2015

The Performance of Bio-produced PE and PET in Flexible Packaging Materials

A benchmarking evaluation

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Abstract

The packaging market is starting to demand renewable materials to face out the fossil based materials mainly used today. This thesis investigate the possibility and advance to switch from conventional grades of polyethylene (PE) and poly(ethylene terephthalate)s (PET) towards bio-produced grades of the same polymers.

The work is divided into two parts starting with a carbon footprint evaluation of the existing products benchmarked against with the two new bio-produced polymer qualities. The two most interesting Flextrus' products were produced with the new grades and benchmarking analyses were performed to investigate if there was any difference towards the conversional ones.

The two most interesting materials chosen for further investigation after the Carbon Footprint evaluation was Fibercote 50/25, a paper coated with a PET layer, and HiLite390/40, a laminated plastic sheet of PET and PE. At production there was some struggle with the Fibercote 50/25 which can have had an extensive impact on some of the tests.

Over all there is no obvious material related difference between the materials. Concluded by the results the sealing temperature is lower for the Bio-HiLite 390/40. Possibly this is because of the lower melting temperatures of the bio-produced PE.

In most of the tests the new grades perform well enough to be used in the same combination as the conventional material and keep the standard of the product. This conclusion is made after only one production and the tests should be repeated in further production to ensure these results.

The cost would increase using the new bio-produced materials. These assumptions is made regarding the low volume price received for test production and is thus only an indication that it could make an impact.

Preface

This work has been performed with Flexstrus in Lund May-November 2015. The project has not only been developing but also combined the most engaging parts of my education with my personal interest in environmental issues. These past months felt inspiring and relevant, especially since the work was performed in an industry where environmental performance of materials gain more and more importance. To be a part of trying to change the market attitude towards a less oil dependent path is something I will take with me further on in my approaching career as a packaging materials engineer.

I want to pass on extra thanks to my corporate supervisor, Nils Lagerwall, who always took time to guide me through a problem, inspiring me towards new angles. It has been a pleasure all the way through.

Thanks to Jessica Mauritsson and Anton Berthold who took me through the nail biting experience of trying out new materials in large scale machinery. Also thank you, Håkan Arnfors, for patiently guide me through all the lab work.

Also thanks to my supervisor at LTH, Baozhong Zhang, for valid tips in the report writing phase.

Last of all a thank you to the employees at Flextrus who made me feel at home for the last 6 months.

Symbols and abbreviations

PE	**Polyethylene**
PET	Poly(ethylene terephthalate)
GHG	Greenhous gas
TPA	Terephthalic acid
PHA:s	Polyhydroxy alcanoates
PLA	Polylactate
NIR	Near infrared technology
PEF	Polyethylene furanoate
CO_2	Carbon dioxide
GSM	Gram per square meter
LDPE	Low density poly ethylene
LLDPE	Linear low density polyethylene
HDPE	High density polyethylene
OTR	Oxygen Transmission Rate
WVP	Water Vapor Permeability
IV	Intrinsic Viscosity
COF	Coefficient of Friction
DSC	Differential Scanning Calorimetry

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1. Introduction

Today the demand for new, less oil dependent products are increasing [1]–[3]. With the raised environmental awareness of the end customer it is possible to compete with better environmental performance of products even if the cost is higher than for the conventional materials. This gives the opportunity to increase the environmental efficiency and performance in many areas none the least packaging materials.

Today packaging is primarily regarded as something that induce waste [3]–[5]. Even if the environmental performance of package many times are limited to small pieces of the entire product the focus is on limiting the material usage and thus the waste management for the end user. Communicated in the right way, bio-materials, new or conventional produced by a new pathway with a biomass feedstock, could give an opportunity to raise the environmental performance of the package without limiting its main properties to protect the product throughout the supply chain.

This thesis focuses on two grades of conventional plastics, polyethylene and poly(ethylene terephthalate)s, produced by a new pathway using a biomass feedstock of sugar cane. The thesis main aim is to investigate the environmental performance of both the conventional fossil based grades used in production today and comparing it to the new qualities with >95 % respectively 30 % of renewable content. The thesis also aim to investigate the production performance of the new qualities to ensure that they are exchangeable in Flextrus' production as well as at their customer sites. This would be done by benchmarking tests on the raw material, as well as the produced plastic laminates.

2. Background

2.1 Flextrus

Flextrus is a part of the AR Packaging Group and are market leaders in flexible packaging solutions for the Scandinavian market. Flexible packaging means soft non-ridged material as pouches thermoformed trays or films. They perform a business to business service where packaging materials, mainly laminated plastic films or cardboard lined with plastic material, are produced and sold in reels. The film materials are then cut, formed and filled at customer production sites.

The company motto is to be close to customer, collaborating solutions and innovations for their special needs and requirements. Still, there are some standard products where components could be varied in thickness after customer requirements. These variations are different qualities with the same prime usage and materials choice. What is varied within a product family is thickness of different laminate layers and sometimes extra packaging related features added to a quality.

The two main market segments are medical and food packaging. Both consumer areas are requiring controlled barrier properties. This is why laminated material is a good choice since it gives a good opportunity to tune these barriers at lower material consumption than within one-layer packaging. Laminated packages can also improve the performance of the containing product since it often improve the shelf life and therefor decrease the food losses. Barrier properties and opportunities are further described below in section 2.7.

In Table 1 a list of standard product families in the food area are briefly described. These are collected from the Flextrus Website.

Table 1. Product families, components and main usage

Product family	Prime usage	Materials incorporated	Example
AirLite®	Base web	Mono-PET, PET-PE, EvOH	Tray for fresh or processed food
FiberLite®	Base web	Mono-PET, PET-PE, EvOH	Tray for fresh or processed food
HiLite	Base web	Mono-PET, PET-PE, EvOH	Lids and trays
NP	Base web	PA, EvOH, PE, PP	Pouches and trays
PaperLite®	Base web	PE, PET, paper, EvOH	Shallow trays
Ecobar	Lidding films	PET, PP, PE, EvOH	Modified atmosphere packaging
EcoLite®	Lidding films	PET	Modified atmosphere packaging
Ecotop®	Lidding films	PP, EvOH, PE	Modified atmosphere packaging
Fibercote®	Lidding films	PE, EvOH, paper	Topfilm and pouches
Clearcote	Sachet and pouches	PE	Fresh food pouches
Foilbond®	Sachet and pouches	Ionomer, paper, PE, aluminum	Dry mixes pouches
Transofoil®	Sachet and pouches	Inomer, PET, PE, aluminum	Dry mixes and fluids pouhces

2.2 Polyethylene (PE) and Poly(ethylene terephthalate) (PET)

In 2013 the total amount of produced plastic reached 299 million tons. In Europe the demand of plastic reached 46.3 million tons whereof 29.6 % counted for different PE qualities and 6.9 % for PET. Totally 39.1 % of the plastic demand was created by packaging [6]. In the sections below some characteristics and production properties are briefly described.

When producing polymer laminates of PE and PET it is important to keep in mind that these polymers are immiscible. It is therfor not possible to laminate the materials, i.e. heat them together, but instead the PET sheet is cast and then coated with the PE using a tie compound or other chemical agents to achieve adhesion.

2.2.1 PE

There are three major types of PE. Low density PE (LDPE), linear low density PE (LLDPE) and High density PE (HDPE). The density is connected to the crystallinity of the polymer. LDPE has a high amount of branching formed in the high pressure and high temperature process, and therefore more steric hindrance for crystallization. HDPE is instead formed in a catalyzed method, often Ziegler-Natta catalyzed, allowing for lower temperatures and pressures where the branching is more limited and thus the density higher. LLDPE is since the gas-phase polymerization was initiated also performed in a low temperature/pressure process with a coordination catalyzed reaction [7]. In Figure 1 the different chain structures are shown.

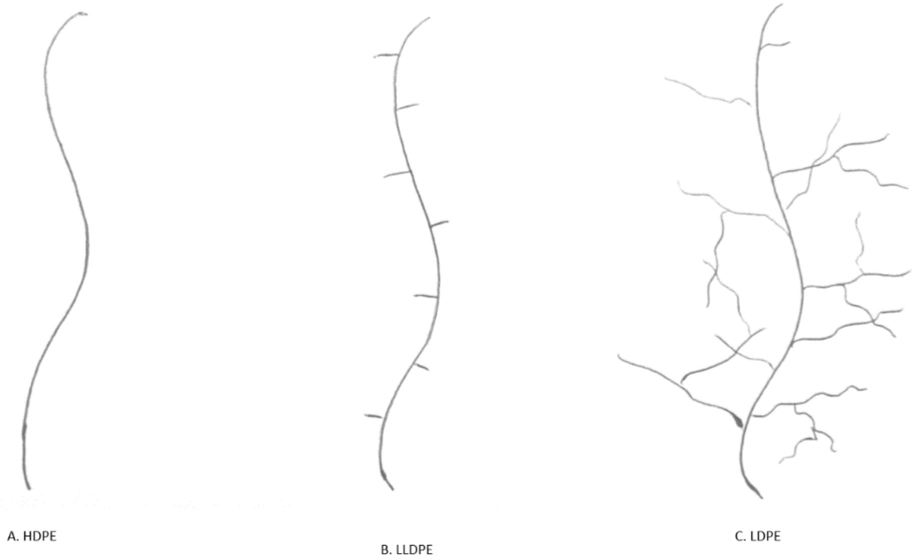

Figure 1. Schematic picture over the distribution of branches for the different densities of polyethylene. Adapted from [7].

The different qualities have different characteristics. For films the LDPE and LLDPE provide a yielding feel while HDPE, with higher crystallinity, feels more brittle and rustling. When producing a film different methods of extrusion are needed [7]. Flextrus is mostly using co-extrusion, casting different layers at the same time or at different co-extrusion units at the same line of production.

Except for packaging, which is a wide area of use for PE, it is also used for extruded pipes and cable insulation [7]. The main part of the LDPE and LLDPE is used for film production [8].

2.2.2 PET

About 60 % of the world demand of ethylene ends up in the PE production but ethylene oxide, further derived to one of the PET monomers, is the second largest demand [9]. The ethylene glycol, produced by hydrolysis of ethylene oxide, is one of the monomers used for PET polycondensated with dimethyl terephthalates or terephthalic acid directly.

The direct esterification with terephthalic acid gained importance since it optimized the reaction rate, produced water as condensate instead of methanol and lowered the storage cost due to lower weight on the raw material. It also obtained higher molecular mass of the end product [10], [11].

When using PET in an extrusion process it is important to dry the raw material. Even small amounts of water will perform a hydrolysis reaction on the ester bonded oxygens of the terephthalate molecules when the polymer is exposed to high temperatures in the extrusion process.

2.2.3 Ethylene production

There are a couple of ways to produce ethylene. The subsections below describe the two mostly used methods.

Cracking of Naphtha or Ethane

A cracker uses steam and heat under short time and controlled parameters to divide a light carbon source in smaller constituents. The hydrocarbons are heated to an ambient temperature and blended with steam. After this, for a short period of time, the temperature is rapidly risen. A number of different radical reactions cleave the hydrocarbons to smaller chemical components. The output is a range of different petrochemicals. The most used feedstocks for this method is naphtha and ethane, both derivatives of fossil crude oil. The ethylene yield of naphta cracking ranges from 25 to 30 wt-% relative to the cracking severity [12].

Hydrolysis of Ethanol

This is a catalytic conversion of ethanol to ethylene. A suggested mechanism for this hydrolysis reaction is presented in Figure 2. With the right support and catalyst a yield as high as 94-99 % can be obtained. The economic viability of this method is dependent on the feed stock cost[12], [13]. The greenhouse gas (GHG) emissions from dehydration of bio-ethanol to produce polyethylene decreases by more than 50 % related to production of the polymer from cracking of naphtha [14]. This production rout to ethylene was carried out commercially until 1960's when the path no longer was economically viable due to low oil prices[15]. Due to this gap of usage developments and upgrades in the near future will probably increase the efficiency even more [9].

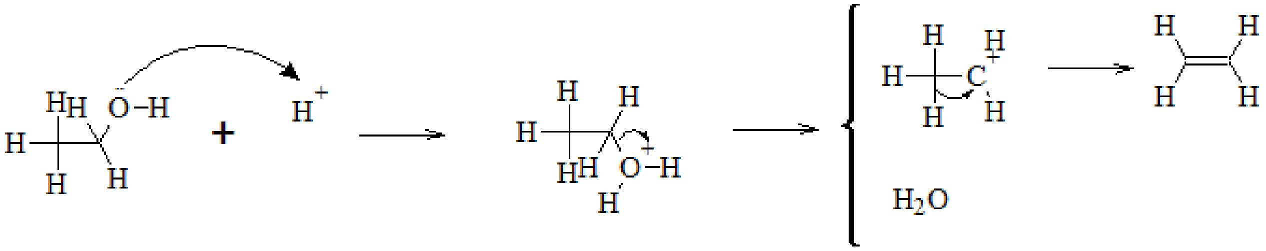

Figure 2. Suggested pathway for ethanol dehydrogenation, adapted from [12].

In Brazil, Braskem produces 200 000 tons of green ethylene annually. The sugar mill produces the sugar with bagasse as heat source. The production overflow of heat is then sold as the town heat supply. The sugar is fermented to ethanol and further hydrolyzed. What make Braskem's bio-PE, I'm Green PE, that environmentally efficient is the way of resource effectiveness in the production and energy extraction from the residue[8], [16].

2.2.4 Terephthalic acid (TPA) production

Terephthalic acid is produced by a catalyzed oxidative reaction under acid conditions. The catalysts used are different metal/heavy metal combinations with cobalt and the solvent is acetic acid. Bromine is used as the radical element and the oxidative agent is oxygen from air. The feedstock is the fossil para-xylene[17]. Today the production TPA from biomass are in the development stage at several different initiatives. Market demands, especially from different soda and beverage companies, are pushing the development at a higher speed [15].

2.3 Biopolymer classification

Bioplastics is a wide expression for polymers produced from biological resources or in a biocompatible way. It is important to avoid confusion and make sure that the expressions are defined.

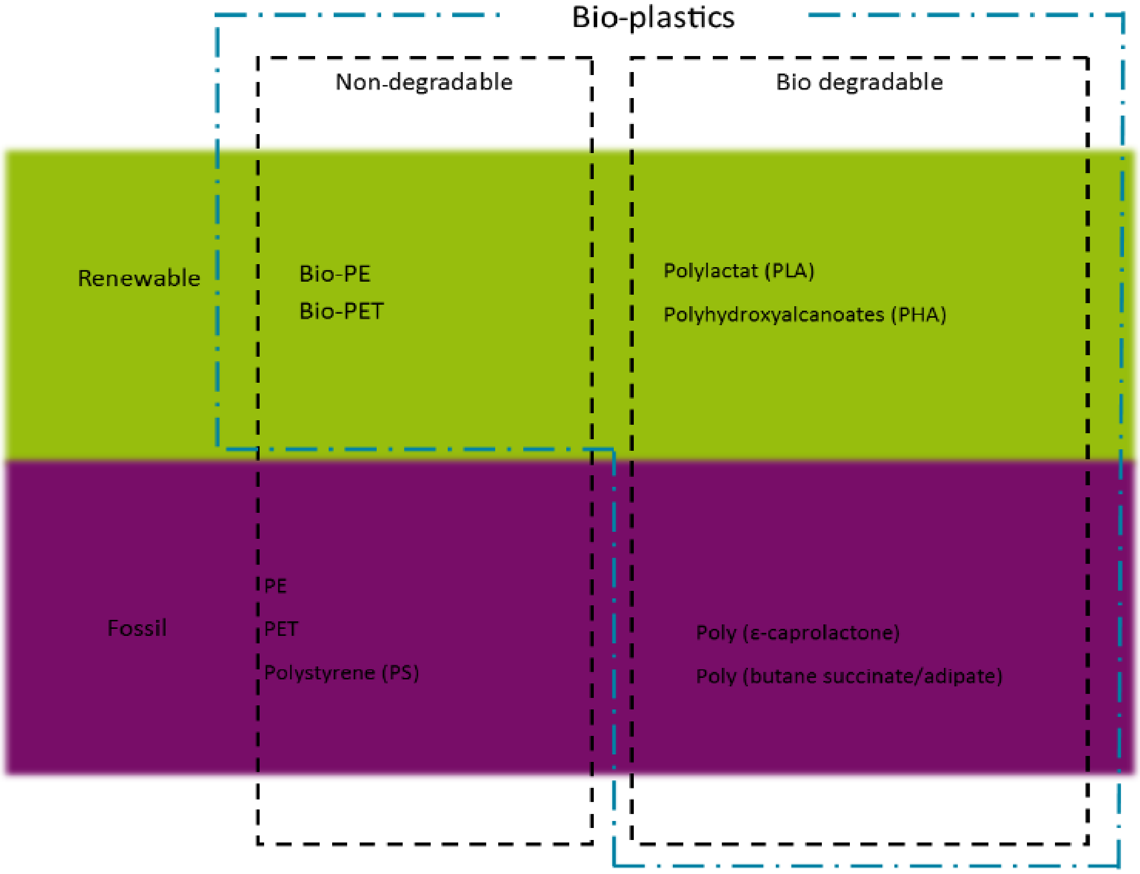

Figure 3. The area enclosed in the blue dashed lines are the polymer types that could be denoted bio-polymers. Adopted from [1].

When talking about bioplastics there are three groups to be mentioned; biodegradable and durable (non-degradable) bio-based plastics and biodegradable fossil-based plastics[1], [5], [18], [19]. In Figure 3 a schematic picture with material examples are presented. A fossil-based plastic defined as a bioplastic has the property to degrade by microbial activity. These polymers consist of ester bonds that are available for cleavage by enzymatic processes. They still consume nonrenewable resources. Examples of these are poly(ε-caprolacton) or poly(butane succinate/adipate) [1].

