 3.1, the heat flux of the black body (Q_{bb}) could be calculated at the different IR intensities (see figure 4.6). The maximum heat flux that is possible to attain from the IR oven when the distance is 50 cm between the IR source and the black body is 15.6 kW/m^2.

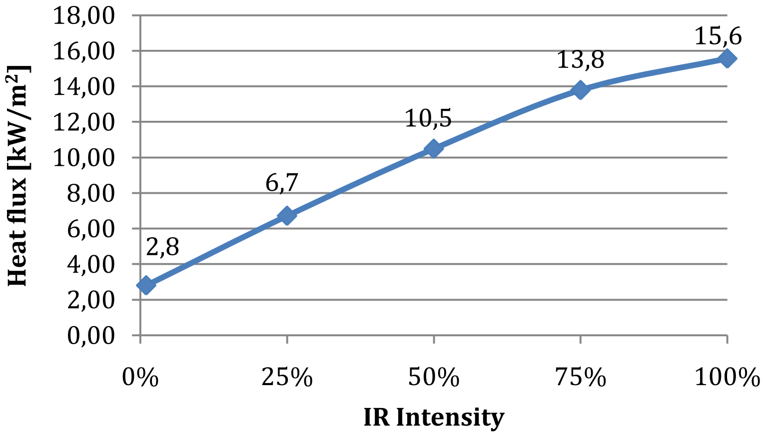


Figure 4.6. *Distance between IR source and black body was 50 cm. The maximum heat flux from the IR source absorbed by the black body is 15.6 kW/m^2.*

4.5 IR effects on materials

The following results show how the IR heating affects plastic packaging materials for food products.

4.5.1 Plastic film on top of the black body

The heat flux for the black body with plastic films (Q_{film}) are calculated and shown in appendix A. The heat fluxes for the black body with films on top were calculated from equation 3.2 (see chapter 3.4.1) and then compared with each other. In figure 4.7 are all materials compared to each other at their different IR intensities. The reference sample is the black body without a plastic film on top.

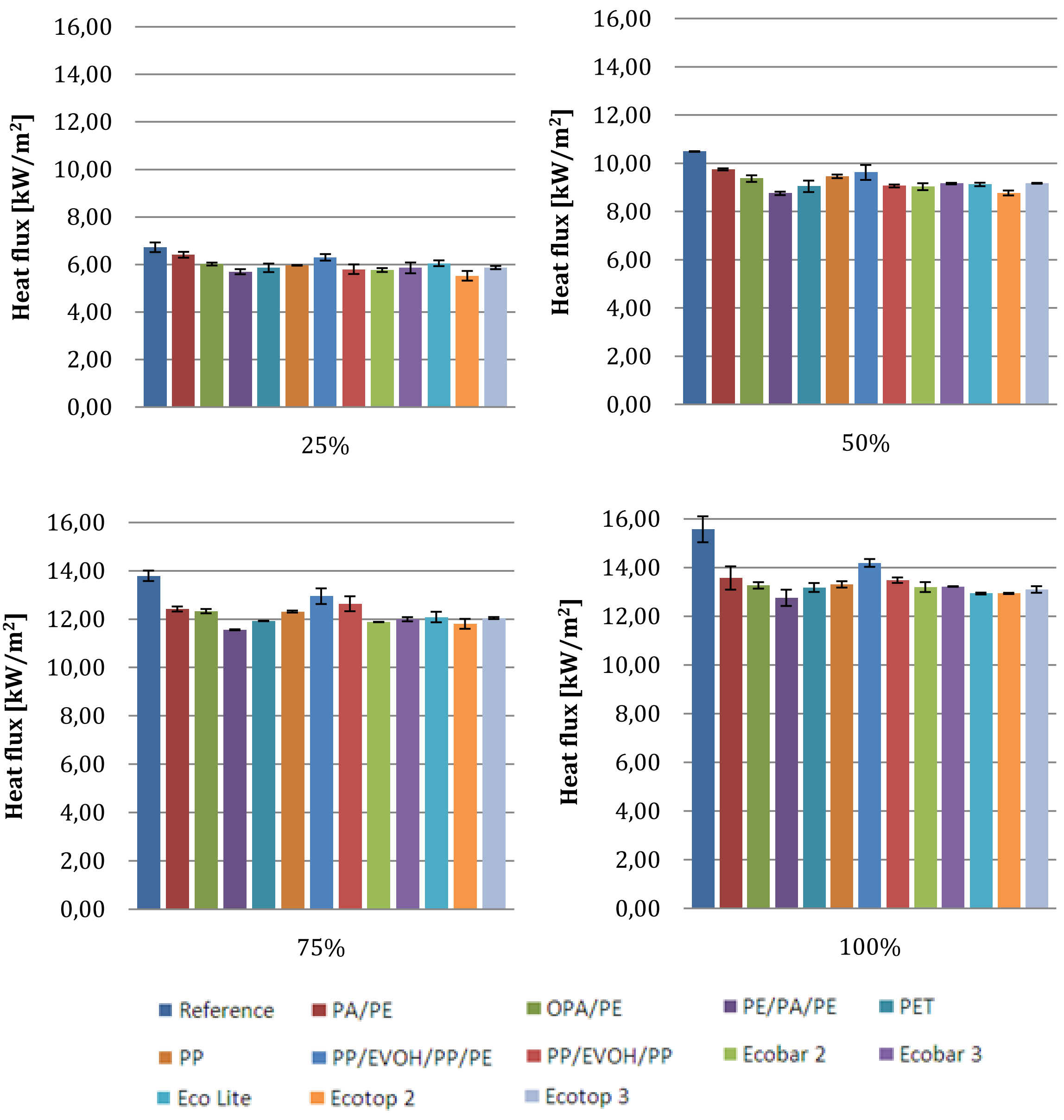


Figure 4.7. *The heat flux of all tested materials at different IR intensities. PP/EVOH/PP/PE has the highest heat flux at all intensities while PE/PA/PE has the lowest heat flux at almost all intensities.*

The materials with the highest transmittance, calculated from equation 3.3, are shown in table 4.2 and table 4.3. The five materials with the highest transmittance were selected from each IR intensity tested and four of the selected materials were represented at all IR intensities, see table 4.2. At lower IR intensities there were some other materials that have high transmittance; these materials are shown in table 4.3.

Table 4.2. *The four plastic films that have a high transmittance [%] at all four tested intensities.*

Material / Intensity	PP/EVOH/PP/PE	PA/PE	PP/EVOH/PP	PP
25 %	93.70 ± 2.04 %	95.30 ± 1.83 %	86.27 ± 3.00 %	88.70 ± 0.17 %
50 %	91.73 ± 2.96 %	92.94 ± 0.41 %	86.38 ± 0.58 %	90.18 ± 0.71 %
75 %	93.87 ± 2.35 %	90.04 ± 0.75 %	91.61 ± 2.25 %	89.26 ± 0.30 %
100 %	91.12 ± 1.03 %	87.15 ± 3.07 %	86.58 ± 0.72 %	85.47 ± 0.84 %

Table 4.3. *Three materials that have a high transmittance [%] at lower intensities (50 % and 25 % IR intensity).*

Material / Intensity	OPA/PE	Ecobar 3	Eco Lite
25 %	89.51 ± 0.90 %	87.09 ± 3.39 %	89.99 ± 1.81 %
50 %	89.29 ± 1.30 %	87.32 ± 0.30 %	86.99 ± 0.69 %
75 %	89.39 ± 0.64 %	86.97 ± 0.63 %	87.63 ± 1.58 %
100 %	85.20 ± 0.85 %	84.91 ± 0.74 %	83.05 ± 0.25 %

4.5.2 Materials in a packaged environment

4.5.2.1 Size of the plastic bag

Figure 4.8 show that the size of the plastic bags has some influence on the results. IR waves do not heat the air in the pouches but depending on the relative humidity and the amount of water in the air, the IR waves will heat the water. The water turns into steam and the temperature in the pouch increase. This temperature increase affects the heating of the black body. The amount of water in the pouch depends on the volume of the pouch and in the bigger pouch there were more water but also a bigger volume to heat up, and in the smaller pouch there were less water but a smaller volume to heat up.

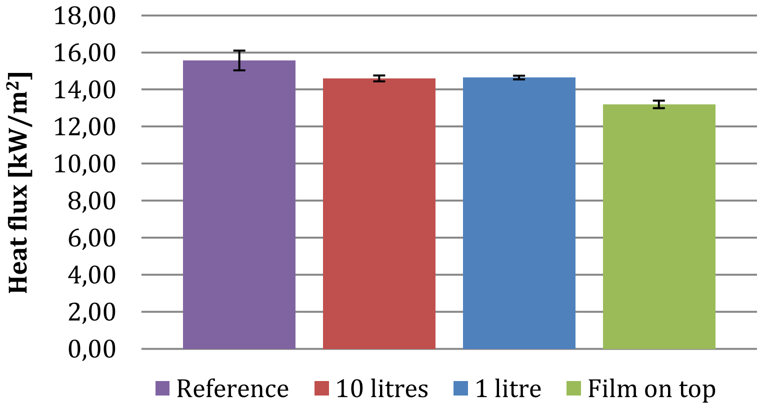


Figure 4.8. *The heat flux difference between two different sizes of a pouch made of same plastic film. The big pouch has a volume of 10 dm^3 and the smaller pouch has a volume of 1 dm^3. The figure also show the heat flux for the same plastic film on top of a black body and a reference sample, which is the black body without any material.*

The sizes of the plastic bags used in the test were around 1-1.5 dm^3 and this small difference in size did not have any substantial effect on the results.

4.5.2.2 Heat flux in a package environment

The heat fluxes for the black body in package environments has been calculated with equation 3.2 (see chapter 3.4.1) and is shown in appendix A. A package environment gives a higher heat flux than the black body itself at lower intensities and a similar or a little lower heat flux compared to the black body at higher intensities (see figure 4.9). Table 4.4 shows the ratio in heat flux of the black body in a package environment and the black body without any materials (equation 3.2).