The bio-based biodegradable polymers are for example polyhydroxy alcanoates (PHA:s), polylactic acid (PLA) and starch based polymers. These degrade by microbial degradation at right conditions [1], [3], [18], [19]. Degradation of PLA has for example been reported slow in soil but moderately fast in controlled composting environments at relatively high temperatures, 50-60°C [20].

A bio-based non-degradable polymer, for example Bio-PET and Bio-PE, are produced of so called drop-in chemicals. They are identical to their fossil counterparts but are instead polymerized from monomers produced by a biological feed stock[8], [19], [21], [22].

2.3.1 Drop-in polymers

Bio based durable plastics, here called bio-produced plastics, such as bio-PE and bio-PET, show a large advantage in their process ability. Since they have the same chemical and functional properties as the fossil plastics they can be used in already existing productions and recycling paths [8].

The potential substitution of the conventional grades of PE and PET towards bio based alternatives was analyzed by Shen et al. [8]. They present a future possibility to substitute 100 % of the fossil based PE and PET where the bio-produced grades stand for the biggest part in the substitution for both polymers, as high as 72% for LDPE and 62 % for HDPE. For PET the bio-produced conventional plastic would stand for a bit less of the substitution at 35 %. There are a larger variety of different new plastic materials weighing up the other shares for a full substitution, but non as large as the bio-PET fraction.

The production of bio-produced ethylene and thus also bio-PE and bio-PET is dependent on the economic viability of the alternative feedstock towards the oil price [22]. Braskem's production was in the early 1990's discarded because of the cheaper production pathways with the fossil feedstock[8].

2.4 Present research in drop-in bioplastics

There is research trying to provide a 100 % renewable PET. Initiatives from the Plant PET Technology Collaborative aim to provide this PET grade to the market in 2020. Coca-Cola state that both monomers already can be produced from biomass in laboratory scale [23].

Other hopes are also turning to PEF, polyethylene furanoate, which would be an alternative to PET. The 2,5-furandicarboxylic acid would then be one of the monomer types instead of terephthalic acid. The opportunity would then be the ability to produce all starting material with a feedstock of sugar. It could also be a better choice in some areas since the difference in structure improve the barrier properties with for example carbon dioxide (CO_2) and water vapor [19].

Braskem, the producer of I'm green PE, also present a sufficient, laboratory scale production of polypropylene from bio-propanol. They have begun collaborative works with Novosymes and W.R. Grace & Co. to be able to scale up this process. Polypropylene is the second most used plastic today after PE [24], [25].

2.5 The environmental performance of bio-produced PE

Kikuchi et al. [14] reveal in their study that bio-produced PE can lower the GHG emissions towards the fossil plastic even if a worst case scenario is implemented. This scenario would be if the surplus biomass was not used in a resource effective manner and the worst imagined emissions by land use transformation occurred. Today the production of ethanol and ethane in Brazil is driven by energy from surplus biomass left over from the ethanol production and the surplus electricity is connected to the municipal energy network. Thus the scenario is brighter than the worst case assumed in the study. In this scenario the GHG emissions was decreased by 75 % towards PE-production in Europe. The life cycle assessment also included transports from Brazil to Japan which corresponded to only a few percentage. This study was done as a cradle to grave assessment assuming carbon neutrality on the end of life incineration of a package made by PE.

The few percentages corresponding to transports can also be confirmed by comparing carbon emissions of the same product including and excluding the transports from Brazil to Europe. This is presented in Table 2 below. The negative values of the carbon emissions correspond to that the investigation is a cradle to gate, end of life not included. See section 2.9 for more information.

Table 2. Comparison between inclusion and exclusion of transportation carbon emissions for I'm Green PE [16], [26].

	I'm Green Braskem	I'm Green after transports to Europe	Increase of GHG emissions
Carbon emissions	-2,15 kg_{CO_2}/kg	-2,10 kg_{CO_2}/kg	2,3 %

2.6 The existing recycling system

The organization of packaging and paper collection in Sweden reported 38,40 % of all plastic packages material recycled in 2014 [27]. Today both soft, plastics and hard packages are sorted in the same stream of household wastes. These are then mechanically separated by blowing the lighter, soft plastics away. Since the majority of soft packages are produced by low density polyethylene (LDPE) this separate is used to produce new shopping bags or tubing for electrical wires.

The hard packaging waste is separated by infrared technology [28]. Laminated plastic packages are not possible to material recycle today since they are not easily delaminated as for example the paper laminates. In Sweden, they are instead incinerated with energy recovery together with the rest of the unidentified plastics. For fossil materials this correspond to a climate change impact while bio-based materials instead are carbon neutral [29]. Other impacts on whether a package is recycled or not are the contamination risk from leftover food or if it is too expensive to separate the different plastic streams. Economics and quality of the recycled material are two parameters with high impact on the recyclability of the material why it is important to keep the different streams clean [3].

In Great Britain an initiative to develop a method for recycling of laminated materials is driven from a previous research results at Cambridge. There is a pilot plant for this method with a microwave pyrolysis technology [30]. This method cleave the polymeric materials in a reductive environment to mainly straight alkenes and alkanes with a smaller fraction of more complex carbon structures. The aluminum from aluminum laminates is recovered to 100 % and at good quality[25]. The project, on pilot scale, is mainly meant for metal-laminates with different organic constituents either to upcycle both fractions or to use the organic fraction as energy for the pyrolysis[31], [32].

Regarding paper and carton laminates the packages are delaminated by dissolving the paper fibers in water. Due to the collection procedure and cost effectiveness of the Swedish recycling system the relatively contaminated fraction is incinerated with energy recovery. The fraction of plastic and aluminum occurring in the delamination is possible to material recycle and done so in Brazil [33]–[35].

2.7 Sustainable packaging

A package's primary functions and their examples are listed below [36], [37]:

- Protection: from damage and product loss
- Promotion: advertising and promote product features
- Information: best before dates and ingredients – legally required
- Convenience: portion size or ready to cook-solutions
- Utilization and handling: Simplify for supply and retail

The most important features of a package has been described as protecting and distributing its content [3], [5], [38]. When regarding a packaging system, including the product it contains, the package only correlate to a small percentage of the total climate change potential. Even so, the package is often regarded as a the prime environmental issue of a product [3]–[5].

Policies towards materials optimization and minimization of materials use is legislated on a European level which signal that materials minimization in packaging is one area where sustainability is often debated. The loss of food coupled to packaging design and function is one that is not discussed as often. Sometimes an increased environmental performance of the packaging system could save environmental damage when looking at the total environmental performance of the packaged goods [3], [4].

The amount of discarded food in our homes is ranging from 15-30 % in Europe and USA [4]. The study related these household wastes caused by packaging issues to about 20-25 % of that amount. With packaging often contributing to only a few percent of the total product and package unit this problem is something that could be solved by upscaling the material usage in some areas. If cheese is taken as example the product has an extensive environmental impact. One kilo of cheese correspond to ten kilos of carbon dioxide equivalents. Materials optimization could for some cheeses risk food waste that would contribute more to the environmental damage than keeping the amount of or even increase the material usage [4].

Laminated plastic packaging is one way to minimize the use of materials while fulfilling the product requirements. When incorporating layers of barrier materials the extended materials can be used to less extent. A higher packaging performance can lead to longer shelf life and less food losses or widen the use of other materials as paper and also make it possible to incorporate recycled material in a food package. This is often not allowed by legislative restrictions regarding recycled materials in food contact do to the contamination risk from previous containment [3]. In a laminate it is though possible to incorporate recycled material between virgin layers and therefor avoid contact.

A barrier material is a material that with different structural and/or chemical properties hinder or minimizes passage of unwanted gas or water vapor into the package. Typical properties in a polymer material is the degree of crystallinity, chemical affinity towards the permeate or thickness of the material. If the crystallites are ordered in a special way they can also obstruct the permeant by prolonging the passage distance and thus minimizing the permeability. Designing a laminate is therefore an opportunity to incorporate materials with specific permeability properties. One example is a layer of EVOH where the alcohol groups interact with each other via hydrogen bonding and thus limit the molecular movement needed for diffusion of oxygen. PET is regarded as a barrier material for both oxygen and water vapor while the properties of PE depend on the crystallinity and orientation of crystallites. This is because the diffusion of gases take place in the amorphous regions of the polymer.

Even if laminates provide a sufficient performance in minimizing material use, a company needs to keep tracking new goals to keep profiling a high environmental awareness. Old products need to be overlooked and redesigned or discarded while new products need to be compared with sustainability measures in the design process. Some key points in the process of a sustainable package development are described below [3]:

- The product requirements need to be described and regarded in the package development.
- Efficiency, the use of renewable materials and recovery at end of life should be considered
- Think of the three corners of the sustainable triple bottom line impacts: Social, Economic and Environmental (Figure 4)
- Avoid burden shifting, as not considering recovery when discussing renewable materials

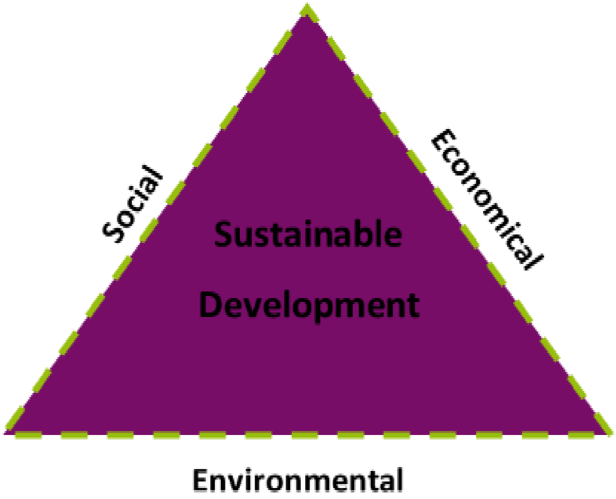

Figure 4. The sustainable development triangle symbolizing the concept of the triple bottom line. Source: [3].

Following the above listed points and always regarding the materials choice that contribute the least to the whole product life cycle should be the way of designing a sustainable package [5].

In Figure 4 the triple bottom line is expressed. This is a description of how sustainable development must attend all three areas and deal with the issues of economic and social viability to reach a sustainable holistic development[3], [39]. If for example new innovative materials are too expensive it is not economically viable and therefore, right now, not sustainable. This rimes well with the definition of sustainable development, derived from 1987's report of World commission on Environment and Development:

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs [40]."

2.8 Land use and bio-polymers

One argument against extended use of biopolymers is the increased use of agricultural land in competition with food production with a growing world population[22], [41]–[43].

The World Bank report on the 2006-2008's price boom of food, Baffes et al. [44] reflect over this topic. They mean that the debate regarding food security and food competition is founded during this time of peeking oil and food prices. During this time research on the biomass allocation in different end use areas was conducted. This is presented in Figure 5 and Figure 6. The study showed that approximately 4 % each of the total biomass produced was used to provide feedstocks for materials respective bioenergy. In materials there is also taken into account the wood used for paper and other wood products as furniture. The total biomass produced this year (2008) was 10 billion tons not including grazing and 14 billion tons with the additional feed source included [42].

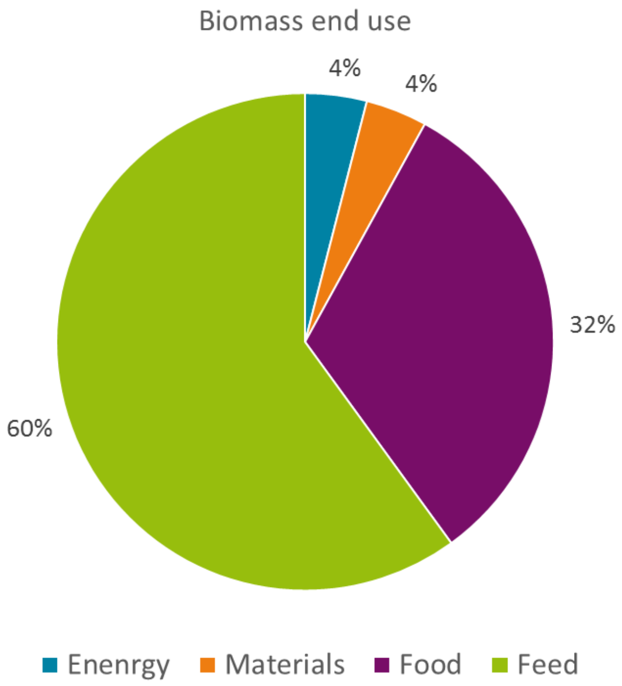

Figure 5. Biomass allocation for different end uses. Grazing not included in Feed.

The total agricultural area for biopolymer production corresponded to 0.2 % of the total agricultural landmass in 2010. If all plastics produced would be switch to bio-materials the allocated biomass percentage would reach 7 %. The share of bio-plastics were predicted by Carrus et al., [43], to reach 0.5 % in 2015.

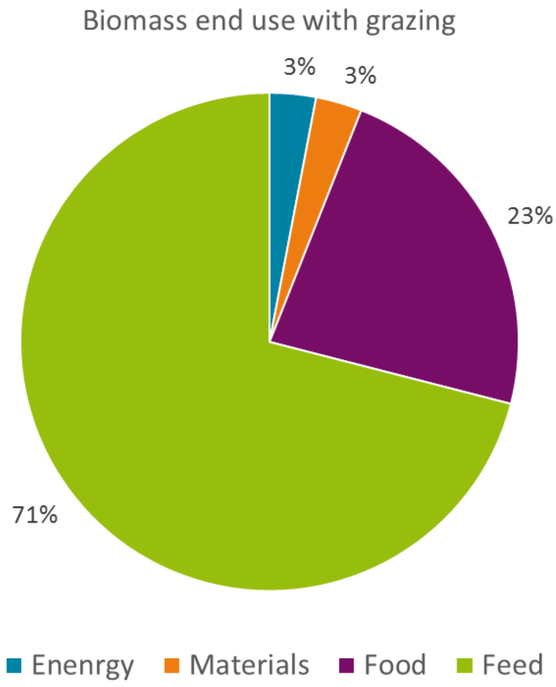

Figure 6. Biomass allocation for different end uses including grazing as feed.

Even if the price raise of food in 2008 was later confirmed more related to peaking oil prices then increased bio-material and bio-energy production [44], materials is not the only area where demands of agricultural land will increase. The food demand is believed to increase by 70 % until 2050. Due to the large part of increased meat and dairy production with enhanced socioeconomic status in developing countries, the share of biomass allocating towards feed production is sharing, if not exceeding, the same projection. In a long time perspective food security is important to keep in mind when further development is increasing the demand on the biomass resource [42], [45].

To be able to assure a sustainable use of the biomass resource and avoid depletion the yield efficiency needs to increase. Reducing food losses and meat consumption, using byproducts in the agricultural production and focus on new effective technological solutions is examples of inducing biomass efficiency [42], [45].

One argument for prioritize development of “green” materials over the energy production is the possibility to change energy source to other renewable sources as solar energy and wind power. Bio-materials have also advantages towards bioenergy production since high-end products are produced that also could contribute to bio-energy when disposed [42].

2.9 Carbon Footprint

One way of assessing the environmental performance of a material is its global warming impact, the carbon emissions related to a unit. You could change the phrase to greenhouse gas inventory right away since it identifies and summarize all carbon equivalent emissions related to a company, production plant, product, person or another unit where an overview is needed. The carbon footprint analysis is one part of a Life Cycle Assessment (LCA) which take other environmental parameters into consideration and therefore should not be confused with each other. When the other parameters are difficult to measure the not as extensive Carbon Footprint Analysis is often employed to give a view over the climate change potential. The unit of measurement is often conducted to ton of GHG emissions per year [39].

There are different boundaries employed in a study like this:

- Cradle to gate
- Cradle to grave
- Cradle to cradle

Cradle to grave describe a unit's total assessment from cradle, in the raw materials choices, to grave, when the unit is disposed of. Sometimes it is inadequate to conduct the analysis further than the processing and storage in house. This can be if the material can be used as an intermediate product for further processing. Then assessment boundaries for cradle to gate is employed. Cradle to gate only take into consideration what happens from raw material until the product leave the production. This method is for example employed in the GHG emission measurements allocated to I'm green PE and Globio. The reason why the emissions related to the PE grade is negative. Cradle to cradle is instead an assessment method where the discarded product instead is used as a raw material in another product cycle [46].

2.10 Expected values of experimental results

The expected values or limits of quality measures are presented in Table 3. Some of the experiments are normally not performed for the materials relevant after the Carbon footprint analysis, see section 5.1 Carbon Footprint Analysis. The intervals accepted for thickness of the HiLite 390/40 is 417-443 µm.

Table 3. Values stated by quality inspections after production. Materials correspond to the ones chosen after the carbon footprint analysis, as described in results.

Experiment	Material	Target value
Intrinsic Viscosity (IV)	APET casting	>0.72
Moisture content	APET granulates after drying	<50 ppm
COF	HiLite 390/40	Not usually tested
Thickness	HiLite 390/40	430 μm
Sealing strength	HiLite 390/40	>30 N/15mm
Sealing temp	HiLite 390/40	130 °C
Oxygen transmission rate (OTR)	HiLite 390/40	<9 ml/(m^2, 24h)
Water vapour permeability (WVP)	HiLite 390/40	Not usually tested
Surface resistivity	HiLite 390/40	Tendency for charging at values >1·10^{11}
COF	Fibercote 50/25	Not usually tested – too high values
Thickness	Fibercote 50/25	72 μm
Sealing strength	Fibercote 50/25	Normally not tested
Sealing temp	Fibercote 50/25	130 °C
Oxygen transmission rate (OTR)	Fibercote 50/25	<150 (ml/(m^2, 24h)
Water vapour permeability (WVP)	Fibercote 50/25	<8 g/(m^2,24h)
Surface resistivity	Fibercote 50/25	Tendency for charging at values >1·10^{11}

3. Method and material

3.1 Pre-Study – Carbon Footprint

The Carbon Footprint analysis was performed in an already consisting model at Flextrus. Input values was data from raw material suppliers, weight, in gram per square meter (GSM) and the share of renewable mass per material used in the laminate. The output values was the total GSM of the laminate, total mass carbon dioxide per mass of laminate and per square meter of laminate (kg_{CO_2}/kg_{film} respective g_{CO_2}/m^2). In Figure 7 the system boundaries are described. In the in-house emissions section only emissions directly related to the production is taken into consideration. In the first stages of investigation 10 % of the materials impact was added to account for the production related emissions. This is an estimation used by Flextrus conducted in previous carbon footprint evaluations.

Later when reviewing the actual emission sources the in-house emissions came to include gas, for printing dryers, natural gas, mainly for plastic smoke cleaning facilities, and the cooling system connected to the district heating. These were locations where carbon dioxide emissions could relate to the products directly. Energy in form of electricity was in this investigation not included since Flextrus recently switched to eco-labeled electricity, wind and water power.

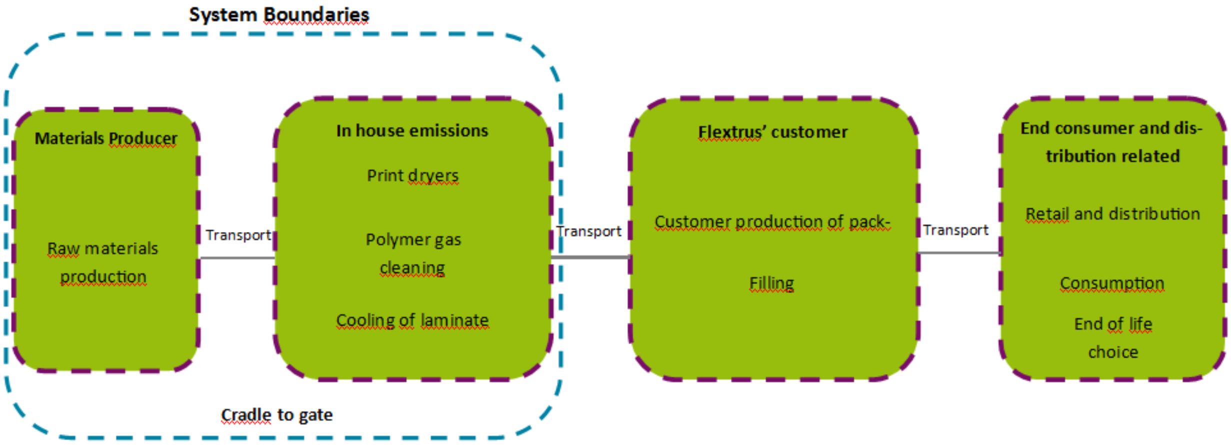

Figure 7. Schematic figure over system boundaries connected to the Cradle to Gate assessment of Carbon Footprint.

3.1.1 Stage 1

Based on the sold amounts of 2014, the quality most produced in each product family, presented in section 2, was chosen for investigation. GSM of each constituent material in every quality was loaded to the model where producer data in $kg_{CO_2}/kg_{plastic}$ were assembled. An assumed addition of 10 % of the material GHG emissions was added to this weight fraction to correspond for the in-house production. This amount has earlier been investigated by the company and used as a schematic contribution. By multiplying the mass GHG emissions per material to this materials incorporated weight per square meter, the total GHG emission for the laminate was retrieved.

To give an annual overview the total GHG per square meter was related to the sales volumes of 2014.

The same products were then modeled again by replacing polyethylene and poly(ethylene terephthalate) one at a time with the new bio-produced qualities presented in section 3.3. The new values were analyzed regarding carbon dioxide emission reduction towards the current values. This showed which family groups to investigate further.

3.1.2 Stage 2

Stage 1 ruled out some of the families that showed good results but included too complicated material combinations, with specialty polymers and films, to achieve the modelled performance when processed. The amount of exchangeable material was therefore small and the products were discarded from further evaluation. The other laminate families were investigated on a more total basis. Some of Flextrus' product families are more diverse then others which was the reason to divide following analysis in two methods.

The larger groups with several subgroups and/or a large amount of product qualities, was analyzed by calculating an average total GSM of that subgroup. The quality corresponding best to this average was chosen to represent the subgroup in the model. The g_{CO_2}/m^2 of this average quality was then correlated to the total annual production, in m^2, of the sub group. Yielding an average gain in carbon emissions per year.

The smaller groups with fewer qualities and only one or two subgroups were analyzed quality for quality and a total impact of the family was calculated by adding all the results, summing up the annual emissions. This methodical difference could be a minor error in the evaluation but was thought as the most time efficient approximation at this stage.

In Figure 8 sketches of the laminates are presented.

Figure 8. Sketches over the cross sections of the chosen materials.

3.1.3 Stage 3

The product HiLite APET/PE 430, was examined for all different materials scenarios, fossil with virgin material, fossil with regrind of PET, green PE and PET virgin material and green PE and PET with regrind of PET. This product has a thickness close to the average investigated in stage 2 and therefore fit well with that comparative analyze. The product was analyzed both by an annual emission, emissions per square meter and per package. This particular product was chosen because of the positive reaction to the project from a Flextrus customer and because of its performance in Stage 2. The product is used for thermoformed trays, often in application for spreads and cold cuts.

The other product chosen for further investigation was Fibercote 50/25 CC APET. This product is interesting from a marketing point of view due to its high renewable content. An improved renewability in PET coated paper package is from a recycling point of view interesting since it lower the lower the greenhouse effect-influence of the incineration emissions. At the end of life treatment of carton laminates the polymer-aluminum fraction is burned and not reused as the paper fibers. This product is used for frozen microwave oven pizza packages.

The relation to the package was done by relating the emissions in g_{CO_2}/m^2 to the area used for one package in the customer’s production. This made it possible to associate the carbon emissions per final product carrier and thus a way to communicate the environmental performance to the customers.

This stage of the analysis was not partaking in the same model as stage 1 and 2. Since Flextrus in January changed towards eco-labeled wind- and water power it was of interest to update the model to show a better approximation of the production than just adding 10 % of the producer values. This led to dividing the emissions into three areas: drying of print, cooling the production and cleaning of polymer smoke. The cooling only burden the polymer materials as an average addition calculated on total mass of laminates produced. The polymer smoke only burdening the polymer materials emitting gases during production and used as a surface material. This was calculated as an average of the annual (2014’s) consumption related to these gas emitting materials. The print addition was calculated as an average on the amount of square meters printed and, this additive was instead on mass based on square meter.

A final comparison of the families' emissions per m^2 was performed to investigate the performance of the new model. The unit was chosen so that the focus would be on the performance of the new model and not a comparison between the different products why an annual investigation was not used. The choice of materials for experimental work, HiLite 390/40 and Fibercote 50/25 however was chosen on the results from the old model assuming the overall picture would not be affected by the new model.

3.2 Experimental work

All experiments was performed on both HiLite 390/40 and Fibercote 50/25 with exception to the UV-VIS experiment only relevant for transparent material. Both laminates with the new, bio-produced qualities and the fossil qualities, normally used in production, was analyzed and compared. It was done to detect any possible differences and obstacles with the new materials. In the Differential Scanning Calorimetry (DSC) and Intrinsic Viscosity (IV) experiments the raw material granulates were also tested.

3.2.1 Differential Scanning Calorimetry (DSC)

The experiments were done on a Mettler Toledo DSC821^e and analyzed with the STARe software version 13.00a. Used in order to examine if there is any difference between the two qualities of PE and PET regarding crystallinity and melting point before and after lamination. The tests were run at temperature interval 25-300-40-300°C and 20°C/min. The values obtained would be compared with the melting temperatures of the raw materials.

Pellet

Sample prepared by a pellet cutter, and the slice placed in an aluminum sample pan, 40µl. An identical, empty, aluminum pan was used as reference.

Laminate

Sample prepared by punching out a piece of the laminate and place it in a sample pan with references as above mentioned.

When testing the conventional Fibercote 50/25 material the plastic layer was delaminated using water and peeled of the paper. Only the plastic film was investigated. The order of cycles in the analyzed plot is black, red and blue. Black and blue being the heating cycles.

3.2.2 UV-VIS Spectrometry

This method is only viable for transparent material and thus only for the Hilite 390/40 qualities. Investigating if there is a difference in the transmission of UV and visible light using the bio-produced qualities and the fossil materials as reference. Equipment used: Perkin Elmer UV-VIS spectrometer Lambda 12 with a sample holder for films.

The sample was prepared by cutting out a piece of the laminate, approximately 9cm^2, and placing it in the sample holder. Transmission over 200-800nm was measured and plotted with Perkin Elmer UN WinLab 6.2.0.0741.

3.2.3 IR spectrophotometry

Performed on a Perkin Elmer precisely Spectrum100 FTIR Spectrometer with software Perkin Elmer Spectrum 10.03.09.0139. The analyses was benchmarking and only referenced to the conventional HiLite 390/40 laminate.

FTIR- Fourier Transform Infrared Spectroscopy

The laminate sample is placed in a sample holder in the spectrophotometer. Infrared light with a wavenumber $\bar{\nu}$=2000-450cm^{-1}, this correspond to wavelengths in an interval of approximately 2200-500nm, are used to identify the materials used in the laminate.

ATR- Attenuated Total reflectance

The adapter Perkin Elmer precisely universal ATR sampling accessory was used in above mentioned apparatus. It was applied to investigate the surface materials in the laminates by help of projecting the light up in the material by a diamond. The light is scattered and then reflected back down the crystal and the total reflectance is measured at $\bar{\nu}$=4000-650cm, this correspond to wavelength in the interval 250-1540nm.

3.2.4 Surface Resistivity

Performed in Hewlet Packard (HP) 16008B Resistivity cell and measured with HP 4339B High resistant meter. Samples were cut out with a diameter of 10 cm with measuring diameter at 5.0 cm, or 39,8cm^{2}. The resistivity, in Ω, was then measured at each polymer side of the material. The measurement was performed after charging the material at 500 V for one minute. The samples were collected left, middle and right of the laminate width four times at each material with 10 cm distance.

A material with values over $1*10^{11}\Omega$ would appear to get charged with static electricity according to Flextrus' quality handbook.

3.2.5 Sealing temperature

The seals in the different materials are performed with a Sencorp Seratek 24ASG/1, with 16 temperatures ranging from 90-146 with 4-6°C distance between the welding points. They are applied simultaneously over the cross directional width of the material. Laminate and top web sealed for 2 seconds with a pressure of 2kp/cm^{2} (~20 000 kPa). The top layer is then quickly peeled off. The correct sealing temperature is found where the two materials do not separate. The target value of the conventional material is 130°C.

3.2.6 Sealing strength

A seal between laminate and top web with above discovered sealing temperature was performed in a KOPP SGPE 3000 in 1 s with a pressure of 250 kPa. A Teflon sheet for machine protection was used in the measurements for HiLite 390/40. This could have lowered the seal strength by reducing the temperature.

Seals were prepared in cross direction left, middle and right of the sheet width. Each sample stripe was prepared perpendicular to the seal with a width of 15 ± 0.5 mm.

The strength of separation was measured in a Telemetrik instrument AB 1ATRI-01-10-22-30-XX. Experimental setup presented in Figure 9. Cross head speed 100mm/s with the separation angle of 90° registering maximal force as N/15mm.

Figure 9. Experimental setup for seal strength measurements.

Target values of these measurements are >30 N/15mm for HiLite 390/40 and non-applicable for the Fibercote 50/25 since the paper fibers normally is weaker than the force to separate the seal.

3.2.7 COF – coefficient of friction

Friction between all surfaces was investigated with a TMI Monitor/Slip & Friction 3206.

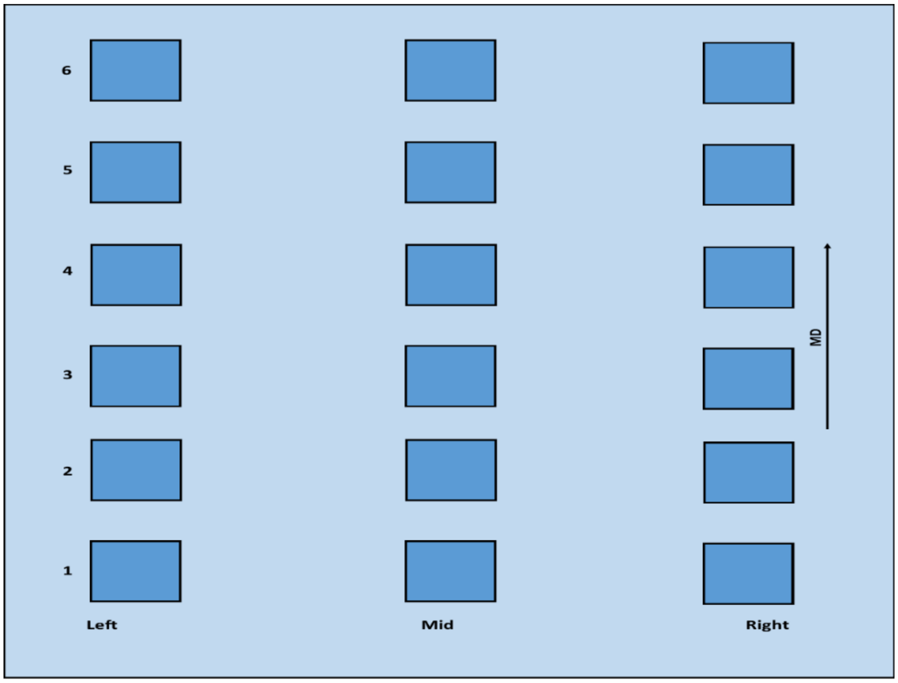

Figure 10. Sample preparation of the COF measurements. 1-2 used for APET-APET/In-In measurements, 3-4 PE-APET/in-out, 5-6 PE-PE/out-out.

A sample for each test of 10 cm^2 was cut from the laminate. One larger square was cut to provide the surface. The test was performed between each side in MD. Samples were extracted as shown in Figure 10. This method was used for both qualities.

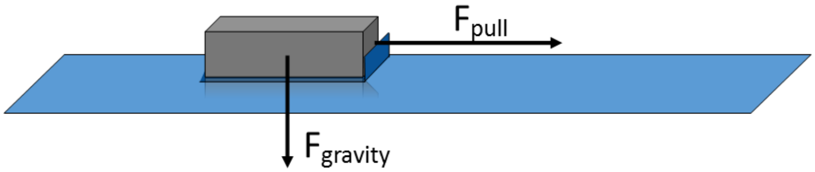

Figure 11. The experimental set-up with the sleigh pulling the sample over a reference sheet of the laminate. The sleigh induce a pressure of 0.05 N/cm^2 and is pulled with a speed of 150mm/min.

Figure 11 describes the experimental set-up for COF measurements. The sleigh induce a pressure of 0.05 N/cm^2 and is pulled with a speed of 150mm/min.

Both dynamic and static friction is measured and recalculated by the built in software to COF (pulling strength by force of gravity) for each friction type.

3.2.8 Permeability

OTR

Equipment: Permox 2000 version 2.1.2 with corresponding software. Samples were prepared as squares of approximately 10·11cm and the area for measurements are a circle at 50 cm^2. See Figure 12 for how the samples were taken out from the film.

The HiLite 390/40 sample were placed with the least permeable side, the PE-side for Hilite 390/40 and the PET side for Fibercote 50/25, towards the oxygen rich atmosphere in the test slot. The other side is in contact with pure nitrogen and 2 % hydrogen. The hydrogen in combination with a catalyst react any contaminant of oxygen to water. The reaction causing an electric current in the sensor and thus the amount of oxygen passing through could be detected.

The temperature was kept at 23°C and an atmosphere at 50 % relative humidity was kept at each side of the sample. The test was done continuously in 30 minute cycles until a constant value was received.

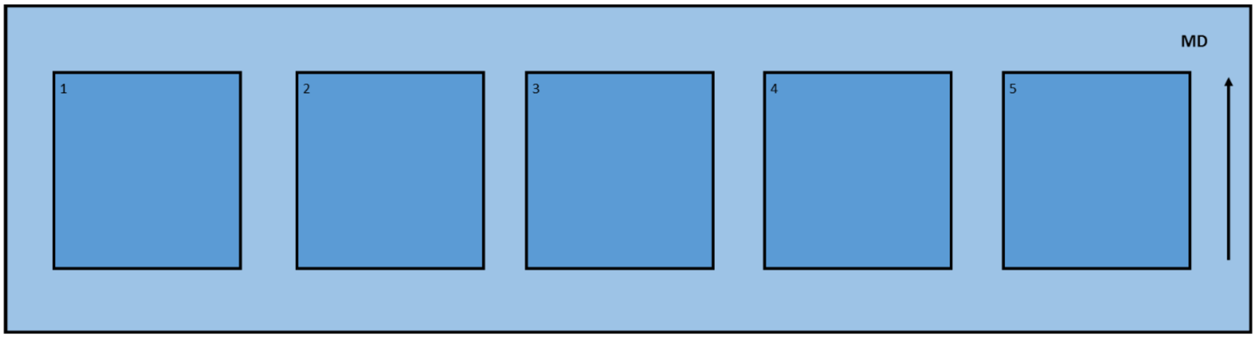

Figure 12. Sample preparation of OTR measurements with indexing. The squares were cut out from the full width of the laminate, described by the lighter blue are, and also used for the thickness measurements after the OTR experiments.

Target values for OTR are <9ml/(m^2, 24h) for Hilite 390/40 and <150ml/(m^2, 24h) for Fibercote 50/25.

WVP

Equipment: Mocon Permatran-W 3/34. Measurements was carried out at 25°C and 38°C and at constant relative humidity of 75 % respective 90 % on one side of the material. The samples were tested until a steady state value was achieved, this value was registered in g per square meter and 24h.

The sample was prepared using a template of a square at 10 cm^2. Target values are non-applicable for the HiLite 390/40 according to the Flextrus Datasheet. For Fibercote 50/25 the value should be below 8g/(m^2, 24h).