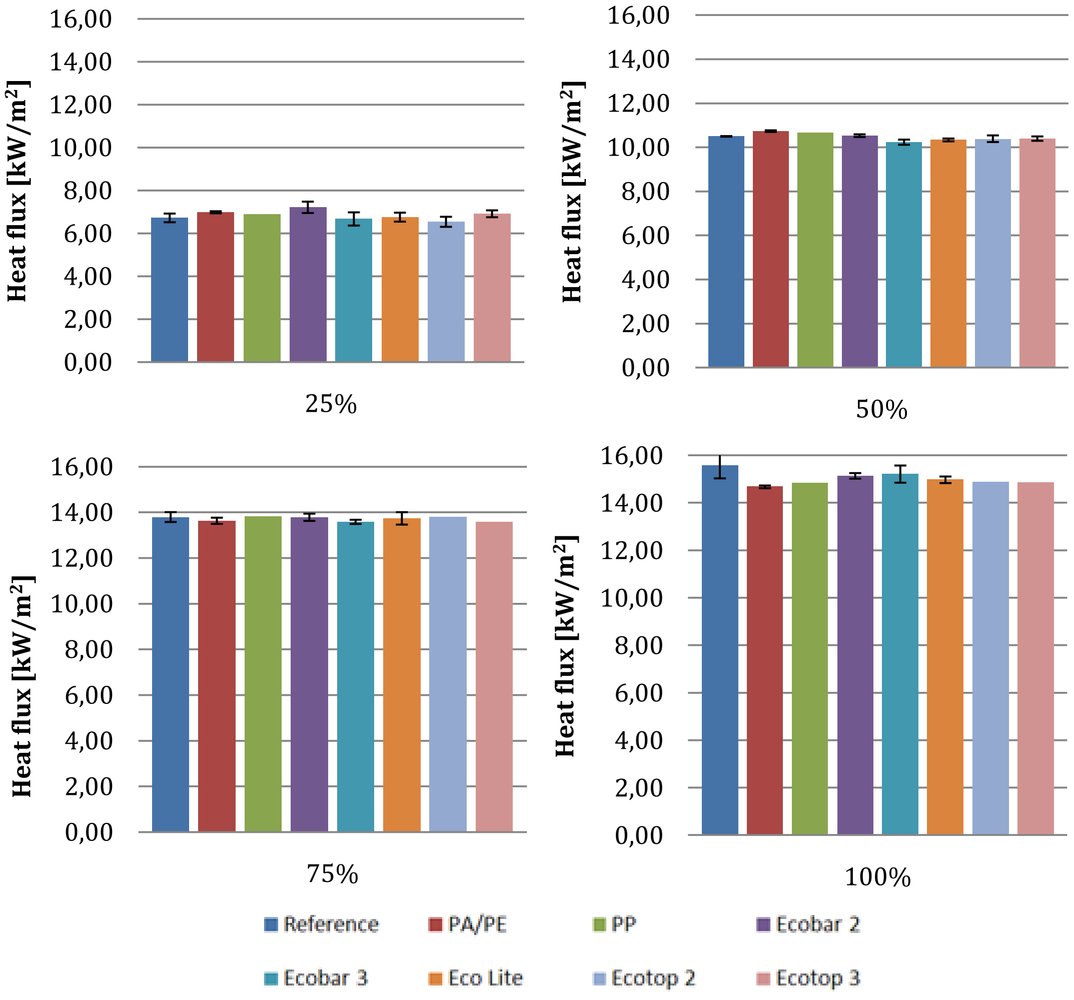


Figure 4.9.*The heat flux of the black body in a sealed pouch of all tested materials at different IR intensities. All materials were not able to be shaped as pouches and the standard deviation was not possible to calculate for some of the tests.*

Table 4.4. *The materials with the highest heat flux of the black body in a package environment. All values are in percent compared to the black body without any materials.*

Material **Intensity**	**Ecobar 2**	**Eco Lite**	**Ecotop 2***	**Ecotop 3***
25 %	107.35 ± 3.93 %	100.53 ± 3.11 %	97.30 ± 3.49 %	102.86 ± 2.39 %
50 %	100.30 ± 0.59 %	98.47 ± 0.61 %	98.99 ± 1.44 %	99.04 ± 0.94 %
75 %	99.93 ± 1.15 %	99.58 ± 1.97 %	100.05 %	98.46 %
100 %	97.26 ± 0.75 %	96.19 ± 0.89 %	95.58 %	95.55 %
Material **Intensity**	**PP***	**PA/PE**	**Ecobar 3**	
25 %	102.48 %	103.91 ± 0.72 %	99.29 ± 4.58 %	
50 %	101.50 %	102.28 ± 0.35 %	97.50 ± 1.11 %	
75 %	100.19 %	98.82 ± 0.98 %	98.47 ± 0.67 %	
100 %	95.33 %	94.27 ± 0.37 %	97.73 ± 2.32 %	

** There are no standard deviations at those tests due to the behaviour of the material or the amount of material available.*

4.5.3 Behaviour of the plastic films during IR treatment

For some of the plastic films the appearance of the material changed and this is not desirable. For most of the materials, when they were placed on top of the black body, they got either more brittle or stiffer. When the materials were shaped as pouches with the black body inside of it, the changes becomes clearer. Some of the materials start to melt and because of this some materials are more suitable than others for the application of IR treatment of foods. Table 4.5 shows a list of which materials that are more suitable than others, based on the behaviour of the plastic film during IR treatment.

Table 4.5. *A list of which tested material that are more or less suitable for IR treatment.*

Material	**Behaviour during IR heating**	**Suitable for IR treatment?**
PA/PE	No big differences between treated and untreated material.	Yes
OPA/PE	No big differences between treated and untreated material.	Yes
PE/PA/PE	Big differences between treated and untreated material. The material changes in colour.	No
PET	No big differences between treated and untreated material. Bags could not be made due to the material.	Yes
PP	Big differences between treated and untreated film, especially at higher IR intensities. IR treated bags made of PP started to melt at higher intensities.	No
PP/EVOH/PP/PE	The IR treated material becomes stiffer. Some small changes in transparency. Bags could not be made due to the thickness of the material.	Yes
PP/EVOH/PP	Some differences in the IR treated material, especially at higher intensities. The material becomes stiffer. Also some small changes in transparency. Bags could not be made due to the thickness of the material.	Yes
Eco Lite	The material becomes more brittle at higher intensities. There are also some changes in colour of the material.	Yes
Ecotop 3	IR treated bags made of Ecotop 3 started to melt and there where big differences in the material between IR treated and untreated film.	No
Ecotop 2	IR treated bags made of Ecotop 2 started to melt and there where big differences in the material between IR treated and untreated film.	No
Ecobar 2	Almost no differences at all in the IR treated material compared to untreated material.	Yes
Ecobar 3	The material becomes a little more brittle but no other differences between IR treated and untreated film.	Yes

4.6 Reflectance

The heat flux from the reflectance of the films is the same as the difference between the heat flux from the black body and the heat flux from the black body with a film, see equation 3.5. In this study, as much energy as possible should be transmitted and as less energy as possible should be reflected or absorbed. Therefore, it is more preferable with a low heat flux from the reflectance. The heat flux from the reflectance for a black body is zero. Figure 4.10 shows the differences in heat flux from the reflectance for the different plastic films.

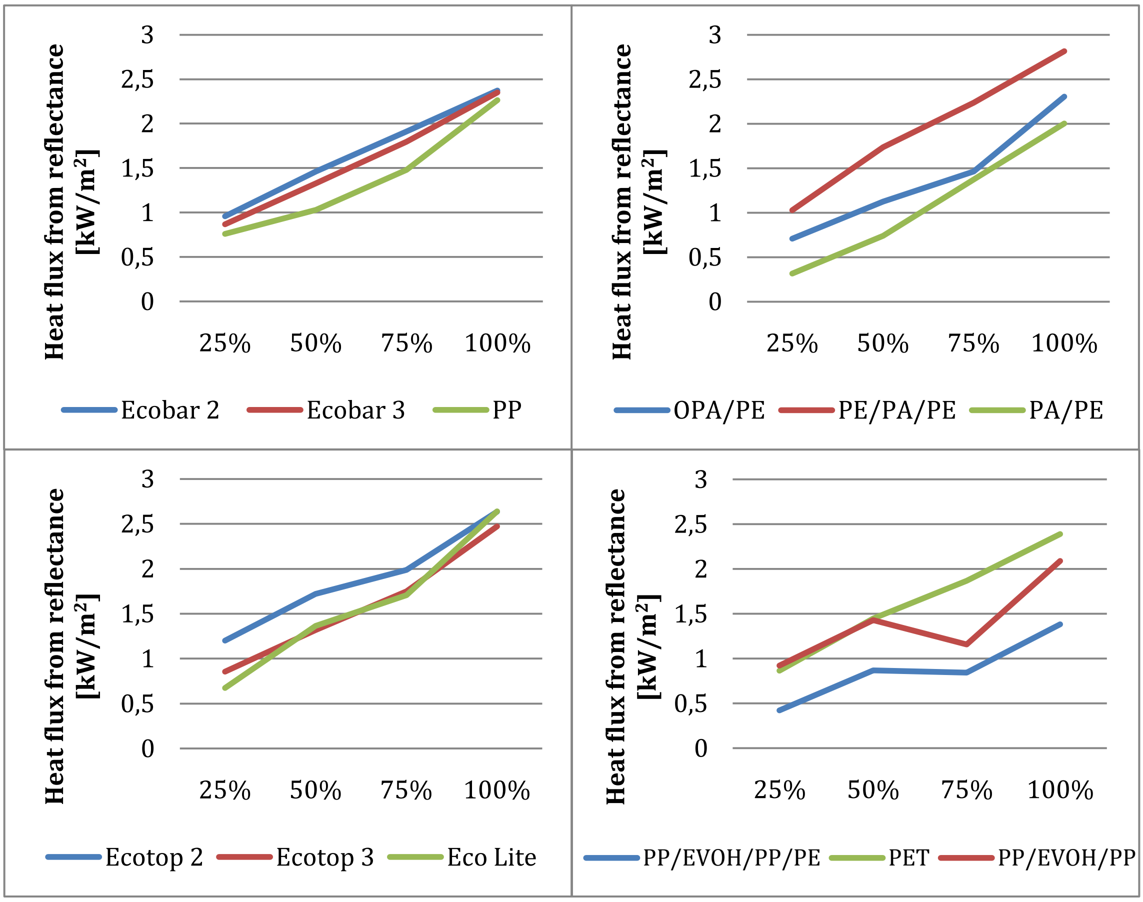


Figure 4.10*. The graphs show how the heat flux from the reflectance in kW/m^2 differs for the different materials tested. A low heat flux from the reflectance is preferable in this study.*

The reflectance [%] for the different films can be calculated with equation 3.6 and the reflectance is the relationships between the total heat flux that hits the plastic film and the heat flux from the reflectance of the film. Table 4.6 and table 4.7 show the reflectance in percent for some of the tested materials with a low reflectance. In table 4.6 are the four plastic films with low reflectance at all IR intensities represented and in table 4.7 are the three materials that have lower reflectance at lower intensities (50 % and 25 % IR intensity) listed.