3.2.9 Laminate Thickness

The HiLite 390/40 was analyzed in a Lorentzen&Wette 51D2-222 and the overall laminated thickness was measured in μm. To be able to only measure the APET thickness of the Fibercote 50/25 Laminates the material was cut and placed in a holder to obtain a clean cross section where after the thickness of the APET layer was measured in a Olympus BH2-UMA. The samples were the ones tested in the OTR experiment and do thus correlated directly to the values gained in that experiment.

The permeability coefficient was den calculated by directly relating the OTR values to the polymer thickness.

3.2.10 IV – [η]

The experiments performed on a Davenport Melt Viscometer which is a capillary melt viscometer. Attached are a Davenport polymer grinder and a Davenport Polymer dryer. The sample (3.8g) was ground and placed in glass vials under vacuum and dried for 3h at 150°C. During these three hours the samples were opened and stirred after half the time and then again evacuated.

The drying is to make sure that there is no water in the samples when melted which would cause hydrolysis of the polymer chains and subsequently a lower intrinsic viscosity.

After drying the samples where poured into the extrusion chamber. A plug on top of the polymer melt and also a probe which followed the plug's descending. The chamber was pressurized with 20-30 bar of nitrogen gas, the pressure was adjusted to achieve a probe speed of 0.5-1.5 mm/min. The capillary was 50 mm long with a diameter of 0.8 mm. The melt temperature was set to 295°C.

The computer software Lloyd Instruments Melt Viscosity windows version 1.20 was used which is the corresponding software for this analysis equipment. At the constant probe speed the Intrinsic Viscosity was plotted against time and then a linear regression was used to determine the IV at zero. The least accepted value of IV at zero was 0.72, this value is based on what viscosity is accepted in production to assure good process ability and final film quality.

3.2.11 Student T-test

The statistical evaluation method student t-test, below referred to as t-test, was used to evaluate if there was a significant different between the qualities. The significance level, α, was set as 5 % in most cases but in one evaluation also to 1 %.

When evaluating the results of the t-tests, performed in MS Excel, the t-value must be lower than the t-critical, sowing the edges of the 5 % significance in a double sided test. The p-value (probability of wrongly discarding the null hypothesis) must lay below the α-value of 0.05 (or 0.01). Then the risk of discarding the null hypothesis of equal mean values even if it is true is acceptably low. Below the abbreviations and calculation background are explained in Table 4.

Table 4. Abbreviations and their calculations for the t-test

Abrevation	calculation	
t-value	$t_{value} = \lvert\bar{x} - \mu_0\rvert \cdot \frac{\sqrt{n}}{s}$	Mean value $\bar{x}$, expected value μ_0, degrees of freedom n, statistical standard deviation s.
t-crit	$t_{\alpha/2,n-1}$	Tabled value. The two sided divides α in half and n is amount of data points.
P-value	P=α for that value where $t_{\alpha/2,n-1}$=t-value	Tabled value of the $t_{\alpha/2,n-1}$=t-value is the obtained probability to wrongly discard the null hypothesis
H_0	$\mu_0=\mu_1$	The null hypothesis of equal mean values.
H_1	$\mu_0\neq\mu_1$	The alternative hypothesis if there is a difference.

3.3 Materials

In Table 5 the materials used in the laminates for the above mentioned experiments are presented.

Table 5. Listed materials used in the laminates produced for experimental part of study.

Material	Material number	Producer	Melting Point	Density	Bio Content
I'm Green PE	SBC 818	Braskem	Not presented	0.918 g/cm^3	>95 %
Globio PET	BCB80	Toyota Tsushio Corporation	248 ±3°C	1.40 ± 0.01 g/cm^3	30 %
CA7230	CA7230	Borealis	100-140°C	0.9-1.0 g/cm^3	0 %
Ramapet	N 180	Indorama Ventures	245 ±5°C	1.2 g/cm^3	0 %

To avoid hydrolysis of the PET during the processing, the granulates were dried overnight.

For the HiLite 390/40 the PET layer is coextruded in different layers incorporating regrind in the middle layer. After casting it is then coated with the PE layer, again coextruded. The second step is similar to the production of Fibercote 50/25 below where you have the paper and extrusion coat it with the PET laminate layer.

The Fibercote 50/25 is performed with the paper getting coated with the coextruded APET layer.

4 Limitations

To be able to process the HiLite 390/40 laminate and detect when the new material is initiated, this production needed to take place somewhere else than in the original machine. The ordinary way of production is a method of co-extrusion where the films are extruded and laminated in the same line. This setting will instead be a co extrusion where the PET layer is produced first and then extrusion coated with the PE layer. This could have some impact on the adhesion performance of the laminate. Still, since the laminate with the original materials is produced in the same way the comparative measurements between the material types would not be suffering.

An ISO standardization for Carbon Footprint Analysis is not jet implementable. ISO, the international standards organization, is reporting that a revised version of assessments standards for direct and indirect emissions is expected to be finished in April 2016 [47]. The Carbon Footprint model in this study is only concidering the production related emissions. It is therefore possible that in the near future the conclusions drawn by this study would need to be reviewed and updated to follow the upcoming standard. This also implies that it is not possible at this day to compare these results with something calculated with a different approach why a standardized method would help to distinguish differences and similarities between different products on the market. Employing this standard in the future would also give a marketing advantage in proving the lower emissions related to the greener plastics and also an opportunity to ensure the producer data is calculated in a correct way.

The molecular weight and distribution are unknown for these industrial grades as is the additives used for improve processing properties of the raw materials. To get some information of the molecular weight of the two qualities a gel permeation chromatography is needed. This was not done for this study since the method and materials were not available at Flextrus and not thought of until late in the project. It is possible to perform in future work if it is interesting to achieve that information.

4.1 Production

During production some things which could influence on the results happened. The Fibercote 50/25 test run was following the conventional material as planned but when switching towards the biomaterial something made it difficult to get into speed with the right cross directional thickness. When rising the production speed the web broke and the production was therefore stopped early. After the web breakage there was no adhesion between the paper and the PET sheet. Unfortunately no tests was made during this run due to the timing of the production and focus on the HiLite 390/40.

The HiLite 390/40 APET casting was tricky since the dryer only took 500kg. This dryer also differ from the one used for the conventional raw material since it uses compressed, heated, dry air instead of only dried hot air. The issue was approached by trying to empty as much as possible of the hopper before loading with the biopolymer, a tandem switch where the new material was placed on a new reel when it was assured that only the bio-quality was left. When loading the biopolymer the inlet tubing of the granulates melted and as a result of that the lane broke. This meant losing some material on a new set-up session.

After the breakage it was found that a loading tube was left in the undried material injecting wet PET into the drier. The solution to this problem was to assume a linear injection to the hopper and end when the die profile changed. This is why comparative IV-tests were made on the end of the product-reel towards the end of the set-up reel. It could also be that some migration of the undried granulates occurred which would influence the results of for example IV. There was also a shift of operational staff between the two materials. Since much things are run by hand and by the knowledge of the operators it could have had an influence on the materials but it is unlikely to have an effect.

5 Results

5.1 Carbon Footprint Analysis

5.1.1 Stage 1

The first stage of the analysis revealed which products that are of most interest for a quality exchange towards the bio-produced polymers. Figure 13 show the results for the qualities in each family with the highest production volume of 2014. In the figure the annual emissions of the present materials are compared with the laminates incorporating either "I'm Green" PE or Globio (PET).

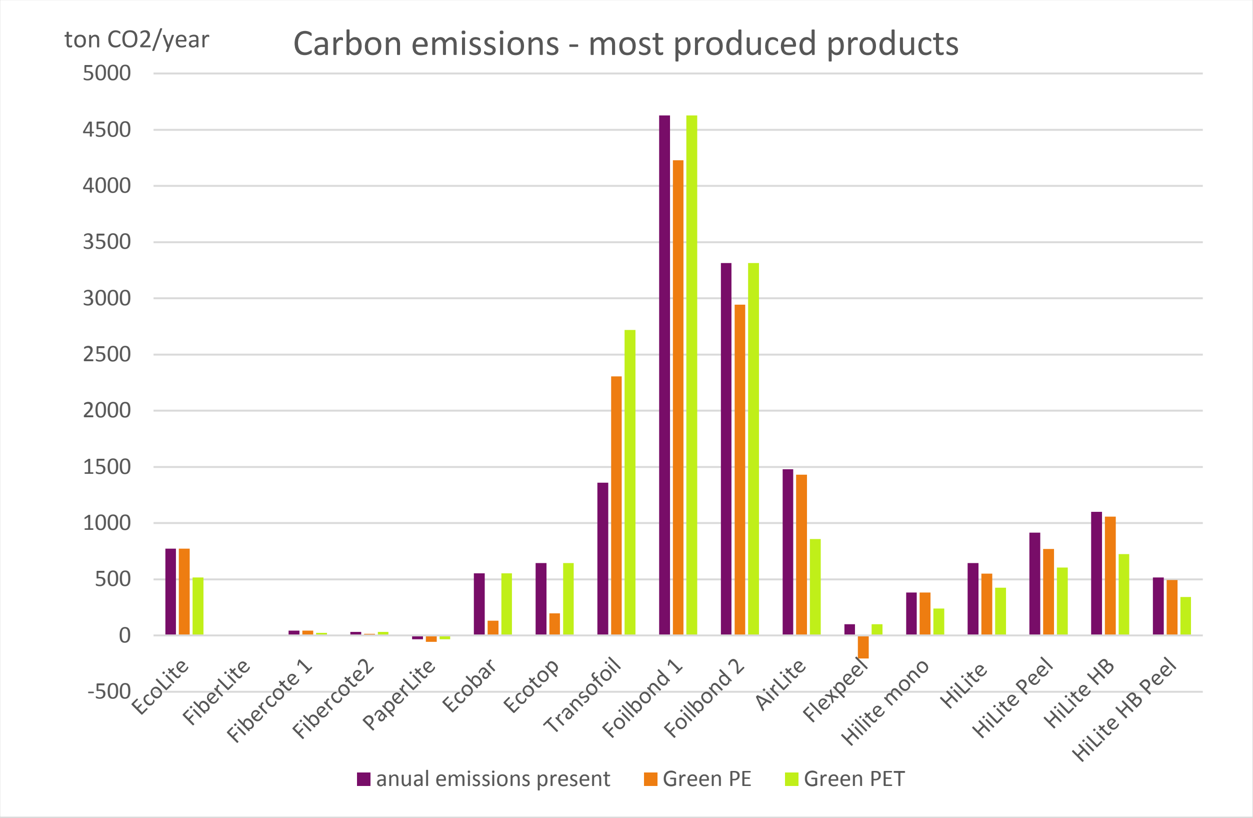

Figure 13. Stage 1, investigation of one quality in each product family with highest annual production. The current annual emission and the two scenarios with either new quality was investigated.

Transofoil and Foilbond showed a positive performance when using Braskem's "I'm Green" PE. The still high values correspond to the high amount of aluminum foil used as a barrier layer in those materials. Since they do not include PET this bar is unchanged when regarding Globio.

The decrease of emissions using I'm Green PE in Ecobar, Ecotop and Flexpeel, Figure 13, is somewhat misleading. They show in stage 1 a promising result but when studying the laminates in detail there are too many intricate layers of different special plastics and compounds to be able to exchange that large amount as in this analysis part. They were therefore excluded from further investigation.

Paperlite show a negative Carbon footprint. This value depends on the paper used in this laminate. As in the emissions corresponding to I'm Green PE this paper receive a negative value due to the carbon sink of new trees for the paper production. The negative value is thus coupled to the good environmental performance of the paper quality and theoretically this product would decrease the greenhouse gasses in the atmosphere with the growing of new trees and sugarcanes. As for Fibercote 1 and 2 (the family had two qualities similar in production volume) there is no information of the paper used from the producers. The paper has therefore been placed as neutral why their results are positive, but small in comparison to other products. The family was kept for further analysis since it had an interesting feature with possibility of a high percentage of renewability. The other Fibercote qualities used layers of polypropylene which is not jet available as a commercial, bio-produced grade. Therefore due to the same reason why Ecobar, Ecotop and FlexPeel were excluded, only the Fibercote 50/25 with paper-PET laminates was examined further.

The HiLite family showed positive results changing both PE and PET. They were kept for further analysis. When comparing the families in this first stage it was obvious that in the next stage all production in the group should be taken into consideration. Each sub-group of the HiLite family contained several qualities that had large production volumes while the rest of the families had one product with high annual volume. The comparison between HiLite and other product groups are therefore misleading

The EcoLite and AirLite showed great performance with lowering the carbon emissions when exchanging the PET quality. These were also kept for further analysis.

5.1.2 Stage 2

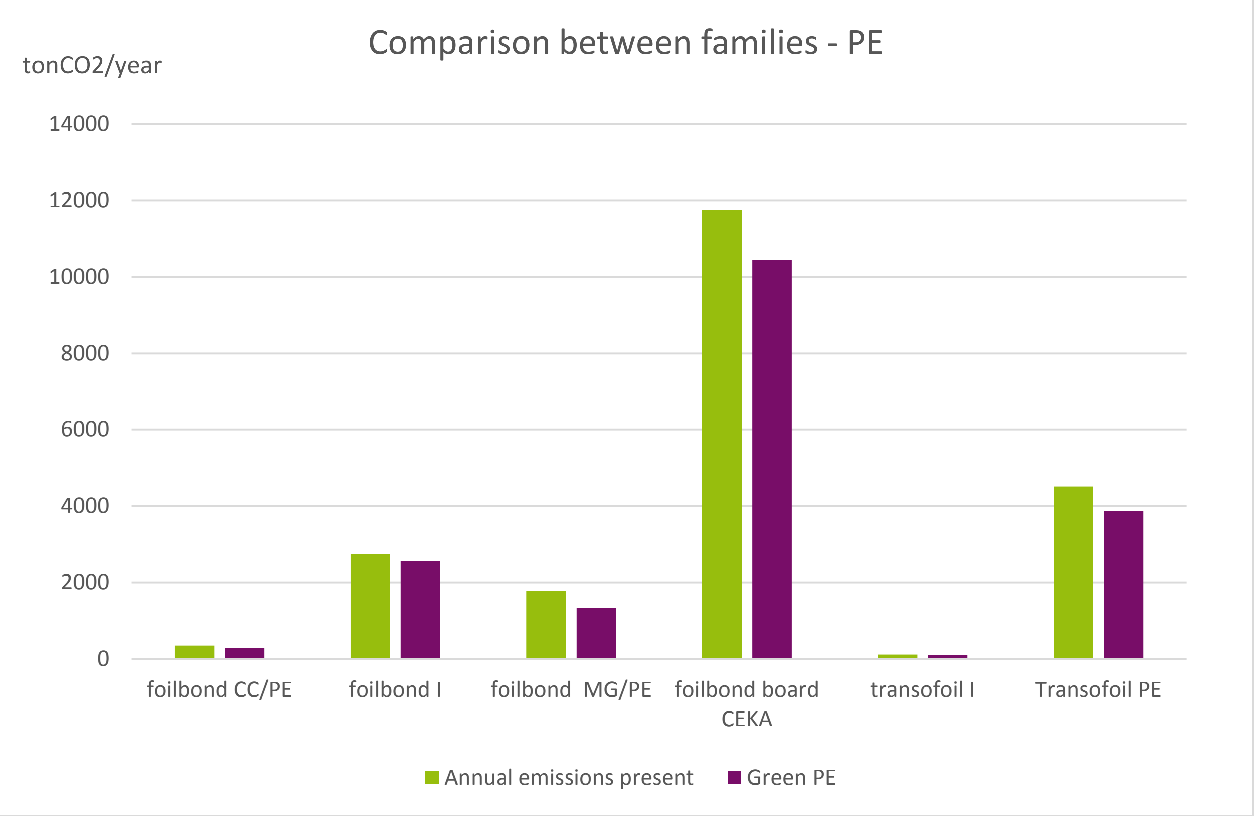

Figure 14. Comparison with the families relevant for only changing the PE quality.

The next stage in the carbon footprint analyses related each family's total production to the carbon emissions. This was to investigate the impact if one family's qualities would all switch towards the greener alternatives. In Figure 14 the laminates related to changing the PE quality is presented. It is visual that only changing PE does not have substantial impact on the total carbon emissions. It has, on the other hand, a positive effect on the renewability of the laminate. In Table 6 the reduction and renewability are presented for each family group in Figure 14. All materials show a high renewability except transofoil. Transofoil consist of a thinner PE-layer above a thicker barrier layer of aluminum foil which lower the renewability aspect of these products. The paper helps increasing the renewability of the foilbonds which play the bigger role since the PE layers are so thin.