Table 4.6. *The four plastic films that have a low reflectance [%] at all four tested intensities.*

Material Intensity	PP/EVOH/PP/PE	PA/PE	PP	OPA/PE
25 %	6.30 ± 2.04 %	4.70 ± 1.83 %	11.30 ± 0.17 %	10.49 ± 0.90 %
50 %	8.27 ± 2.96 %	7.06 ± 0.41 %	9.82 ± 0.71 %	10.71 ± 1.30 %
75 %	6.13 ± 2.35 %	9.96 ± 0.75 %	10.74 ± 0.30 %	10.61 ± 0.64 %
100 %	8.88 ± 1.03 %	12.85 ± 3.07 %	14.53 ± 0.84 %	14.80 ± 0.85 %

Table 4.7. *Three materials that have a low reflectance [%] at lower intensities (50 % and 25 % IR intensity).*

Material **Intensity**	**PP/EVOH/PP**	**Ecotop 3**	**Eco Lite**
25 %	13.73 ± 3.00 %	12.71 ± 1.02 %	10.01 ± 1.81 %
50 %	13.62 ± 0.58 %	12.55 ± 0.17 %	13.01 ± 0.69 %
75 %	8.39 ± 2.25 %	12.67 ± 0.30 %	12.37 ± 1.58 %
100 %	13.42 ± 0.72 %	15.88 ± 0.87 %	16.95 ± 0.25 %

4.7 Changes of film packaging quality during IR heating

The results from the tensile test were varying significantly and it was therefore hard to get a good result. If just studying the difference in tensile strain at break between an untreated film, a film treated with an IR intensity of 100 % and a film treated with an IR intensity of 25 %, the standard deviation should be as low as possible. Otherwise, there will be bigger differences in the mechanical properties of the materials. Figure 4.11 shows the tensile strain at break and the standard deviation for the different materials tested. The material PP/EVOH/PP is not in this test due to no results at all. More data from the tensile tests can be found in appendix B.

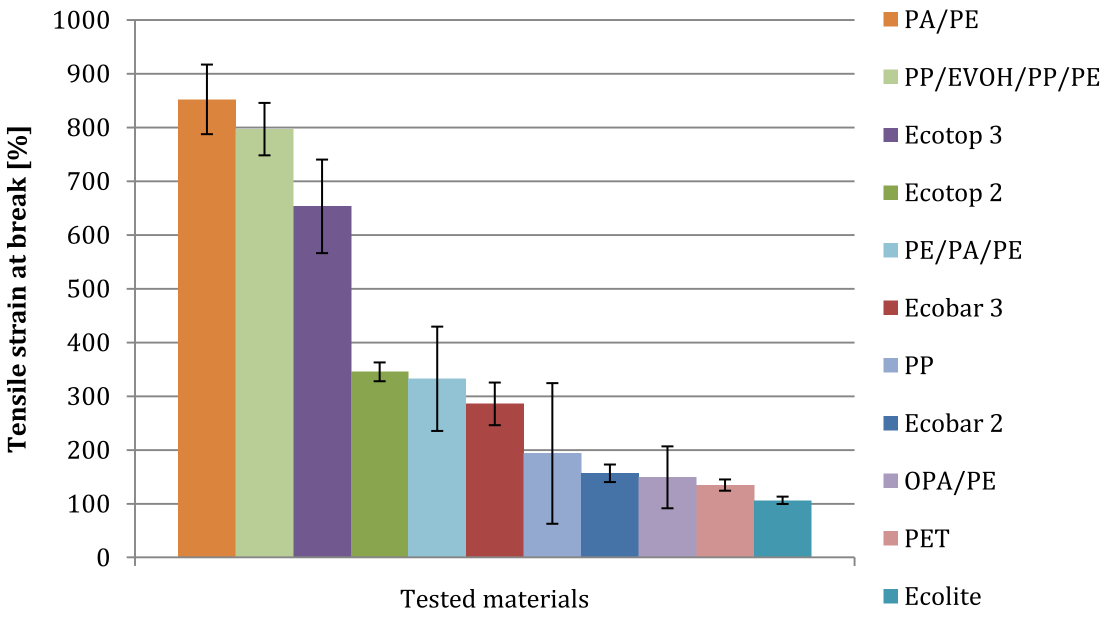


Figure 4.11. *The tensile strain at break for all tested materials except PP/EVOH/PP. The standard deviation in tensile strain at break is drawn and a low standard deviation means small differences in mechanical properties between untreated and IR treated plastic films. Eco Lite got the lowest standard deviation and has therefore the smallest differences.*

4.8 Thickness

Different thicknesses have been used for some of the tested materials for example Ecotop 2 and Ecotop 3. The materials are almost the same but the thickness is 60 µm for Ecotop 2 and 47 µm for Ecotop 3. The heat flux for the black body with the thinner film

(Ecotop 3) is higher and the transmittance is therefore higher for the film with the thickness of 47 µm than the film with the thickness of 60 µm (see figure 4.12).

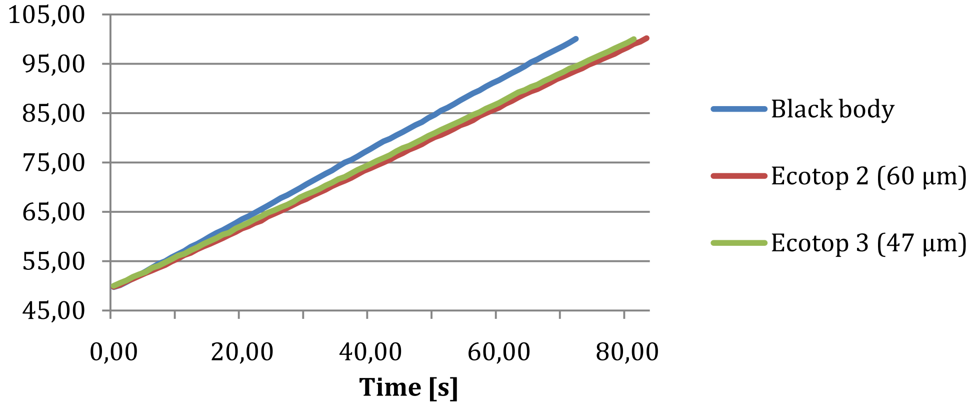


Figure 4.12. *Almost the same materials but different thickness is compared. The heating of the black body with the thinner material on top goes faster than heating with the thicker material on top.*

Generally, there is no relationship between thickness and heat flux when comparing different materials. Figure 4.13 shows the thickness of the different material and the bars in the bottom have the lowest heat flux while the bars in the top have the highest heat flux.

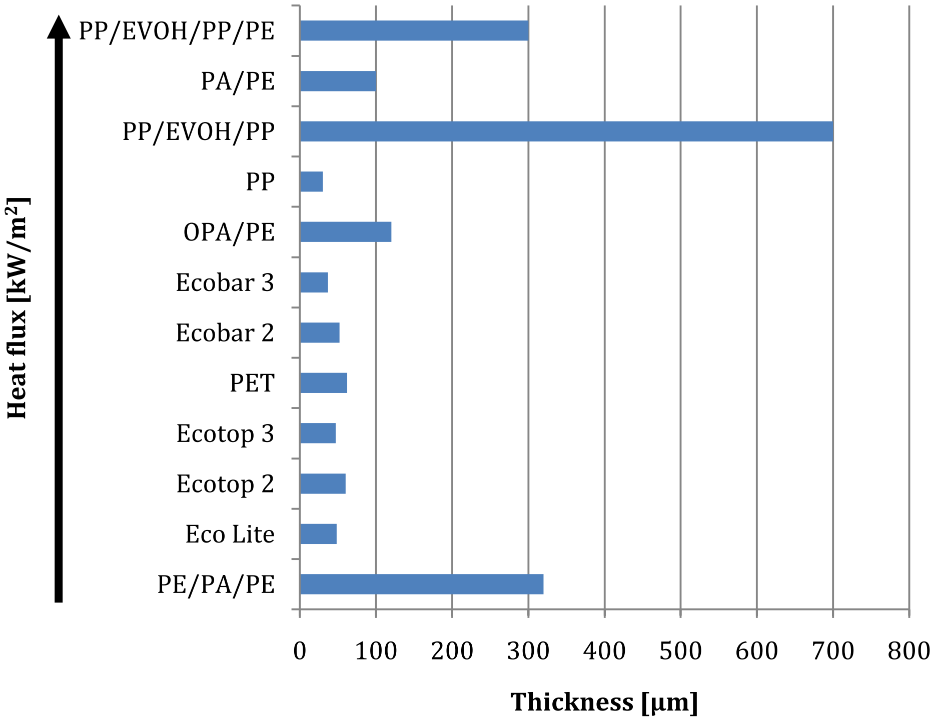


Figure 4.13. *The thickness of the tested materials. The heat flux is increasing from PE/PA/PE in the bottom to PP/EVOH/PP/PE in the top.*

4.9 Ranking and scoring

A ranking and scoring list (see appendix C) of the tested properties; transmitivity, optical changes, tensile test, reflectance and heat flux in a packaged environment, shows the best suited materials for this application. Because all materials were not able to form pouches there are two types of ranking list, one where the heat flux in a packaged environment is taken into account and one where it is not counted. The highest ranked materials in both cases are shown in table 4.8. PP/EVOH/PP is not within any of the tables because several of the properties could not be tested for this material.

Table 4.8. *The ranking and scoring list of all tested materials except PP/EVOH/PP.*

Ranking order	**Ranking with pouch**	**Ranking without pouch**
1	PA/PE	PP/EVOH/PP/PE
2	OPA/PE	PA/PE
3	Ecobar 3	OPA/PE
4	Ecobar 2	PET
5	PP	Ecobar 3
6	Eco Lite	Ecobar 2
7	Ecotop 2	PP
8	Ecotop 3	Eco Lite
9	PE/PA/PE	Ecotop 2
10	-	Ecotop 3
11	-	PA/PA/PE

4.10 Tests with bread

The final test was to try the best suited materials with a food product. In this case, white bread was used. The materials tested were PA/PE, OPA/PE and PP/EVOH/PP/PE. Figure 4.14 shows how the temperature in the black body increases when it was exposed for IR heating and bread with a plastic film was placed on top of the black body.

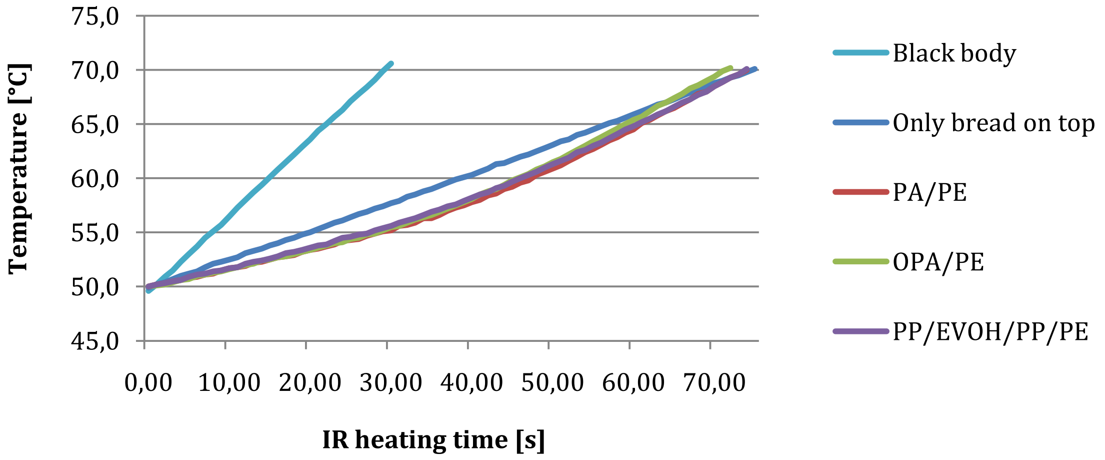


Figure 4.14. *The graph shows the increase of temperature in the black body when there was a piece of bread and a plastic film on top of it.*

Figure 4.14 shows that there is a small difference when heating bread with or without a plastic film on top. But at the same time the heating rate of bread with a plastic film on top increase after some seconds and is similar to the heating rate of bread without film, after around 70 seconds.

Figure 4.15 shows how the water activity in the white bread has changed after IR heating. When heating the bread with a plastic film on top of it, the water activity changes less than when heating the bread without anything on top of it. PA/PE results in the highest water activity of the white bread after IR heating. However, not statistically different to the other materials.

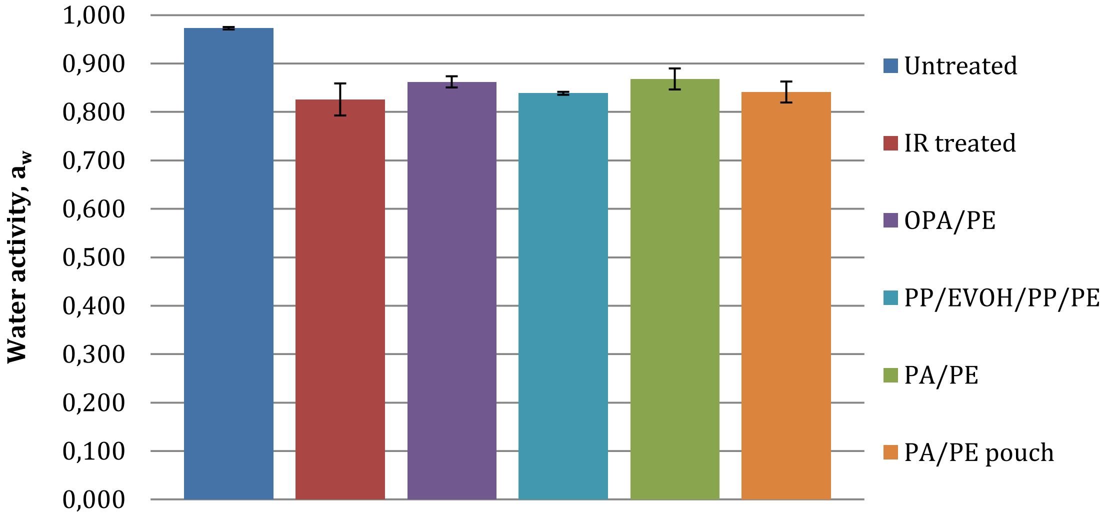


Figure 4.15. *The water activity (a_w) of white bread measured before IR heating, after IR heating and after IR heating when a plastic film have been on top of the bread.*

The weight of the bread was measured before and after IR heating, see figure 4.16. The weight loss was calculated with equation 3.7 and the results are shown in figure 4.17.

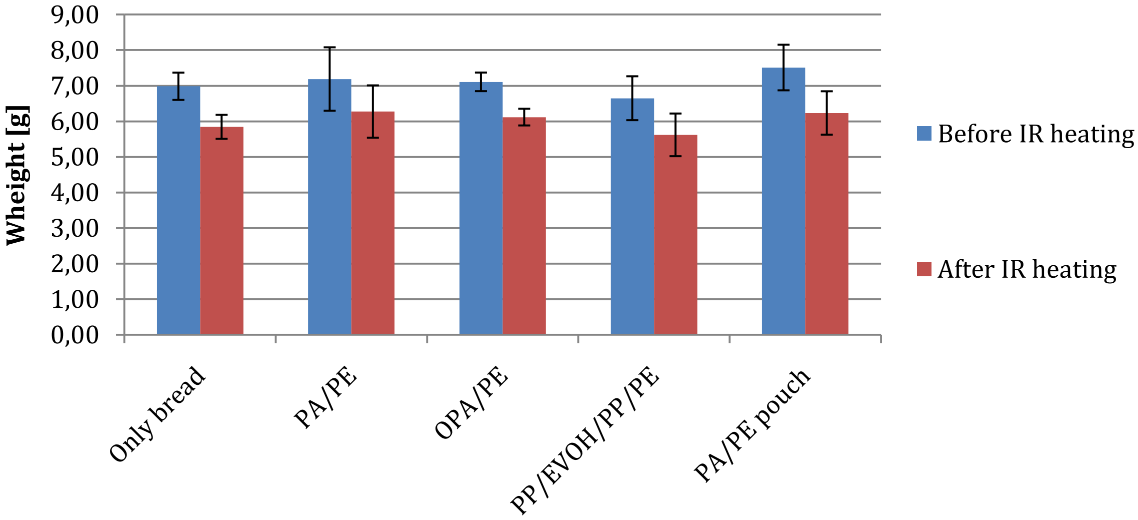


Figure 4.16. *The weight of the white bread before and after IR heating.*

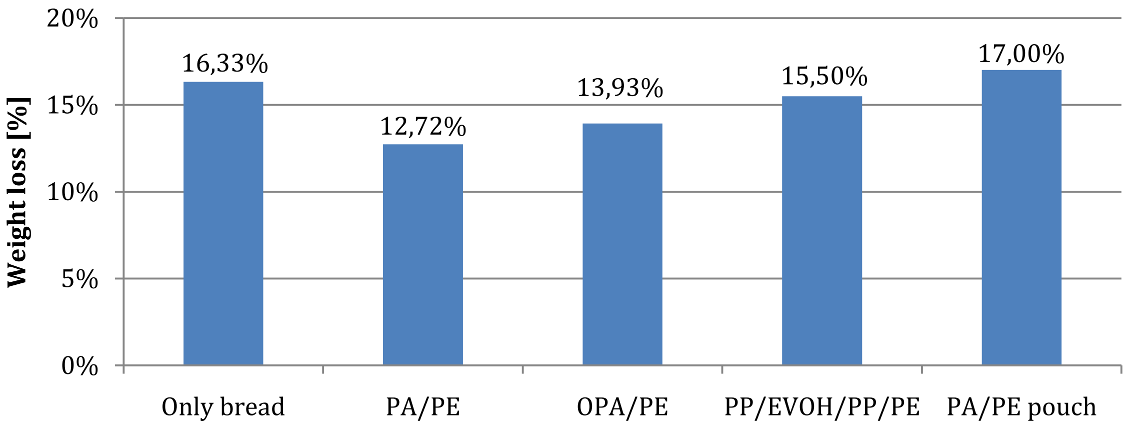


***Figure 4.17**. The weight loss of the bread in percent for the different samples.*

The biggest weight loss is when the bread is packed in a sealed pouch. The lowest weight loss is when the plastic film PA/PE is placed on top of the white bread. One reason to why the sealed pouch gives the biggest weight loss could be that the same settings has been used for all test but as seen in figure 4.18, the heat rate in the pouch is higher and the bread therefore reaches higher temperature during the 90 seconds of IR heating. If just comparing the bread that has been placed on the black body with or without a plastic film, the bread without a plastic film on top got the highest weight loss.

Figure 4.18 shows the difference between the heating in the centre of the bread when the plastic film is put on top of the bread or shaped as a pouch around the bread. The plastic film used for this test was PA/PE, which was one of the best suited plastic films for applications with IR heating on foods.

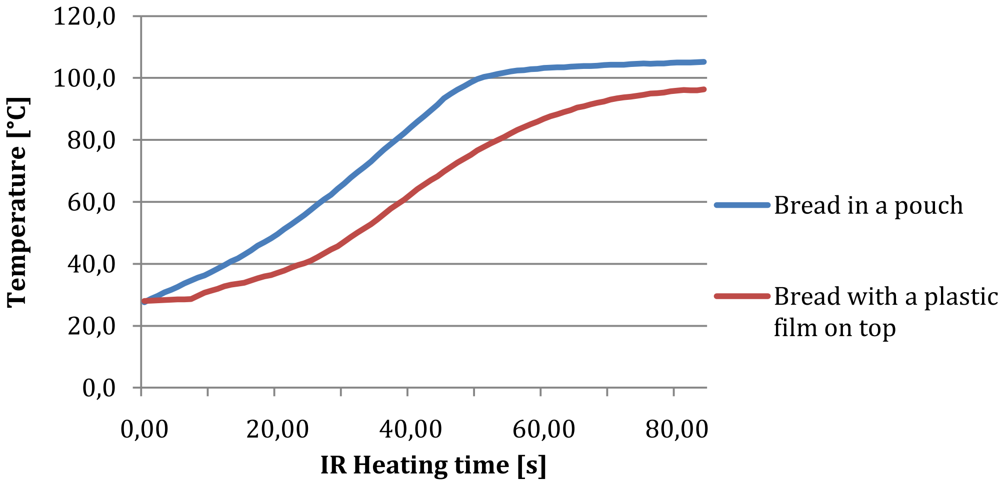


***Figure 4.18.** Comparison between the temperature in the centre of the bread when the plastic film is on top of the bread or shaped as a pouch around the bread.*

5 Conclusions

The aim with this project was to evaluate the effect of packaging materials on IR heating and to select the most suitable packaging materials for food products. Expected results were to find a methodology to assess packaging materials for IR heating and to evaluate the performance of different packaging material regarding IR heating.

The methodology that proved to work well and that was used for all tests with plastic films and some of the tests with bread, was the black body at a height around 5 cm from the metal grid and around 50 cm from the IR source. The black body was always placed in the middle of the grid due to that the heat flux was greatest there. The highest heat flux at those settings and only IR lights from the upper IR lamps gave a maximum heat flux of 15.6 kW/m^2.

The distance at 50 cm was chosen because it gives a more uniform heating even if the black body was small enough to not be affect by an uneven heating. On the other hand, the tests with bigger pouches could be affected by an uneven heating and therefore it was necessary with a larger distance at all tests.

The two different methods with plastic films were a good way to study the behaviour of the plastics during IR heating. When the plastic films were placed on top of the black body, the transmittance and reflectance of the films could be calculated and compared to each other. The tests, when the plastic films were shaped as pouches around the black body, could tell how the materials behave when the water in the air inside the pouch got warm and the hot steam affected the materials. Many food products have high water content, thus this is therefore an important aspect.