Table 6. The reduction of CO_2-emissions and renewability in percentage when changing towards I'm Green - PE

Family group	% CO_2-emission reduction	% renewable material
foilbond CC/PE	18%	72%
foilbond I	7%	51%
foilbond MG/PE	25%	79%
foilbond board CEKA	11%	83%
transofoil I	8%	15%
Transofoil PE	14%	25%

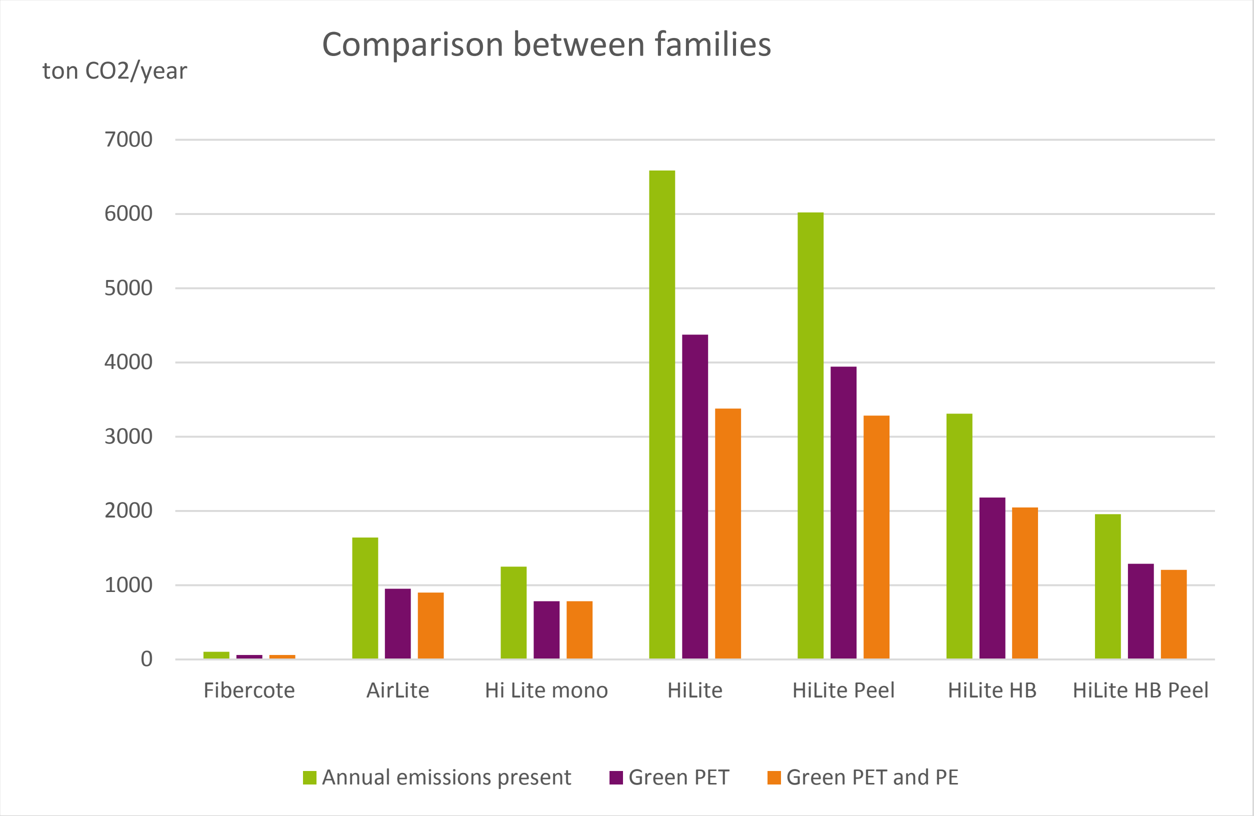

Figure 15. Comparison with the families relevant for the exchange of the PE and PET or only the PET quality.

When instead comparing the families relevant for PET and in some types both PE and PET the percentage of emission reduction. Almost 50 % in HiLite when using both Globio and I'm Green. Figure 15 shows the staple diagram of the carbon emissions for present material usage and if changing to Green PET, Globio, or both plastics.

Table 7 shows the reduction of carbon emissions and renewability of the alternatives.

Table 7. Reduction and renewability of the family groups relevant for changing PE and/or PET.

Family group	Globio	Globio + I'm Green	Globio2	Globio + I'm Green
	% decreased emissions	**% decreased emissions**	**% renewable material**	**% renewable material**
Fibercote	45%	▪	72%	▪
AirLite	42%	45%	28%	31%
Hi Lite mono	37%	▪	30%	▪
HiLite	34%	49%	27%	36%
HiLite Peel	35%	45%	27%	34%
HiLite HB	34%	38%	27%	30%
HiLite HB Peel	34%	38%	27%	30%

The performance of the combination of PET and PE led to a selection to keep investigating the category HiLite. The renewability of Fibercote 50/25 at 72 % showed interest in a marketing aspect.

This quality consist of paper with a PET-layer and often used for frozen pizza. The HiLite is used for thermoformed trays, often containing cold cuts and spreads.

5.1.3 Stage 3

The results from the third analysis with the new model is presented in Table 8. The fully virgin green material is as you can see receive lower related carbon emissions. In this table the cost analysis is also presented. Comparing the cost on a packaging level the biomaterial is only a few Swedish öre more expensive than for the bio material. Comparing only the materials cost the biomaterial increased 36 % towards using the conventional grade, after adding operating cost the difference of the two materials is limited to only 13 % rise. The Fibercote 50/25 is as mentioned used for small portions of frozen pizza. A relatively low-priced preprocessed food.

Table 8. The final comparison of carbon footprint analysis with Fibercote 50/25 using the improved method.

Fibercote 50/25	**Conventional**	**Bio**
gCO_2/m^2	123	77.3
ton CO_2/year	81.2	51.1
gCO_2 /package	12.6	7.66
Price per package	0.411 sek	0.466 sek
Compared price per m^2	100 %	113 %

As seen in Table 9 the cost analysis for Hilite 390/40 does not show as promising results as in the Fibercote 50/25 case. Due to the thicker layers of the new Bio-qualities of the ingoing material the materials cost exceed the production cost and thus the raise is of 90 % compared to the 13 % cost increase of Fibercote 50/25.

Table 9. Cost analysis for HiLite 390/40

HiLite 390/40	**Conventional**	**Bio**
gCO_2/m^2	1920	1050
ton CO_2/year	832	456
gCO_2 /package	36,1	19,7
Price per package	0.190 sek	0.361 sek
Compared price per m^2	100%	190%

The prices used in this evaluation is based on the small order for this project. A commercial price would probably be lower and is at the moment in negotiation.

The result of the updated model is presented in a comparative graph in Figure 16. You can clearly see that the new model generally lower the emissions related to the laminates compared to the model used in stage 1-2. It relates different emission posts in the production to the materials that are relevant. One example is that PET is not of need of any cleaning of polymer smoke which PE is. Even so the materials with a larger amount of PE is lowered substantially. Often a PE layer is used in combination with either PET, which is not as large in its related emissions. Why the higher loads of emissions to PE get little effect. The highest difference in carbon footprint performance comparing the models was the material with large surface weights paper or aluminum foil. These are not related to either cooling or smoke cleaning, why they have no emissions associated to the materials.

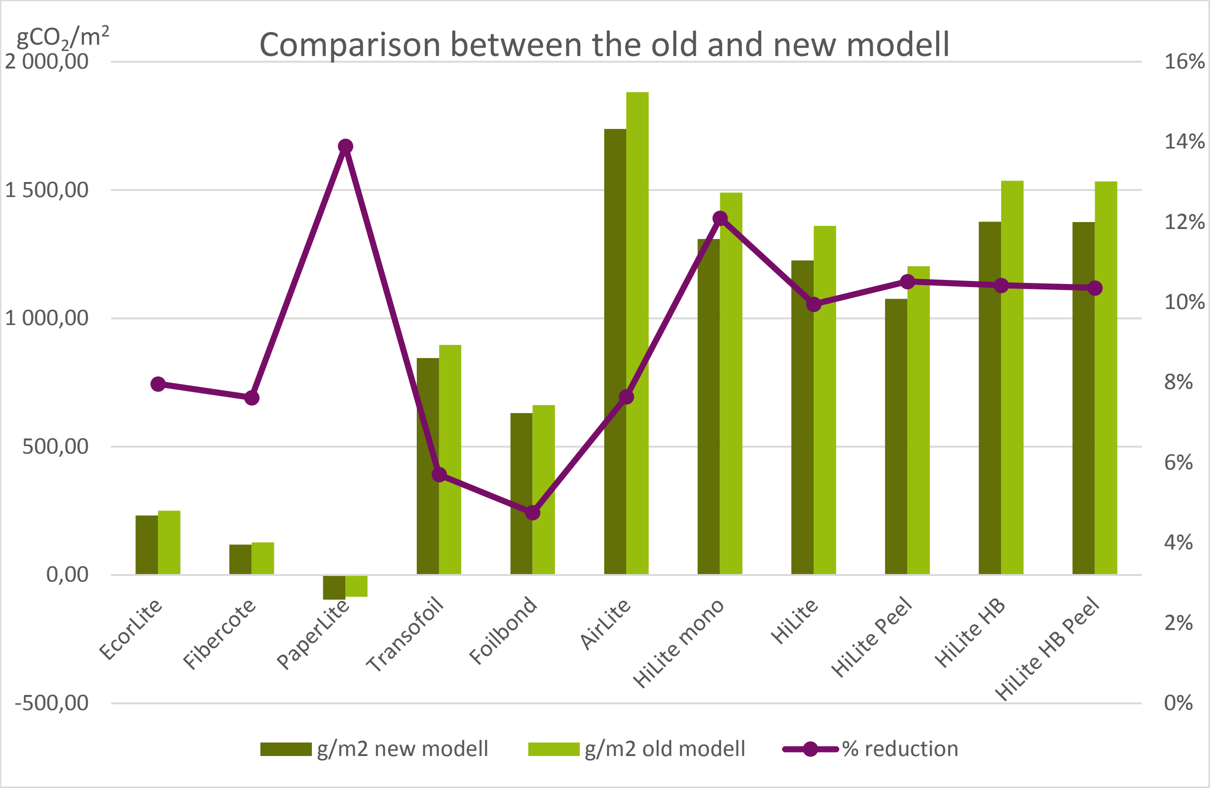

Figure 16. The comparative study between the two models using the scenario with PET or both PET and PE in the material composition. The percental reduction of the results of the new model.

5.2 Experimental results

For the results no raw data is presented. Data underlying mean values and statistical tests are presented in the Appendix.

5.2.1 Intrinsic Viscosity (IV)

While investigating the benchmarking results of IV for the two APET qualities it is evident that there is a possible difference. This is confirmed both by the average values presented in Figure 17 and the student t-test performed on the data. Since P<α (both at a significance level of 5% and 1%, Table 10 (showing the example of α=0.01) and the t-value is outside the critical limit, the null hypothesis (H_0) of equal mean values can be discarded. The risk of discarding the null hypothesis even if it is the correct one is at 1 % significant as low as 0.002 %.

Table 10. Student t-test with unequal variances discarding the hypothesis of similar mean values on 1 % significance.

	GLOBIO	*Ramapet*
Mean value	0.718	0.742
Variance	$2.08 \cdot 10^{-5}$	$6.70 \cdot 10^{-6}$
Observations	5	5
Assumed difference in mean value	0	
Degrees of freedom	6	
t-value	-10.5	
P(T<=t) two sided	$4.41 \cdot 10^{-5}$	
t-critical two sided	2.45	

To ensure quality of the produced biomaterial comparative measurements between the end of the set-up reel and the end of the product-reel was performed. The results was above the accepted value at 0.720 as was the set-up reel. These values are differing a bit from the experiments done later where 3 of 5 data points are below 0,720 and therefore also the mean value, Table 10. Even when including these values it was possible to discard H_0 by using the 1 % limit of significance. Which further solidify the discarding hypothetic equality.

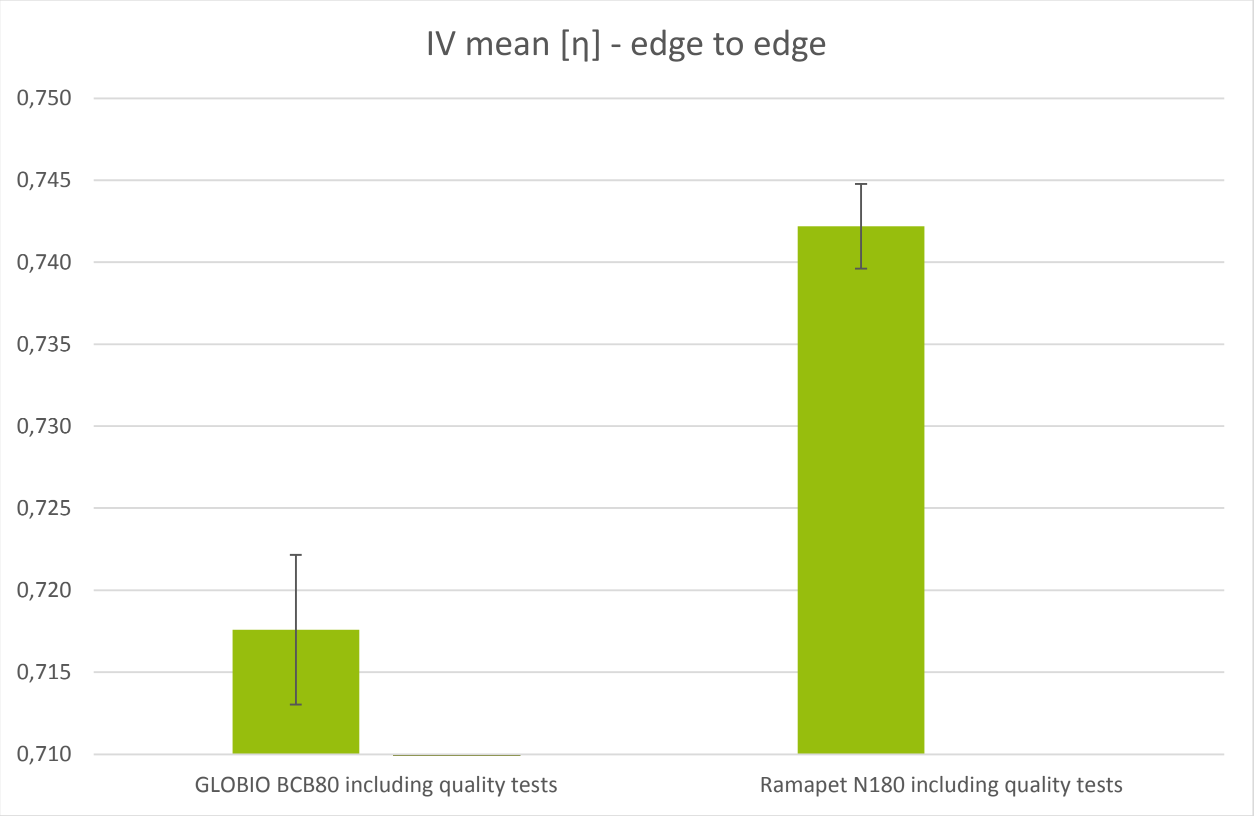

Figure 17. Mean values of the experiments with five data points of each material showing the standard deviation for each material.

In Figure 17 the mean values of IV for both materials are presented with respective standard deviation. The deviations are narrow and thoroughly divided which also state a difference between the produced materials. The results in Figure 17 are based on the edge to edge results listed in appendix.

Benchmarking tests on the Fibercote 50/25 material was not practicable since there was paper fibers left on the conventional material after delamination with water. On the biomaterial the IV was performed on the part after the line brake where the paper did not adhere. These tests yielded a low value of IV with an average at 0.65.

When studying the intrinsic viscosity of the starting material no obvious difference could be detected. Too few measurements were done in order to statistically back this hypothesis up. The values were at 0.78 for GLOBIO and 0.79 for Ramapet N180. Within the standard deviations of the values presented for the raw material in Table 3.

5.2.2 Sealing strength

The sealing strength results are not showing any differences in the HiLite 390/40 case. The t-test shows that a similarity is not to be discarded. This is presented in Table 11.

The results may have been affected of the sealing top film which in all samples were stretched out before any delamination of the seal was observed. This stretching may have been inducing toughness in the film which would induce a greater force on the seal after some time of measurement.

Table 11. T-test of the HiLite 390/40 seal strength results show that with a significance level at 5 % the null hypothesis of equal mean values is not possible to discard.

	HiLite 390/40 Conventional	*HiLite 390/40 Bio*
Mean value	35.9 N/15mm	37.7 N/15mm
Variance	10.3	6.05
Observations	9	9
Assumed difference in mean value	0	
Degrees of freedom	15	
t-value	-1.34	
P(T<=t) two sided	0.201	
t-critical two sided	2.13	

In Figure 18 the mean values for HiLite 390/40 are presented.

The results for Fibercote 50/25 were excluded since it was the sealing strength for both materials was above the tear resistance of the paper layer as predicted.

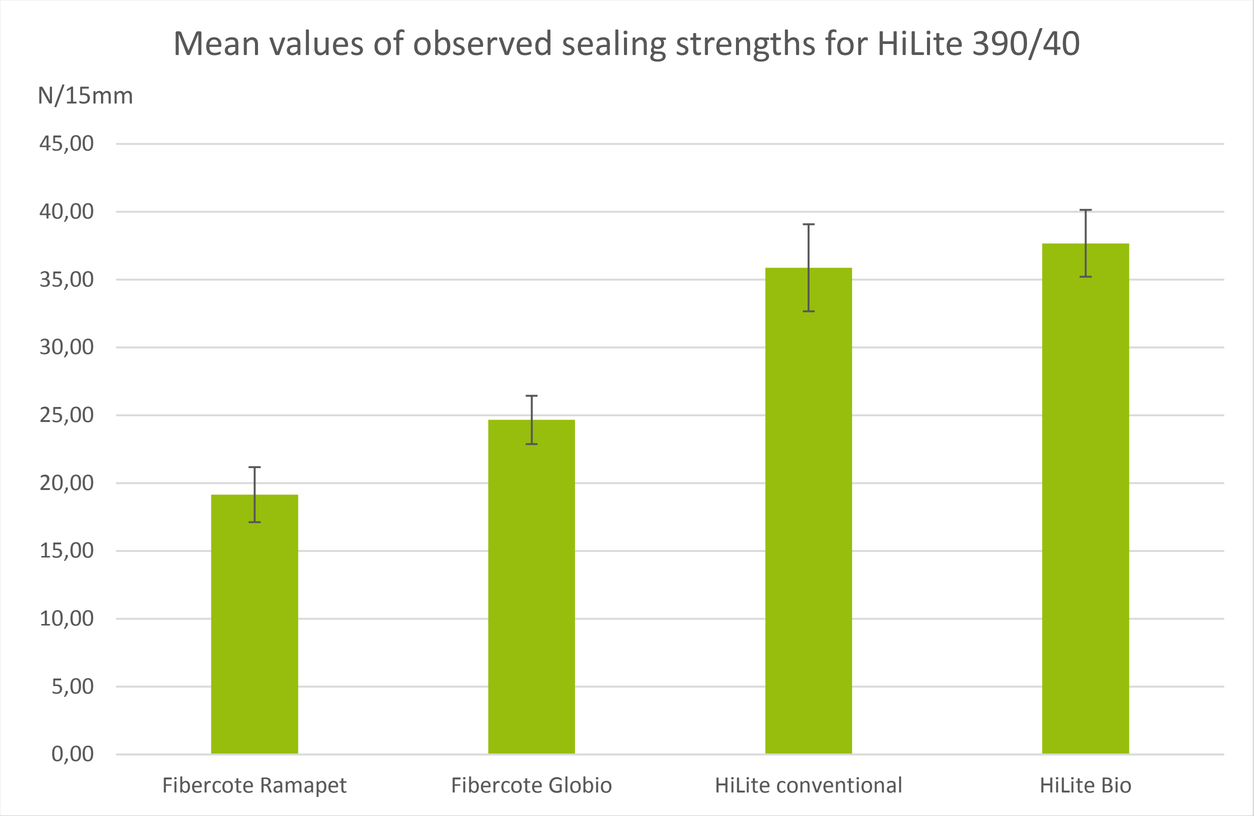

Figure 18. Graph of mean values and standard deviation for the sealing strength measurements. The mean values are in the range of the other materials standard deviation.