If comparing the heat flux for the black body with a film on top and the black body inside a pouch, the heat flux is much higher for the black body in the pouch, sometimes even higher than the heat flux for the black body without any materials. Therefore it could be advantageous to use IR heating for food products packaged in sealed pouches.

Three of the best plastic films suited for IR heating were PA/PE, PP/EVOH/PP/PE and OPA/PE and those materials were tested in contact with a food product, in this case a piece of white bread. The water activity of the IR treated bread should be as similar as possible to the water activity for the untreated bread. PA/PE got the lowest reduction in water activity after IR treatment. Generally, IR treated bread with a plastic film on top gave a lower reduction in water activity than the IR treated bread without a plastic film. When the bread was treated in a sealed pouch made of PA/PE, the water activity of the bread had a larger reduction than the water activity of the bread IR heated with PA/PE on top of it. This probably depend on the higher heating rate of the bread in the pouch so therefore, IR heated bread in sealed pouch needs a shorter heating time or lower IR intensity.

6 Further work

For further work there is an interest in study other plastic materials and shapes, for example plastic trays or containers, and not only thin plastic films. There could also be interesting to study materials that not are totally plastic, for example laminates with aluminium foil which are sometimes used in other heat treatments of packaging materials.

It could be interesting to study more mechanical properties of the materials to see if some other important property changes e.g. oxygen- or moisture barrier properties. Also the storage time of an IR treated material could be necessary to evaluate.

Tests with other food products also need to be done, both foods with high water contents and low water content, to see which type of foods that is most suitable for the application with IR heating of packaged food. Different materials are probably suited for different types of food products and this need more research.

7 References

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7.1 Suppliers to the plastic films:

Amcor Flexibles. *www.amcor.com /* Gäsene Mejeri. *www.gasenemejeri.se*

Flextrus AB. *www.flextrus.com*

Kontikigroup AB. *www.kontikigroup.se*

Appendix A

The heat flux for the black body (the reference sample, “*ref”*), the black body with a material on top of it and the black body in a packaged environment was calculated with equation 3.1. The transmittance was calculated from equation 3.2.

Table A.1. *PA/PE, Thickness 100 µm*

Intensity	Heat flux (ref) [kW/m^2]	Heat flux with a material on top [kW/m^2]	Heat flux in a packaged environment [kW/m^2]	Transmittance [%]
25 %	6.72 ± 0.20	6.41 ± 0.12	6.98 ± 0.05	95.30 ± 1.83
50 %	10.49 ± 0.01	9.75 ± 0.04	10.73 ± 0.04	92.94 ± 0.41
75 %	13.79 ± 0.22	12.42 ± 0.10	13.63 ± 0.14	90.04 ± 0.75
100 %	15.57 ± 0.53	13.57 ± 0.48	14.68 ± 0.06	87.15 ± 3.07

Table A.2. *PET, Thickness 62 µm*

Intensity	Heat flux (ref) [kW/m^2]	Heat flux with a material on top [kW/m^2]	Transmittance [%]
25 %	6.72 ± 0.20	5.86 ± 0.18	87.12 ± 2.67
50 %	10.49 ± 0.01	9.05 ± 0.24	86.22 ± 2.27
75 %	13.79 ± 0.22	11.92 ± 0.01	86.45 ± 0.07
100 %	15.57 ± 0.53	13.18 ± 0.18	84.65 ± 1.18

Table A.3. *PP/EVOH/PP/PE, Thickness 300 µm*

Intensity	Heat flux (ref) [kW/m^2]	Heat flux with a material on top [kW/m^2]	Transmittance [%]
25 %	6.72 ± 0.20	6.30 ± 0.14	93.70 ± 2.04
50 %	10.49 ± 0.01	9.62 ± 0.31	91.73 ± 2.96
75 %	13.79 ± 0.22	12.95 ± 0.32	93.87 ± 2.35
100 %	15.57 ± 0.53	14.19 ± 0.16	91.12 ± 1.03

Table A.4. *PP/EVOH/PP, Thickness 700 µm*

Intensity	Heat flux (ref) [kW/m^2]	Heat flux with a material on top [kW/m^2]	Transmittance [%]
25 %	6.72 ± 0.20	5.80 ± 0.20	86.27 ± 3.00
50 %	10.49 ± 0.01	9.06 ± 0.06	86.38 ± 0.58
75 %	13.79 ± 0.22	12.63 ± 0.31	91.61 ± 2.25
100 %	15.57 ± 0.53	13.48 ± 0.11	86.58 ± 0.72

***Table A.5.** PP, Thickness 30 µm*

Intensity	Heat flux (ref) [kW/m^2]	Heat flux with a material on top [kW/m^2]	Heat flux in a packaged environment [kW/m^2]	Transmittance [%]
25 %	6.72 ± 0.20	5.96 ± 0.01	6.89*	88.70 ± 0.17
50 %	10.49 ± 0.01	9.46 ± 0.07	10.65*	90.18 ± 0.71
75 %	13.79 ± 0.22	12.31 ± 0.04	13.82*	89.26 ± 0.30
100 %	15.57 ± 0.53	13.31 ± 0.13	14.84*	85.47 ± 0.84

** There is no standard deviation at those tests due the amount of material available.*

***Table A.6.** Eco Lite, Thickness 48 µm*

Intensity	Heat flux (ref) [kW/m^2]	Heat flux with a material on top [kW/m^2]	Heat flux in a packaged environment [kW/m^2]	Transmittance [%]
25 %	6.72 ± 0.20	6.05 ± 0.12	6.76 ± 0.21	89.99 ± 1.81
50 %	10.49 ± 0.01	9.13 ± 0.07	10.33 ± 0.06	86.99 ± 0.69
75 %	13.79 ± 0.22	12.09 ± 0.22	13.74 ± 0.27	87.63 ± 1.58
100 %	15.57 ± 0.53	12.93 ± 0.04	14.98 ± 0.14	83.05 ± 0.25

***Table A.7.** Ecobar 2, Thickness 52 µm*

Intensity	Heat flux (ref) [kW/m^2]	Heat flux with a material on top [kW/m^2]	Heat flux in a packaged environment [kW/m^2]	Transmittance [%]
25 %	6.72 ± 0.20	5.76 ± 0.08	7.22 ± 0.26	85.75 ± 1.22
50 %	10.49 ± 0.01	9.03 ± 0.14	10.52 ± 0.06	86.08 ± 1.36
75 %	13.79 ± 0.22	11.88 ± 0.01	13.78 ± 0.16	86.13 ± 0.06
100 %	15.57 ± 0.53	13.20 ± 0.20	15.14 ± 0.12	84.76 ± 1.31

***Table A.8.** Ecobar 3, Thickness 37 µm*

Intensity	Heat flux (ref) [kW/m^2]	Heat flux with a material on top [kW/m^2]	Heat flux in a packaged environment [kW/m^2]	Transmittance [%]
25 %	6.72 ± 0.20	5.85 ± 0.23	6.67 ± 0.31	87.09 ± 3.39
50 %	10.49 ± 0.01	9.16 ± 0.03	10.23 ± 0.12	87.32 ± 0.30
75 %	13.79 ± 0.22	12.00 ± 0.09	13.58 ± 0.09	86.97 ± 0.63
100 %	15.57 ± 0.53	13.22 ± 0.11	15.22 ± 0.36	84.91 ± 0.07

Table A.9. *Ecotop 2, Thickness 60 µm*

Intensity	Heat flux (ref) [kW/m^2]	Heat flux with a material on top [kW/m^2]	Heat flux in a packaged environment [kW/m^2]	Transmittance [%]
25 %	6.72 ± 0.20	5.52 ± 0.20	6.54 ± 0.23	82.14 ± 3.03
50 %	10.49 ± 0.01	8.77 ± 0.10	10.39 ± 0.15	83.61 ± 0.97
75 %	13.79 ± 0.22	11.81 ± 0.21	13.80*	85.59 ± 1.49
100 %	15.57 ± 0.53	12.94 ± 0.03	14.88*	83.08 ± 0.17

** There is no standard deviation at those tests due to the behaviour of the material during IR heating.*

Table A.10. *Ecotop 3, Thickness 47 µm*

Intensity	Heat flux (ref) [kW/m^2]	Heat flux with a material on top [kW/m^2]	Heat flux in a packaged environment [kW/m^2]	Transmittance [%]
25 %	6.72 ± 0.20	5.87 ± 0.07	6.91 ± 0.16	87.29 ± 1.02
50 %	10.49 ± 0.01	9.18 ± 0.02	10.39 ± 0.10	87.45 ± 0.17
75 %	13.79 ± 0.22	12.04 ± 0.04	13.58*	87.33 ± 0.30
100 %	15.57 ± 0.53	13.10 ± 0.14	14.87*	84.12 ± 0.87

** There is no standard deviation at those tests due to the behaviour of the material.*

Table A.11. *OPA/PE, Thickness 120 µm*

Intensity	Heat flux (ref) [kW/m^2]	Heat flux with a material on top [kW/m^2]	Heat flux in a packaged environment [kW/m^2]	Transmittance [%]
25 %	6.72 ± 0.20	6.02 ± 0.06	6.75 ± 0.01	89.51 ± 0.90
50 %	10.49 ± 0.01	9.37 ± 0.14	9.60 ± 0.65	89.29 ± 1.30
75 %	13.79 ± 0.22	12.33 ± 0.09	12.70 ± 0.53	89.39 ± 0.64
100 %	15.57 ± 0.53	13.27 ± 0.13	13.73 ± 0.76	85.20 ± 0.85

Table A.12. *PE/PA/PE, Thickness 320 µm*

Intensity	Heat flux (ref) [kW/m^2]	Heat flux with a material on top [kW/m^2]	Heat flux in a packaged environment [kW/m^2]	Transmittance [%]
25 %	6.72 ± 0.20	5.69 ± 0.11	6.75 ± 0.01	84.71 ± 1.58
50 %	10.49 ± 0.01	8.76 ± 0.07	9.60 ± 0.65	83.45 ± 0.68
75 %	13.79 ± 0.22	11.56 ± 0.02	12.70 ± 0.53	83.80 ± 0.15
100 %	15.57 ± 0.53	12.76 ± 0.33	13.73 ± 0.76	81.92 ± 2.15

Appendix B

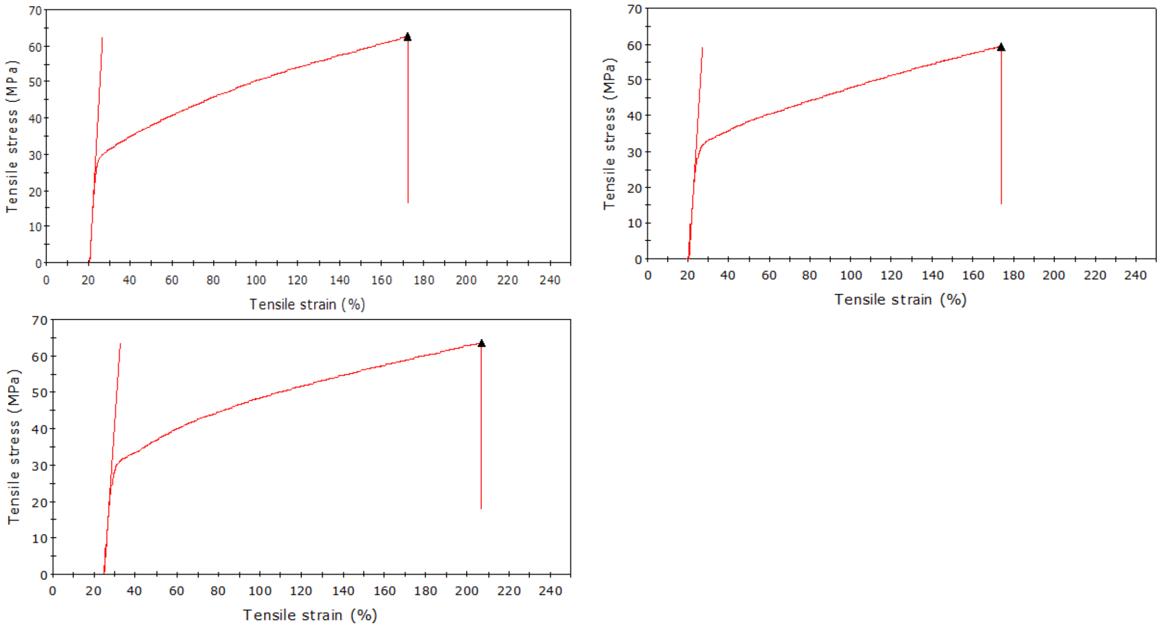

Figure B.1. *Tensile stress and tensile strain curves for Ecobar 2, a) untreated b) treated with IR of an intensity of 100% and c) treated with IR of an intensity of 25%.*

Table B.1. *Measured properties from tensile test of Ecobar 2.*

	Tensile strain at Break (%)	Tensile stress at Break (MPa)	Modulus (E-modulus) (MPa)	Load at Break (Standard) (N)	Extension at Break (Standard) (mm)
Untreated	172,41	62,45	877,69	19,48	44,89
100 % IR	173,86	59,21	748,83	18,48	39,79
25 % IR	206,89	63,58	701,59	19,84	45,00
Mean	**184,39**	**61,75**	**776,04**	**19,27**	**43,23**
STDAV	**19,50**	**2,27**	**91,15**	**0,71**	**2,98**

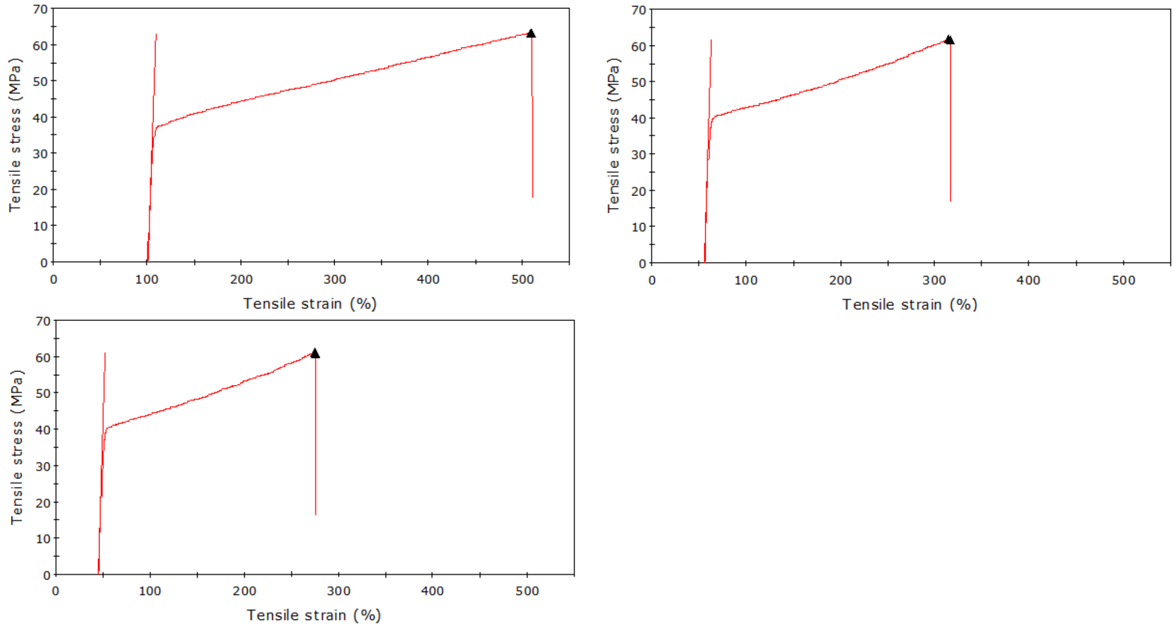

Figure B.2. *Tensile stress and tensile strain curves for Ecobar 3, a) untreated b) treated with IR of an intensity of 100% and c) treated with IR of an intensity of 25%.*

Table B.2. *Measured properties from tensile test of Ecobar 3.*

	Tensile strain at Break (%)	Tensile stress at Break (MPa)	Modulus (E-modulus) (MPa)	Load at Break (Standard) (N)	Extension at Break (Standard) (mm)
Untreated	510,36	62,91	605,34	15,10	73,09
100% IR	316,28	61,59	798,17	14,78	51,96
25% IR	275,15	60,83	797,07	14,60	48,81
Mean	**367,26**	**61,78**	**733,53**	**14,83**	**57,95**
STDAV	**125,62**	**1,05**	**111,01**	**0,25**	**13,20**

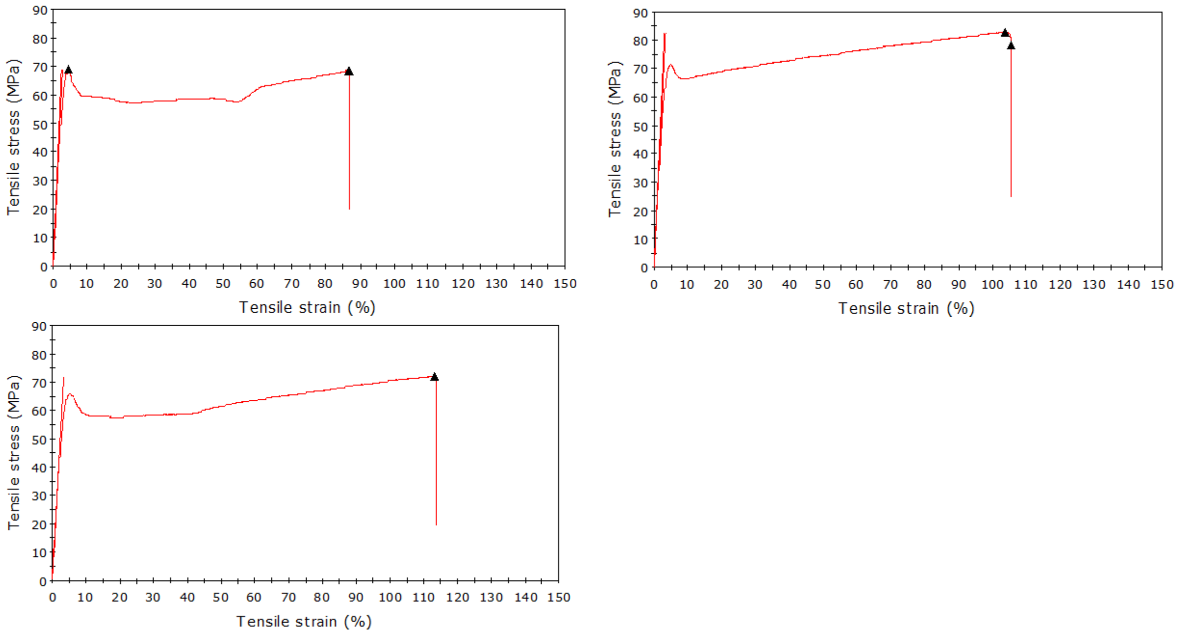

Figure B.3. *Tensile stress and tensile strain curves for Eco Lite, a) untreated b) treated with IR of an intensity of 100% and c) treated with IR of an intensity of 25%.*

Table B.3. *Measured properties from tensile test of Eco Lite.*

	Tensile strain at Break (%)	Tensile stress at Break (MPa)	Modulus (E-modulus) (MPa)	Load at Break (Standard) (N)	Extension at Break (Standard) (mm)
Untreated	86,58	68,45	2218,86	21,36	31,04
100% IR	105,45	78,31	2206,60	24,43	37,05
25% IR	113,39	72,27	1962,16	22,55	39,02
Mean	**101,81**	**73,01**	**2129,21**	**22,78**	**35,70**
STDAV	**13,77**	**4,97**	**144,80**	**1,55**	**4,15**

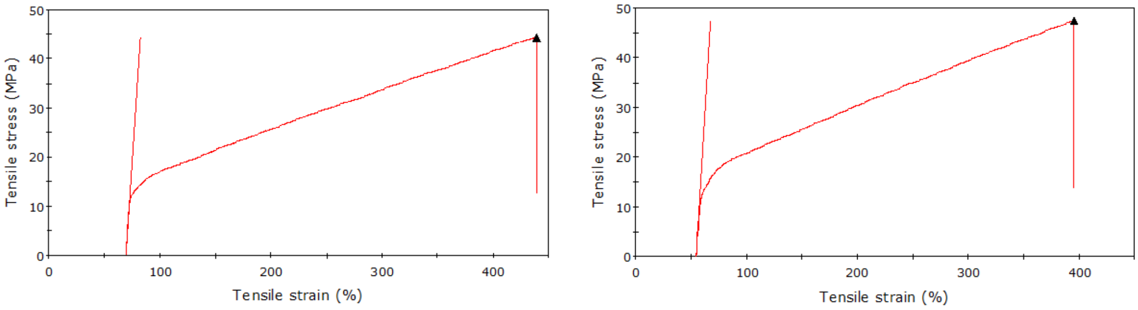

Figure B.4. *Tensile stress and tensile strain curves for Ecotop 2, a) untreated b) treated with IR of an intensity of 100%.*