5.2.3 Sealing temperature

The sealing temperatures for Fibercote 50/25 showed a variation within the materials data sets while HiLite 390/40 showed equal sealing temperatures for the main part of the result groups. The HiLite 390/40 material differed between both qualities, at 5 % significance level shown in Table 12, while the deviation is to large in the case of Fibercote 50/25 to prove any differences. This is shown in Figure 17 where the standard deviation bars clearly overlap for all mean values in the case of Fibercote 50/25 while being separated in for the HiLite 390/40 materials. Table 12 also reveal that a difference could not be proved with a significance at 5 %. Figure 20 show that no evident difference correlated to the placement of the seal could be established for Fibercote 50/25. A variety of temperature depending on which direction the seal was done would be noted but this variance is rather within both material groups than a difference between the different qualities.

Since HiLite 390/40 showed steady temperature results for all cross directional positions and only variated occasionally there was no reason for doing the same comparison for that material.

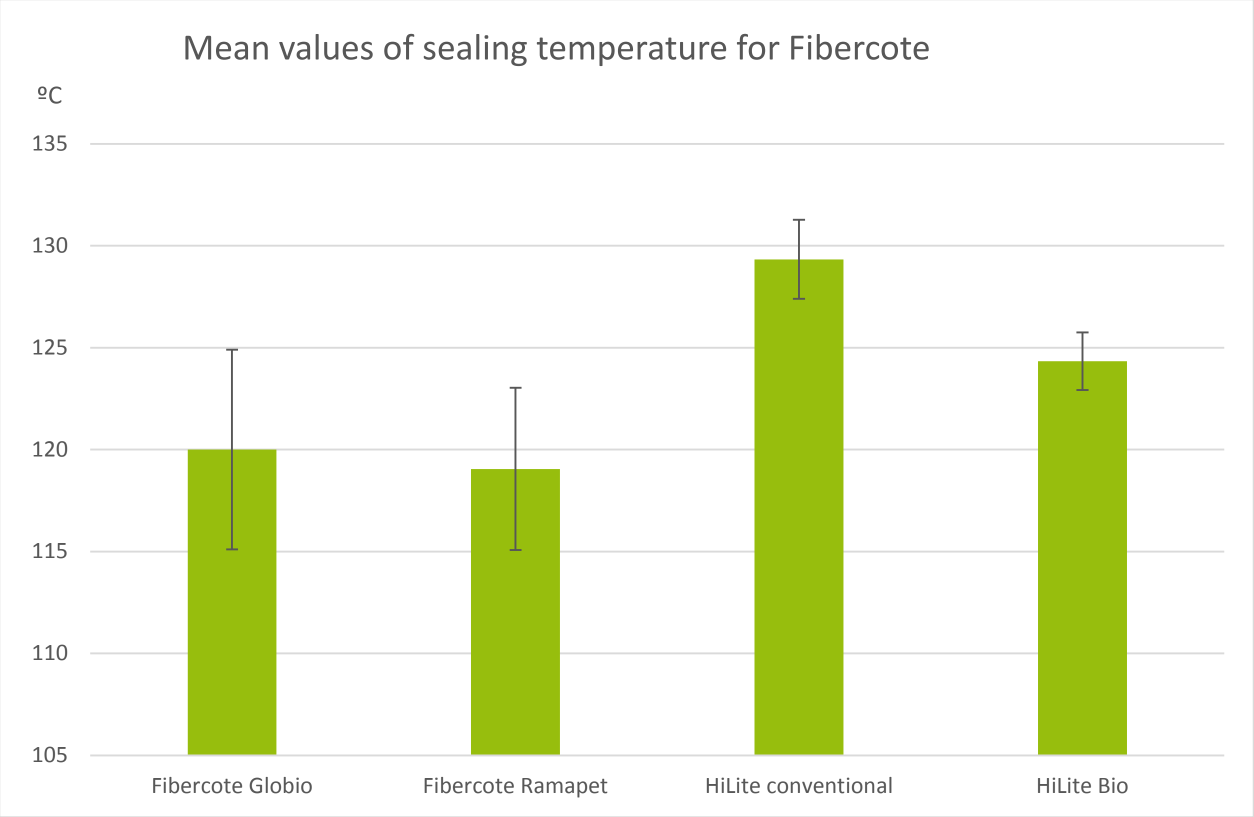

Figure 19. Mean values per material and standard deviations. The deviations do not overlap in the case for HiLite 390/40. The deviations for Fibercote 50/25 is broad which imply that it is not possible to conclude that there is any difference between the materials.

Table 12. T-test of sealing temperature data for HiLite 390/40.

	HiLite 390/40 conventional	*HiLite 390/40 Bio*
Mean value	129 ºC	124 ºC
Variance	3.76	2.00
Observations	18	18
Assumed difference in mean value	0	
Degrees of freedom	31	
t-value	8.83	
P(T<=t) two sided	$5.65 \cdot 10^{-10}$	
t-critical two sided	2.03	

Table 13. T-test of sealing temperature data for Fibercote 50/25.

	Fibercote 50/25 Globio	*Fibercote 50/25 Ramapet*
Mean value	120 ºC	119 ºC
Variance	24.0	15.8
Observations	21	21
Assumed difference in mean value	0	
Degrees of freedom	38	
t-value	0.691	
P(T<=t) two sided	0.494	
t-critical two sided	2.02	

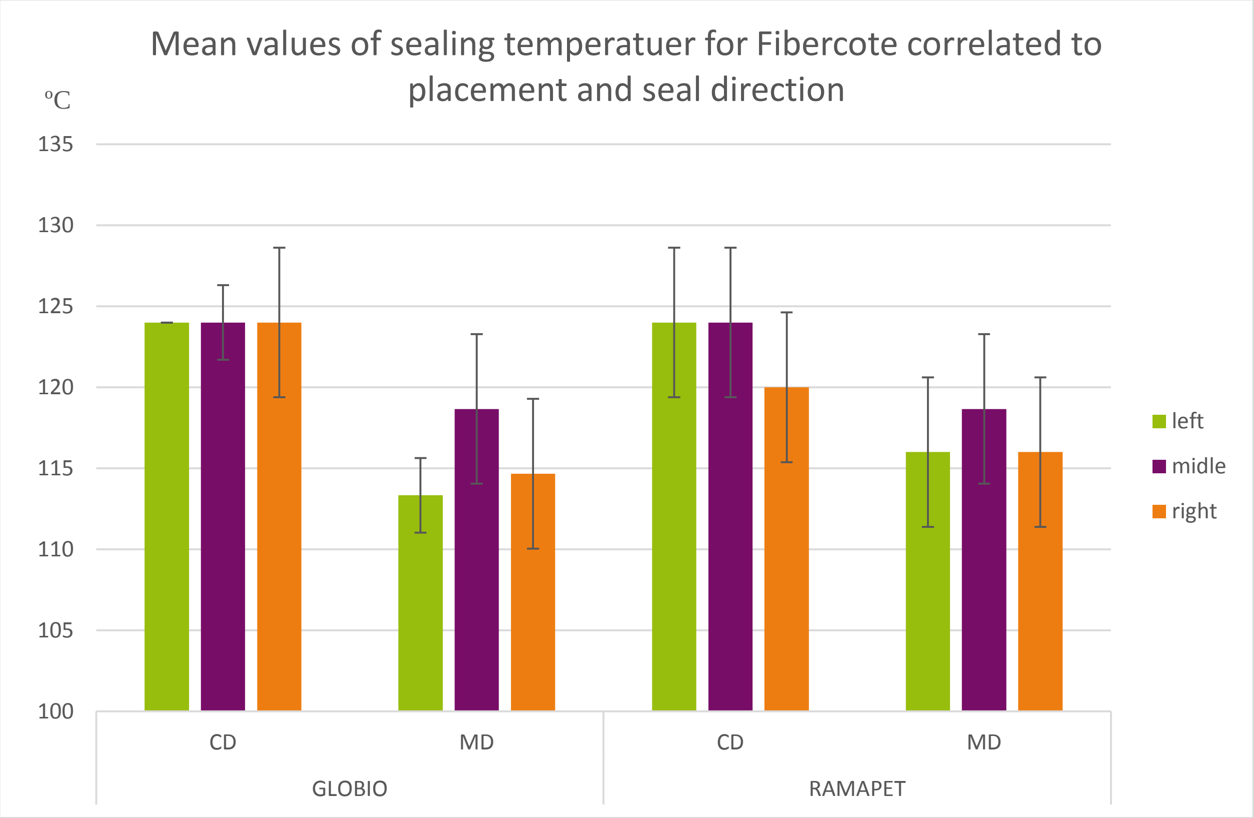

Figure 20. The mean values investigating if there is a difference correlated to the edges or in the middle of the material as well as between the directions of the seal. No difference can be proven between positions of the sample.

5.2.4 Coefficient of Friction (COF)

T-tests investigating the equality of mean values in Table 14, Table 15 and Table 16 shows that the hypothesis of equal mean values can be discarded in both APET vs. APET friction and APET vs. PE friction experiments, with only 0.8 % respective 0.6 % possibility to incorrectly discard this hypothesis. Studying the bar graph in Figure 21 the results of discarding the null hypothesis in the APET vs APET case is more insure than the t-test tell. The standard deviation of the conventional material is broad and the mean value of the Bio-material is on the edge of the conventional material's lower standard deviation bar. It is by this figure hard to tell if there is a significant difference. The same goes for the PE-PE where the t-test was not able to prove any difference in the material because of the wide variety in the data set. The risk of wrongly discarding the null hypothesis (the p-value) is only at 9 % which is not that much higher than the 5 % significant level chosen for this investigation.

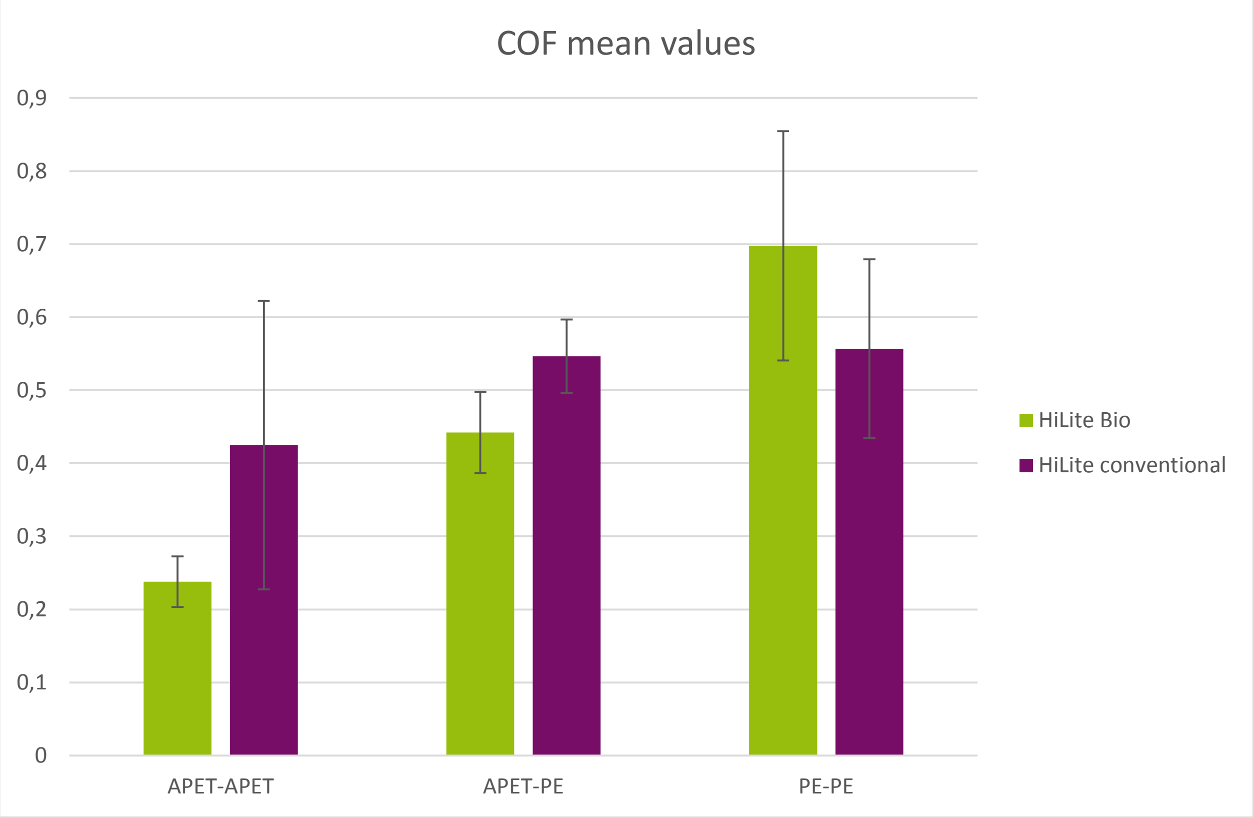

Figure 21. The comparison between COF values for the different side combinations in the HiLite 390/40 experiment.

Table 14. T-test investigating the equality of coefficient of friction mean values of APET vs. APET sides in HiLite 390/40 materials.

	HiLite 390/40 conventional	*HiLite 390/40 Bio*
Mean value	0.349	0.238
Variance	$5.21 \cdot 10^{-3}$	$1.20 \cdot 10^{-3}$
Observations	5	6
Assumed difference in mean value	0	
Degrees of freedom	9	
t-value	3.35	
P(T<=t) two sided	$8.46 \cdot 10^{-3}$	
t-critical two sided	2.26	

Table 15. T-test investigating equal mean values between the APET vs. PE side of the HiLite 390/40 materials.

	HiLite 390/40 conventional	*HiLite 390/40 Bio*
Mean value	0.547	0.442
Variance	$2.56 \cdot 10^{-3}$	$3.08 \cdot 10^{-3}$
Observations	6	6
Assumed difference in mean value	0	
Degrees of freedom	10	
t-value	3.40	
P(T<=t) two sided	$6.74 \cdot 10^{-3}$	
t-critical two sided	2.23	

Table 16. T-test investigating the equality of mean values in coefficient of friction between the two PE sides of the HiLite 390/40 materials.

	HiLite 390/40 Conventional	*HiLite 390/40 Bio*
Mean value	0.511	0.671
Variance	$3.13 \cdot 10^{-3}$	$2.56 \cdot 10^{-2}$
Observations	5	5
Assumed difference in mean value	0	
Degrees of freedom	5	
t-value	-2.12	
P(T<=t) two sided	$8.78 \cdot 10^{-2}$	
t-critical two sided	2.57	

5.2.5 Surface Resistivity

For Fibercote 50/25 the resistivity varied a lot between the tests. This is evident in Figure 22 where the standard deviations are wide. To draw any conclusions from this is difficult. The t-test, presented in Table 17, support this analysis since it is roughly a 50 % chance to incorrectly discard any equality of the materials.

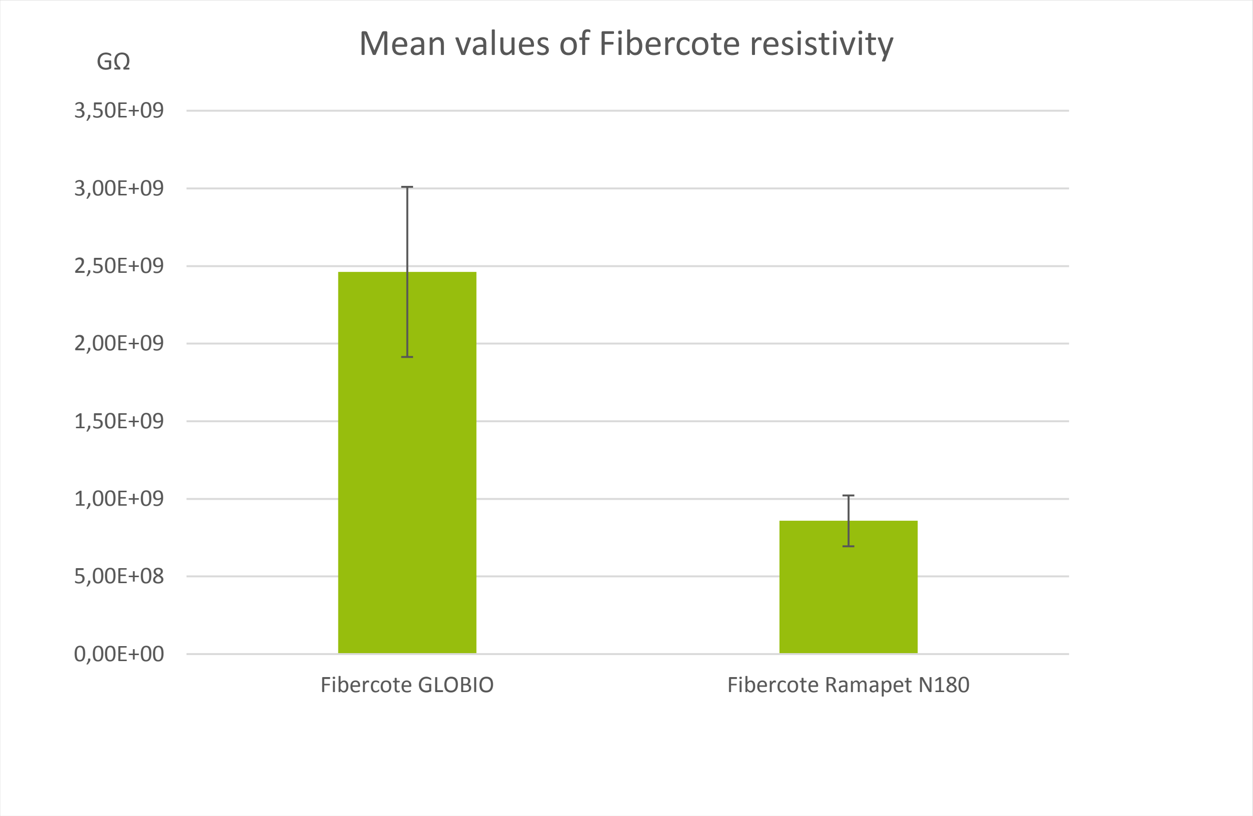

Figure 22. The graph presents the mean values of the resistivity for Fibercote 50/25. No conclusion of if the materials differ in any way could be concluded from this.