Table B.4. *Measured properties from tensile test of Ecotop 2.*

	Tensile strain at Break (%)	Tensile stress at Break (MPa)	Modulus (E-modulus) (MPa)	Load at Break (Standard) (N)	Extension at Break (Standard) (mm)
Untreated	438,80	44,42	102,88	15,99	77,93
100% IR	395,72	47,54	120,79	17,11	70,34
Mean	**417,26**	**45,98**	**111,84**	**16,55**	**74,13**
STDAV	**30,46**	**2,21**	**12,66**	**0,79**	**5,37**

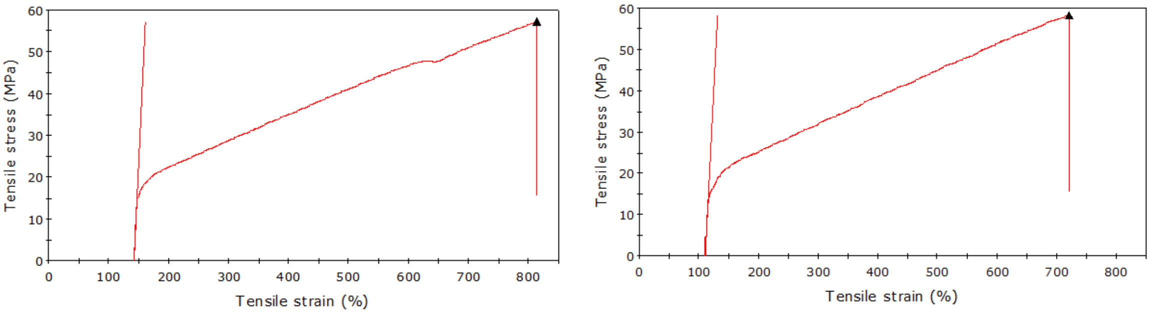

Figure B.5. *Tensile stress and tensile strain curves for Ecotop 3, a) untreated b) treated with IR of an intensity of 100%.*

Table B.5. *Measured properties from tensile test of Ecotop 3.*

	Tensile strain at Break (%)	Tensile stress at Break (MPa)	Modulus (E-modulus) (MPa)	Load at Break (Standard) (N)	Extension at Break (Standard) (mm)
Untreated	814,80	57,24	210,33	16,14	99,11
100% IR	721,02	58,44	171,61	16,48	93,03
Mean	**767,91**	**57,84**	**190,97**	**16,31**	**96,07**
STDAV	**66,31**	**0,85**	**27,38**	**0,24**	**4,29**

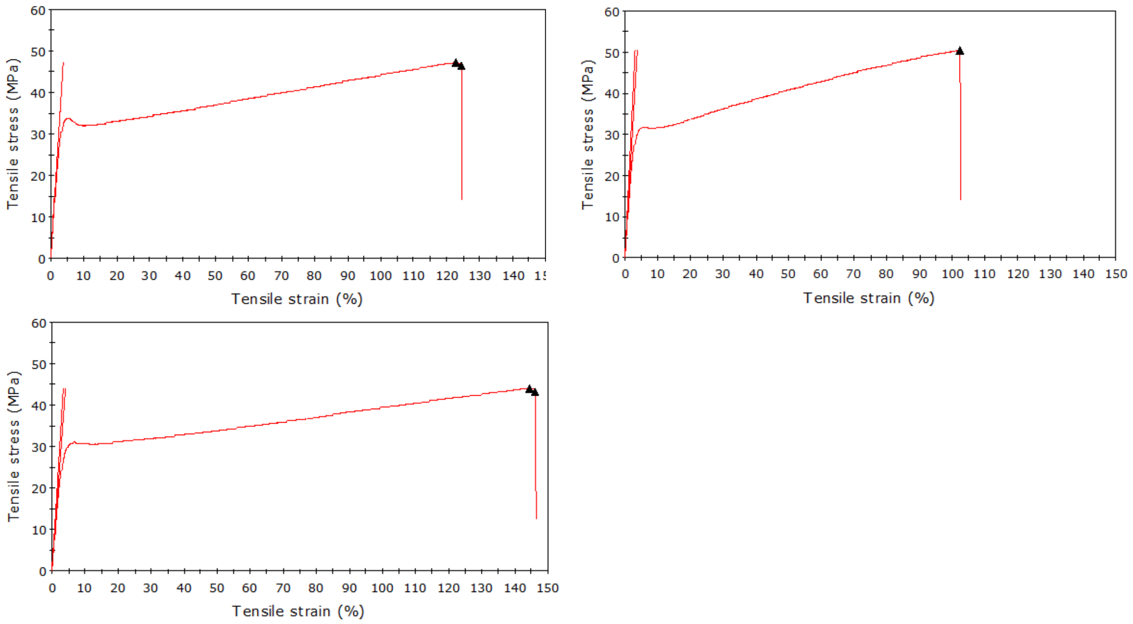

Figure B.6. *Tensile stress and tensile strain curves for PET, a) untreated b) treated with IR of an intensity of 100% and c) treated with IR of an intensity of 25%.*

Table B.6. *Measured properties from tensile test of PET.*

	Tensile strain at Break (%)	Tensile stress at Break (MPa)	Modulus (E-modulus) (MPa)	Load at Break (Standard) (N)	Extension at Break (Standard) (mm)
Untreated	124,39	46,56	1047,74	19,56	33,04
100% IR	102,45	50,56	1034,31	21,24	27,24
25% IR	146,29	43,14	828,13	18,12	38,72
Mean	**124,38**	**46,75**	**970,06**	**19,64**	**33,00**
STDAV	**21,92**	**3,71**	**123,10**	**1,56**	**5,74**

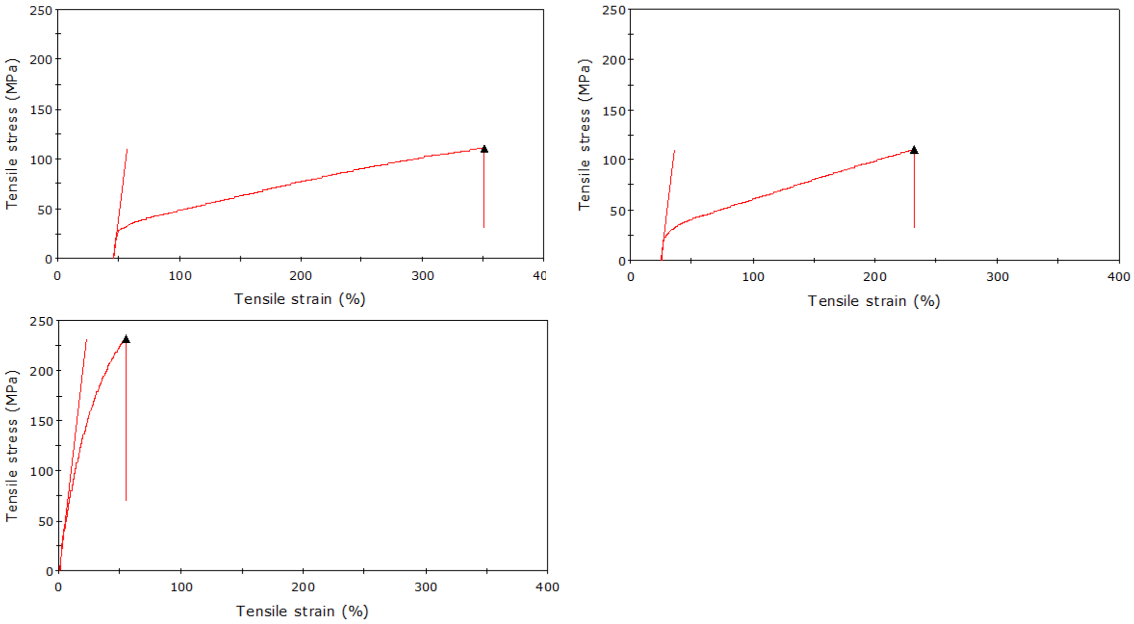

Figure B.7. *Tensile stress and tensile strain curves for PP, a) untreated b) treated with IR of an intensity of 100% and c) treated with IR of an intensity of 25%.*

Table B.7. *Measured properties from tensile test of PP.*

	Tensile strain at Break (%)	Tensile stress at Break (MPa)	Modulus (E-modulus) (MPa)	Load at Break (Standard) (N)	Extension at Break (Standard) (mm)
Untreated	351,21	110,89	937,58	23,2875	57,4589
100% IR	232,07	110,2	998,01	23,14095	58,08515
25% IR	54,86	232,45	1543,93	48,81543	18,56593
Mean	**212,71**	**151,18**	**1159,84**	**31,75**	**44,70**
STDAV	**149,12**	**70,38**	**334,00**	**14,78**	**22,64**

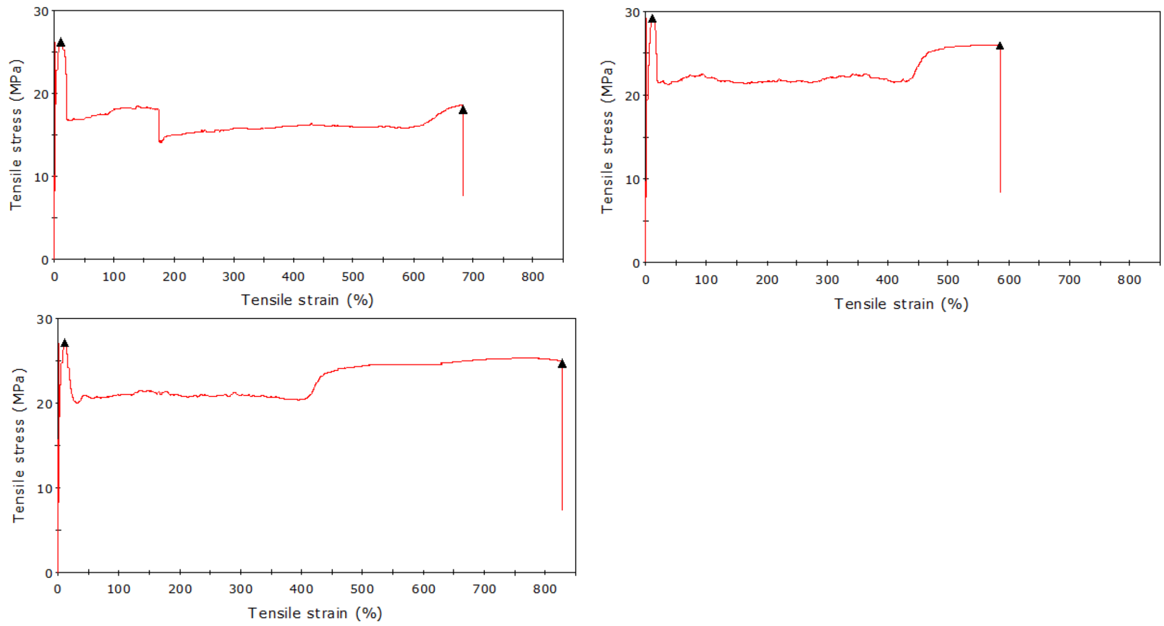

Figure B.8. *Tensile stress and tensile strain curves for PP/EVOH/PP/PE, a) untreated b) treated with IR of an intensity of 100% and c) treated with IR of an intensity of 25%.*