Table 17. The t-test investigating the equality of mean values for Fibercote 50/25 resistivity.

	Fibercote 50/25 Globio	Fibercote 50/25 Ramapet
Mean value	$2.05 \cdot 10^{8}$ GΩ	$7.16 \cdot 10^{7}$ GΩ
Variance	$3.00 \cdot 10^{17}$	$2.69 \cdot 10^{16}$
Observations	12	12
Assumed mean difference	0	
df	13	
t-value	0.809	
P(T<=t) two sided	0.433	
t-critical two sided	2.16	

In Figure 23 the mean values for both sides of HiLite 390/40 is presented with respective standard deviation. In this figure it looks like there is a significant difference for both the material sides between the qualities. The t-test in Table 18 and Table 19 show that this is only the case in the PE measurements with only 0.1 % probability to wrongly discard equality on a 5 % significance. The probability to incorrectly discard the hypothesis of equal mean values for the APET measurements is higher at 10 %, larger than α=0.05. The significant difference is marked by * in Figure 23.

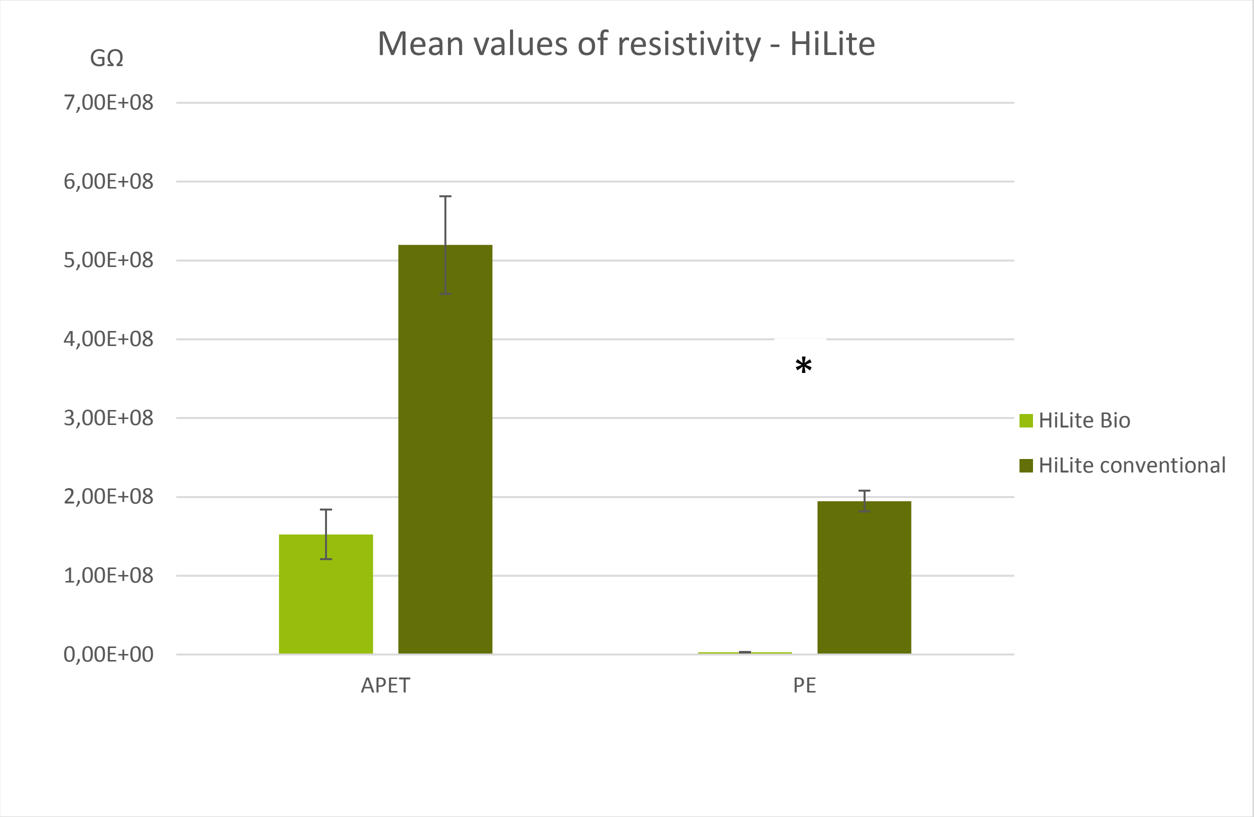

Figure 23. The mean values seem to differ in both the APET and the PE measurements but only the means marked with * proved difference at significance. Probably it is hard to distinguish any significal difference when the variance is so large.

Table 18. T-test results of the investigation for equal mean values in the measurements of the PE side of HiLite 390/40.

	HiLite 390/40 conventional	*HiLite 390/40 Bio*
Mean value	$2.56 \cdot 10^5$ GΩ	$1.62 \cdot 10^7$ GΩ
Variance	$1.15 \cdot 10^{11}$	$1.71 \cdot 10^{14}$
Observations	12	12
Assumed mean difference	0	
df	11	
t-value	-4.23	
P(T<=t) two sided	$1.41 \cdot 10^{-3}$	
t-critical two sided	2.20	

Table 19. T-test results of the investigation of equal mean values at the APET side of HiLite 390/40.

	Bio-HiLite 390/40	*HiLite 390/40 Conventional*
Mean value	$1.27 \cdot 10^{7}$ GΩ	$2.95 \cdot 10^{7}$ GΩ
Variance	$9.90 \cdot 10^{14}$	$4.15 \cdot 10^{14}$
Observations	12	10
Assumed mean difference	0	
df	19	
t-value	-1.51	
P(T<=t) two sided	0.148	
t-critical two sided	2.09	

5.2.6 Permeability

OTR

The OTR measurements were done over several days to obtain steady state values. A mean over each material of these steady state values are presented in Figure 24. As can be seen the standard deviation is narrow for the conventional material while the bio material vary more.

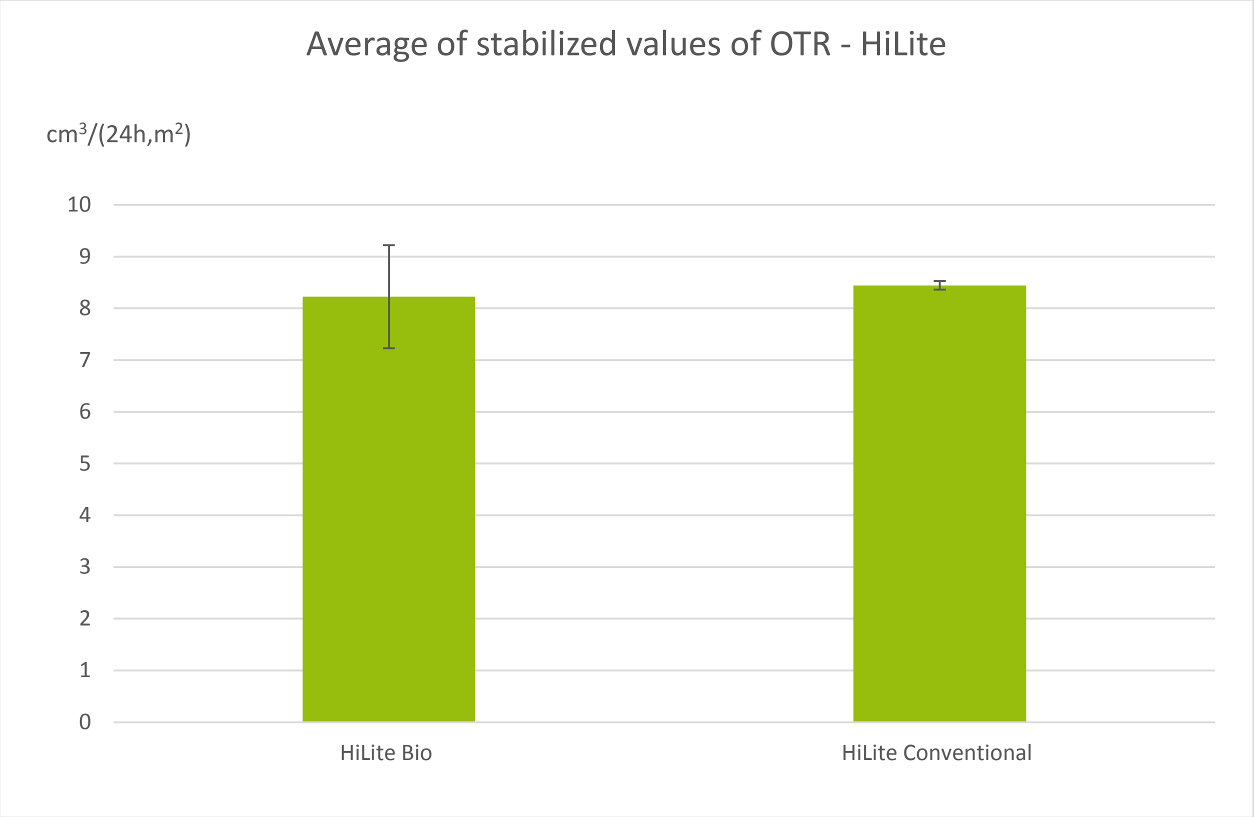

Figure 24. OTR mean values after samples reached steady state. Biomaterials vary more in amount oxygen than the conventional material.

The mean values seem to be close and this is validated by the t-test, Table 20, which shows that it is not possible to discard an equality between the mean values.

Table 20. T-test investigating the null hypothesis of equal mean values between the OTR values for HiLite 390/40 on 5 % significance

	HiLite 390/40 Bio	HiLite 390/40 Conventional
Mean value	8.23 $cm^3/(24h,m^2)$	8.44 $cm^3/(24h,m^2)$
Variance	0.989	$7.48 \cdot 10^{-3}$
Observations	5	5
Assumed difference in mean value	0	
Degrees of freedom	4.00	
t-value	-0.488	
P(T<=t) two sided	0.651	
t-critical two sided	2.78	

For Fibercote 50/25 there was an evident difference between the materials both shown in the bar graph displaying narrow standard deviation and a clear mean difference but also confirmed by the t-test on a 5 % significance. Figure 25 describe the mean values and standard deviation for OTR in Fibercote 50/25 and Table *21* presents the t-test performed on the data.

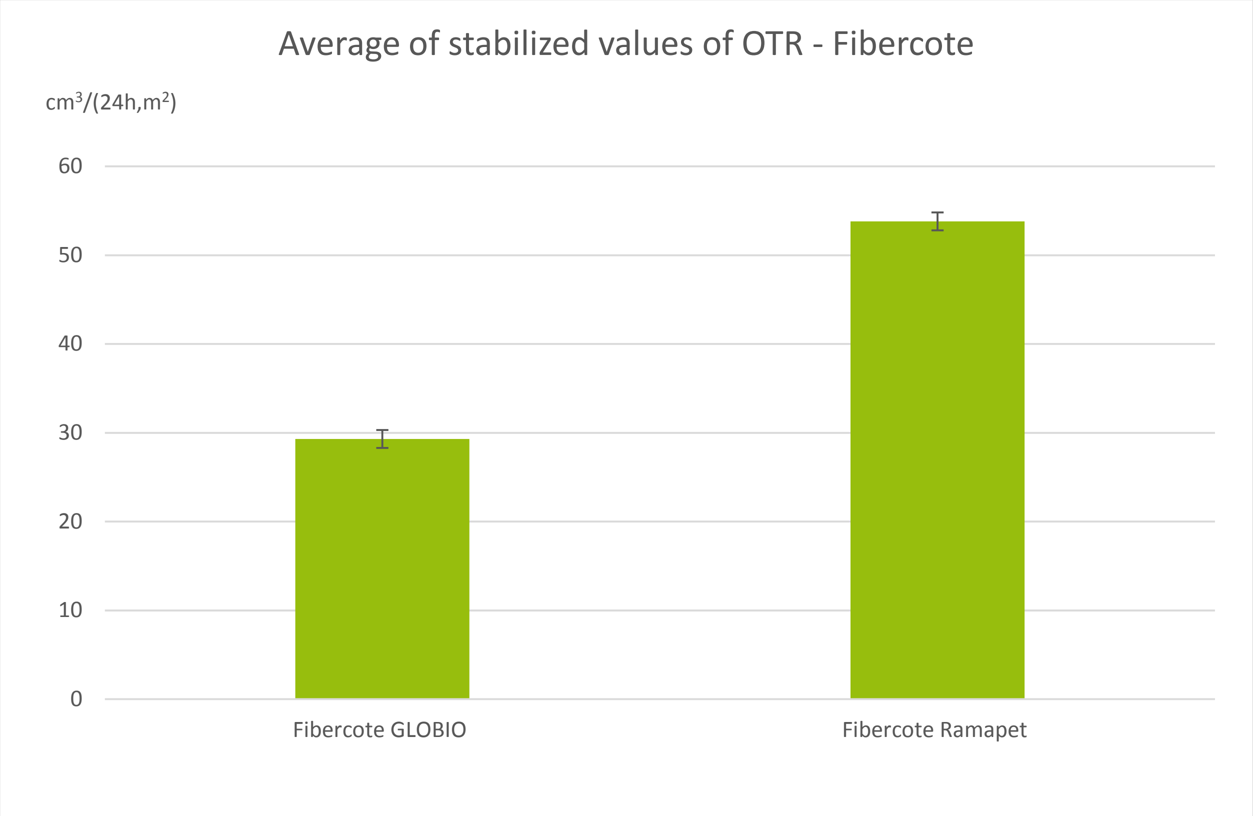

Figure 25. The average of the Fibercote 50/25 materials' OTR values after steady state show a clear difference. The standard deviations are narrow which solidify this

Table 21. T-test investigation the null hypothesis of equal mean values for OTR values of Fibercote 50/25 after stabilization

	Fibercote 50/25 GLOBIO	**Fibercote 50/25 Ramapet**
Mean value	29.4 cm^3/(24h,m^2)	52.3 cm^3/(24h,m^2)
Variance	0.433	12.3
Observations	5	5
Assumed difference in mean value	0	
Degrees of freedom	4	
t-value	-14.4	
P(T<=t) two sided	$1.35 \cdot 10^{-4}$	
t-critical two sided	2.78	

To reach steady state the HiLite 390/40 material needed 6 days while Fibercote 50/25 was canceled after only four days where the two last days was during the weekend. It is therefore possible that they reached steady state even before that time.

WVP

Presented in Table 22 is the results from the WVP measurements. The equipment only had room for one sample of each material why only one data point for each material and each different temperatures is obtained. No statistical test is there for possible in this case and the conclusions drawn by this test are vague since they regard the full sample width and the total production of the material. The results show that the mass flow of water vapor through the material highly depend on temperature and relative humidity. For the 25°C measurements the relative humidity was 75 % while in the 38°C example it was risen to 90 %. The water vapor transport was increased10 times. Between the HiLite 390/40 materials there is no substantial difference in WVP at those temperatures and humidity.

Table 22. WVP results for the two HiLite 390/40 qualities at different temperature and relative humidity

	HiLite 390/40 bio [g/(m^2, 24h)]	**HiLite 390/40 Conventional [g/(m^2, 24h)]**	**Fibercote 50/25 Globio [g/(m^2, 24h)]**	**Fibercote 50/25 Ramapet [g/(m^2, 24h)]**
25.0	10.0	9.9	17.4	24.2
38.0	99.8	100.3	47.1	65.6

Fibercote 50/25 does not show the same magnitude of increase when raising the temperature and relative humidity as the HiLite 390/40 material but the difference between the materials is as in the case of the oxygen transmission significantly different.

5.2.7 Laminate thickness

In Table 23 the mean values of the polymer thickness and the permeability coefficient is presented. The values for both materials now related to the polymer thicknes does not show any large deviation between qualities. A small significance is found between the Fibercote 50/25 qualities but this significance is small nearly not accepted. The results of the student t-test is shown in Table 24.

Table 23. The mean thickness of the polymer in the laminates and the permeability coefficient

	Mean thickness of polymer [µm]	*Permeability coefficient [µm·g/(m^2, 24h)]*
Fibercote 50/25 Globio	22.2	1350
Fibercote 50/25 Ramapet	46.0	1160
HiLite 390/40 Bio	433	3740
HiLite conventional	441	3720

Table 24. T-test examining the equality of mean values between the permeability coefficients of Fibercote 50/25

	Fibercote GLOBIO	*Fibercote ramapet*
	1350	1160
Mean value	11900	19900
Variance	5	5
Observations	0	
Assumed difference in mean value	8	
Degrees of freedom	2.36	
t-value	0.0229	
P(T<=t) two sided	1.86	
t-critical two sided	0.0459	
Mean value	2.31	

5.2.8 IR

As was expected by the equality in chemical composition by the different qualities there is no difference between the two films in the IR-ATR measurements. This is shown by Figure 26 and Figure 27 where the ATR graphs are showing absorption and transmission at the same wavelengths. Larger versions of the figures in this section is found in Appendix. The ATR measurements are only taking place in the outer atom layers why this gives a good validation that there is nothing ells in the bio-polymer qualities than the conventional ones used today and the results were quite expected.