Table B.8. *Measured properties from tensile test of PP/EVOH/PP/PE.*

	Tensile strain at Break (%)	Tensile stress at Break (MPa)	Modulus (E-modulus) (MPa)	Load at Break (Standard) (N)	Extension at Break (Standard) (mm)
Untreated	682,27	18,15	652,56	43,56	197,03
100% IR	586,04	25,91	730,04	62,19	180,06
25% IR	826,75	24,73	704,32	59,36	253,55
Mean	**698,35**	**22,93**	**695,64**	**55,04**	**210,21**
STDAV	**121,16**	**4,18**	**39,46**	**10,04**	**38,47**

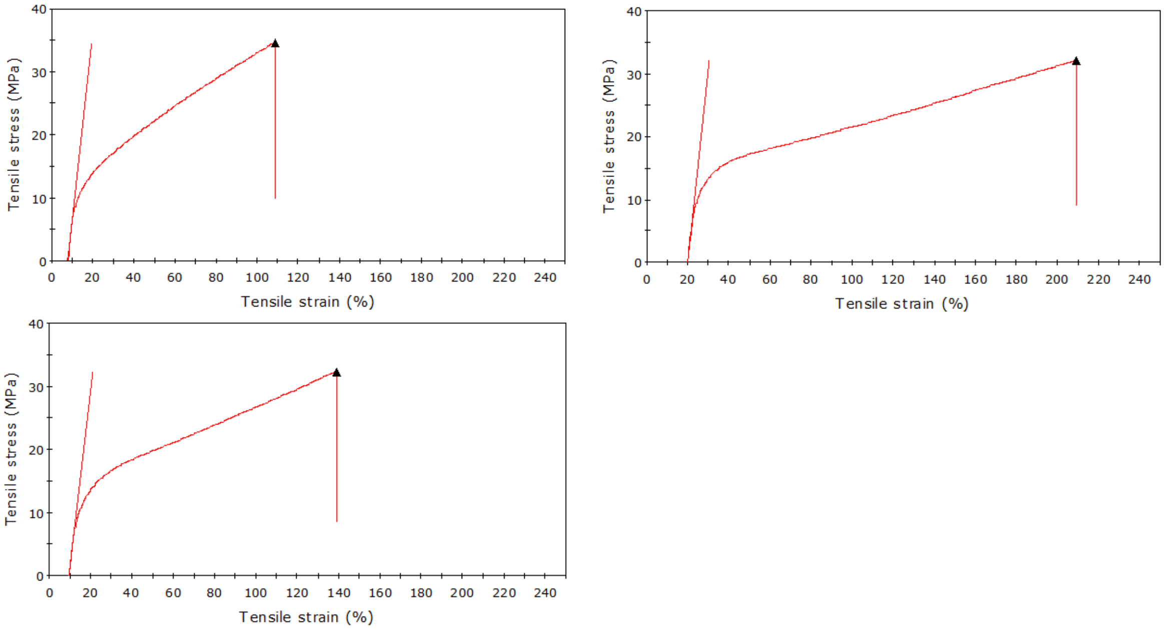

Figure B.9. *Tensile stress and tensile strain curves for OPA/PE, a) untreated b) treated with IR of an intensity of 100% and c) treated with IR of an intensity of 25%.*

Table B.9. *Measured properties from tensile test of OPA/PE.*

	Tensile strain at Break (%)	Tensile stress at Break (MPa)	Modulus (E-modulus) (MPa)	Load at Break (Standard) (N)	Extension at Break (Standard) (mm)
Untreated	108,49	34,65	66,78	24,95	34,30
100% IR	209,24	32,09	72,60	23,10	41,39
25% IR	139,08	32,31	75,57	23,26	-----
Mean	**152,27**	**33,02**	**71,65**	**23,77**	**37,84**
STDAV	**51,65**	**1,42**	**4,47**	**1,02**	**5,01**

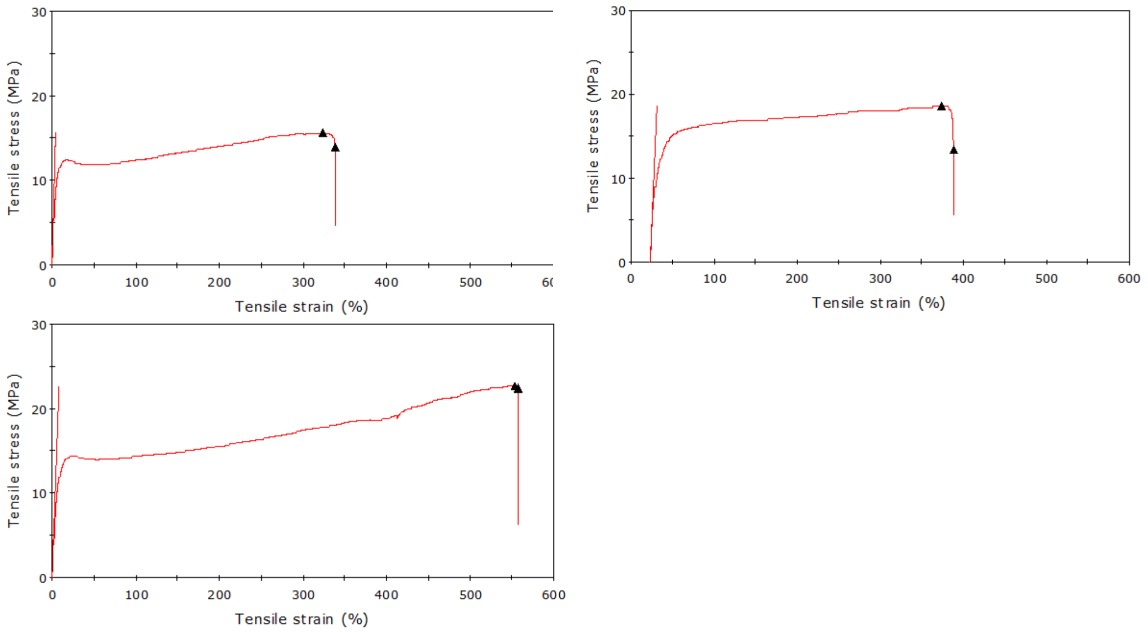

__Figure B.10.__ Tensile stress and tensile strain curves for PE/PA/PE, a) untreated b) treated with IR of an intensity of 100% and c) treated with IR of an intensity of 25%.

__Table B.10.__ Measured properties from tensile test of PE/PA/PE.

	Tensile strain at Break (%)	Tensile stress at Break (MPa)	Modulus (E-modulus) (MPa)	Load at Break (Standard) (N)	Extension at Break (Standard) (mm)
Untreated	338,17	13,9	35,39	26,69503	123,5722
100% IR	388,65	13,34	46,99	25,60381	-----
25% IR	557,9	22,38	64,62	42,96515	194,9197
Mean	**428,24**	**16,54**	**49,00**	**31,75**	**159,25**
STDAV	**115,09**	**5,07**	**14,72**	**9,72**	**50,45**

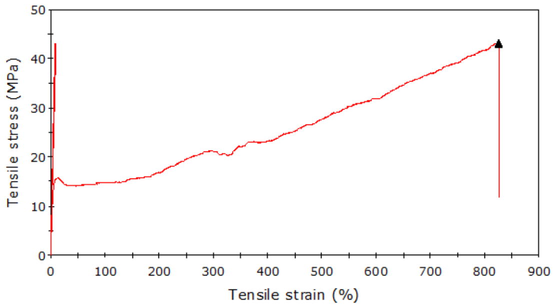

__Figure B.11.__ Tensile stress and tensile strain curve for PA/PE. The curve shows the untreated plastic film and there were no good results for IR treated PA/PE.

__Table B.11.__ Measured properties from tensile test of PA/PE.

	Tensile strain at Break (%)	Tensile stress at Break (MPa)	Modulus (E-modulus) (MPa)	Load at Break (Standard) (N)	Extension at Break (Standard) (mm)
Untreated	827,16	43,09	174,94	7,7557	231,2179

Appendix C

***Table C.1**. A ranking and scoring table where all materials except PET, PP/EVOH/PP/PE and PP/EVOH/PP are in because they cannot be shaped as pouches.*

	Transmitivity		Behaviour during heating		Reflectance		Tensile Test		Heat flux in a pouch		Score
Material	Rank	Score (WF=10)	Rank	Score (WF=8)	Rank	Score (WF=6)	Rank	Score (WF=4)	Rank	Score (WF=2)	Total
PA/PE	9	90	8	64	9	54	5	20	3	6	234
OPA/PE	7	70	8	64	7	42	4	16	1	2	194
PE/PA/PE	1	10	1	8	1	6	3	12	1	2	38
PP	8	80	1	8	8	48	1	4	4	8	148
Eco Lite	2	20	5	40	2	12	9	36	7	14	122
Ecotop 3	4	40	1	8	4	24	2	8	6	12	92
Ecotop 2	3	30	1	8	3	18	7	28	5	10	94
Ecobar 2	5	50	6	48	5	30	8	32	8	16	176
Ecobar 3	6	60	6	48	6	36	6	24	9	18	186
Totalt*		**90**		**64**		**54**		**36**		**18**	**262**

**The maximum score that each property can give and the total sum of the maximum a material can have.*

***Table C.2**. A ranking and scoring table where all materials except PP/EVOH/PP are in because there are no results in tensile testing for PP/EVOH/PP.*

	Transmitivity		Behaviour during heating		Reflectance		Tensile Test		Score
Material	Rank	Score (WF=10)	Rank	Score (WF=8)	Rank	Score (WF=6)	Rank	Score (WF=4)	Total
PA/PE	10	100	9	72	10	60	5	20	252
OPA/PE	8	80	9	72	8	48	4	16	216
PE/PA/PE	1	10	1	8	1	6	3	12	36
PET	5	50	9	72	5	30	10	40	192
PP	9	90	1	8	9	54	1	4	156
PE/PP/EVOH/PP/PE	11	110	7	56	11	66	6	24	256
Eco Lite	2	20	7	56	2	12	11	44	132
Ecotop 3	4	40	1	8	4	24	2	8	80
Ecotop 2	3	30	1	8	3	18	8	32	88
Ecobar 2	6	60	5	40	6	36	9	36	172
Ecobar 3	7	70	5	40	7	42	7	28	180
Total*		**110**		**72**		**66**		**44**	**292**

**The maximum score that each property can give and the total sum of the maximum a material can have.*