For FTIR measurements, Figure 28, you can also see that this is valid for the laminated films. The bio-composed laminate only show a little less transmittance of IR at some of the non-absorbed wavelengths.

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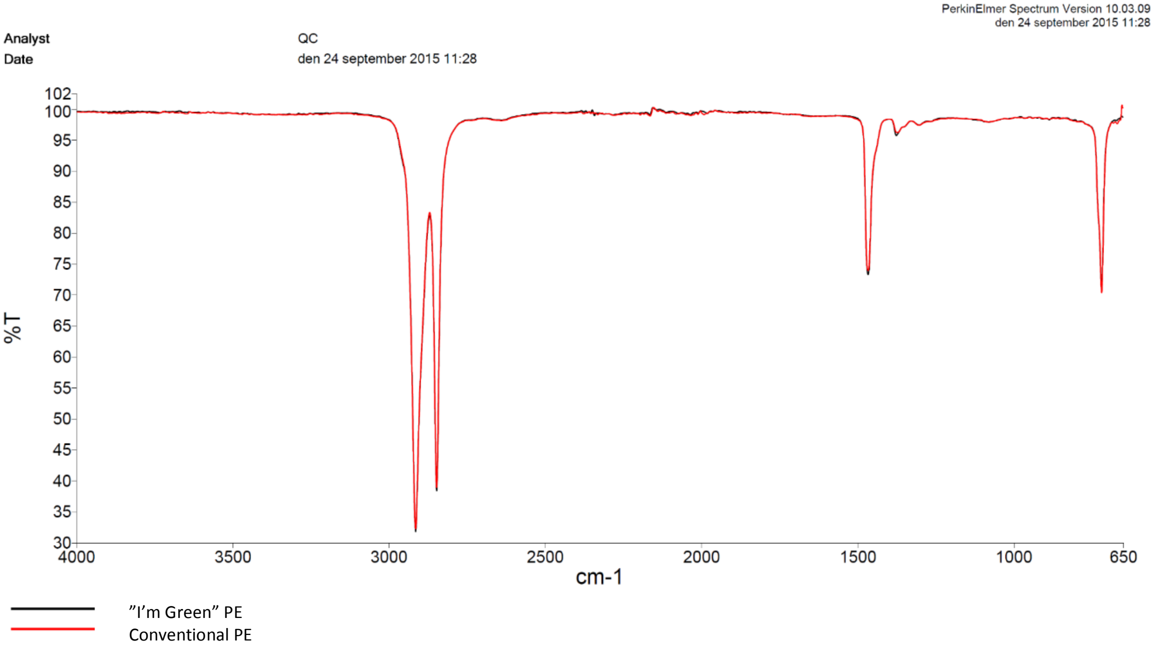

Figure 26. ATR measurements of the PE side showing no molecular difference to the fossil material.

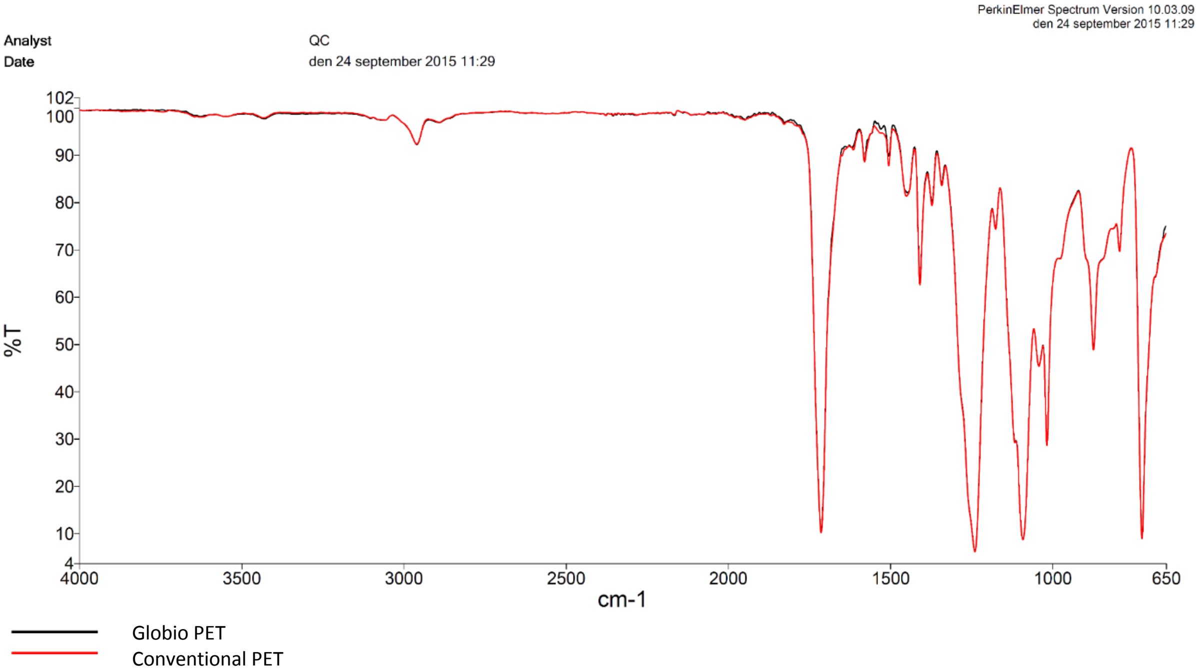

Figure 27. ATR measurements for the APET side of both the materials showing equal transmission in the infrared scan.

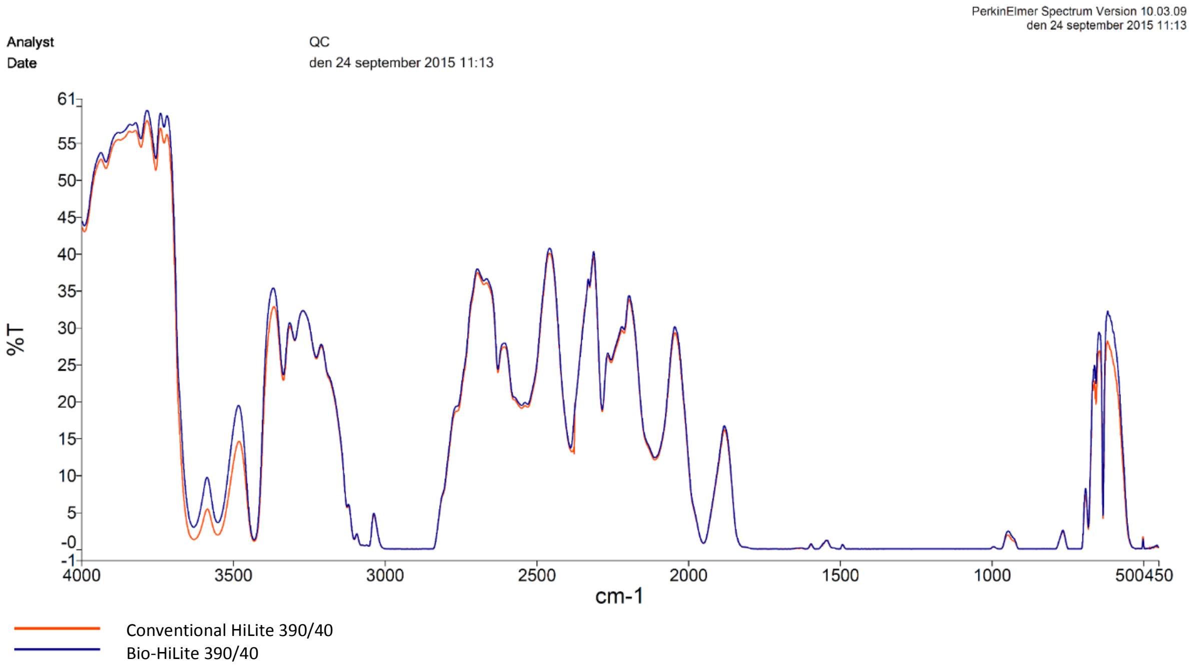

Figure 28. FTIR for both the laminates. The Bio-HiLite 390/40 is marginally less absorbing at some of the absorption peaks.

5.2.9 UV-Vis

When investigating the transmission of visible light through the HiLite 390/40 material no difference regarding placement of the sample or between the two materials could be detected. Figure 29 shows the similarity between the samples. As in the IR example the larger image is presented in Apendix. At approximately 380 nm there is an absorption dip for the left and right samples of the biomaterial which could indicate a difference between the center and edges in this produced sheet of the biomaterial.

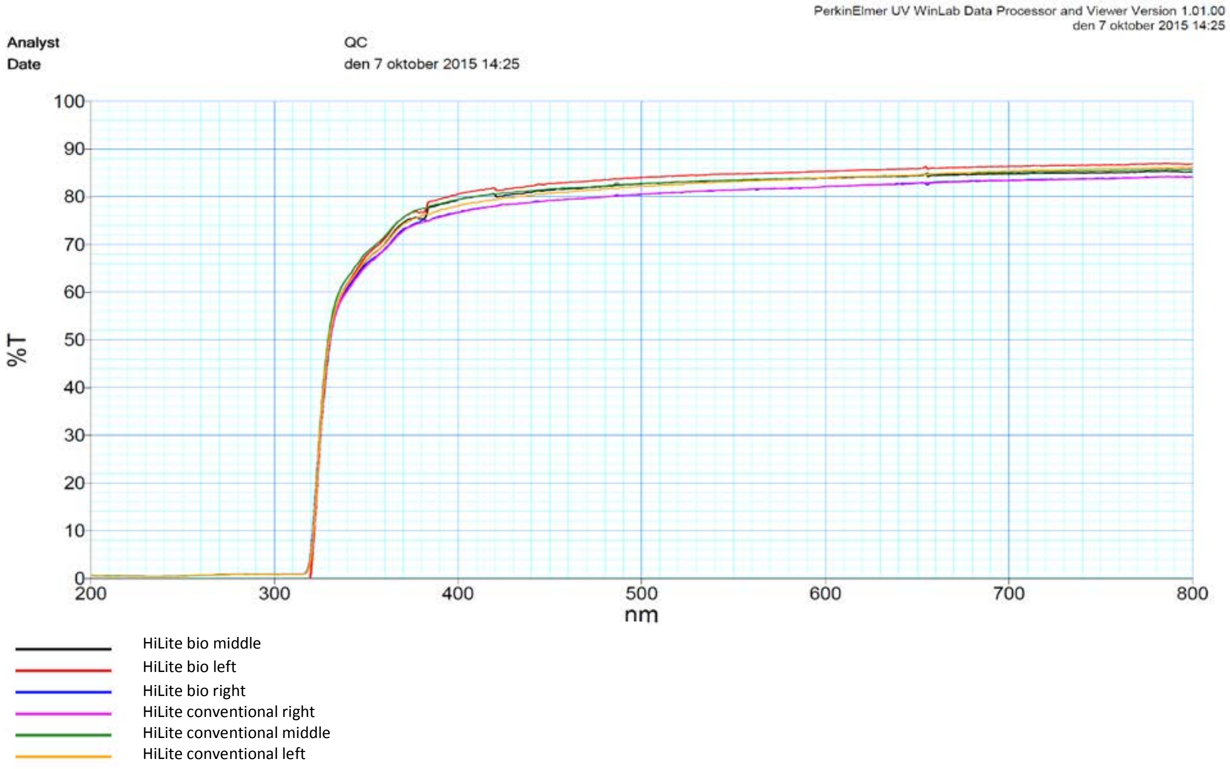

Figure 29. UV-VIS results of all HiLite 390/40 materials edge to edge. A minor difference for the right and left sample of the Bio-HiLite 390/40 with a dip in transmission at 380nm.

5.2.10 DSC

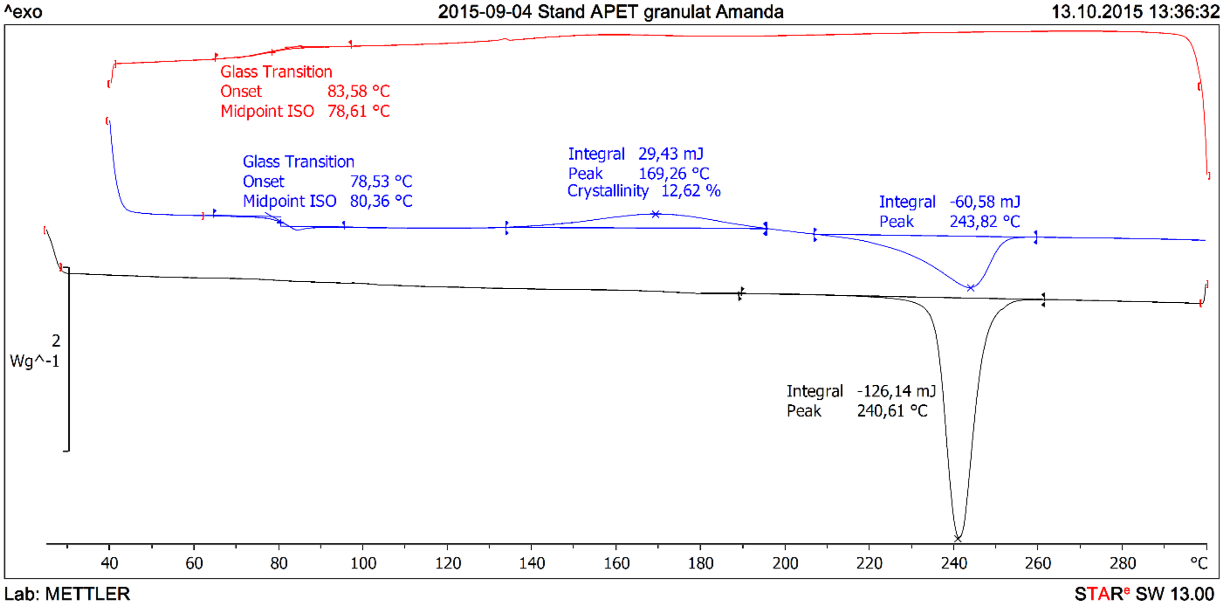

Figure 30. DSC-plot of Ramapet granulates. Wider peaks after heating. The order of curves is Black, red and blue with a heating of 20°C/min.

For the PET starting materials melting points at the first heating cycle are similar. Not varying much. What can be detected is the melting peak being slightly wider for Globio than for Ramapet. What is obvious in both cases is the smeared out crystallization in the red curves, see Figure 30. In the Globio plot, Figure 31, this crystallization is not even detectable. This could indicate a degradation in the initial heating curve. If that is the case there is probably some water leaking into the testing equipment. The samples were not dried before loading. Even if dry nitrogen gas is used in the system it is possible that the samples did not manage to dry properly in the heating cycle of 20°C/min. this would explain the wider peaks since there would be a wider range of polymer chain lengths that would differ grater in crystallinity. No evident shift of the melt peak temperature was detected between the heating cycles for either Ramapet or Globio. What contradict this theory of degradation in the DSC test is that the peak temperature probably would lower when the chains degrade since a larger part of the polymer sample would melt at an earlier stage.

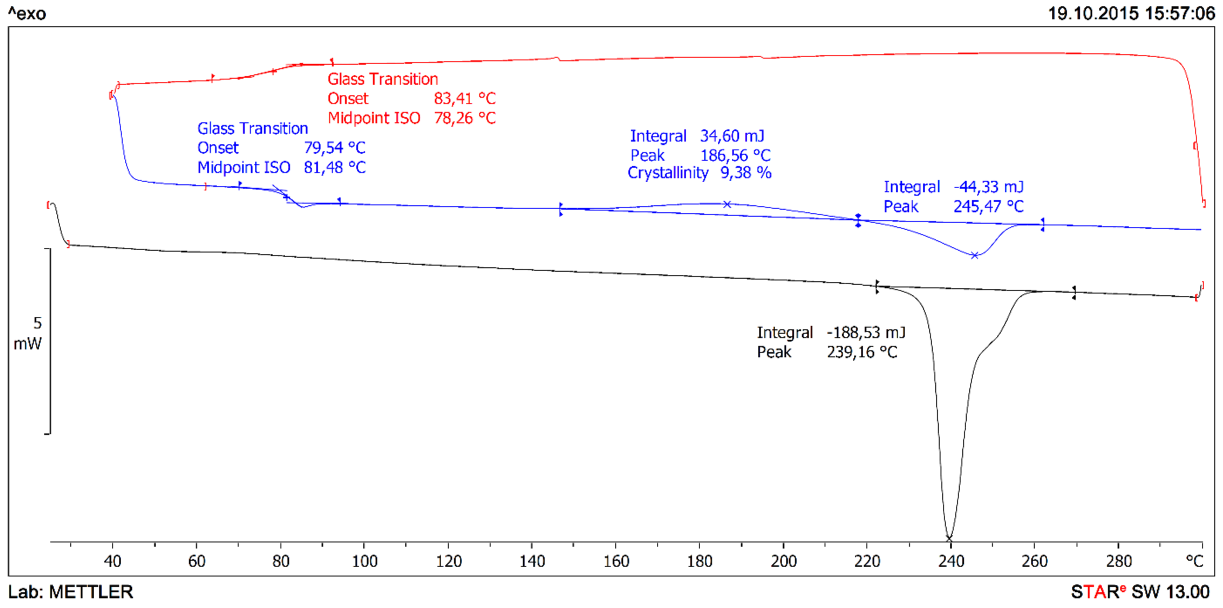

Figure 31. DSC plot of GLOBIO granulates. First melting peak wider than for the fosil material. Same melting point. The order of curves is Black, red and blue with a heating of 20°C/min.

Following with the same comparison for the PE granulates there is a slight difference in crystallization and melting temperatures with a hint to wider peaks than for the standard PE used today. This is presented in Figure 32 and Figure 33.

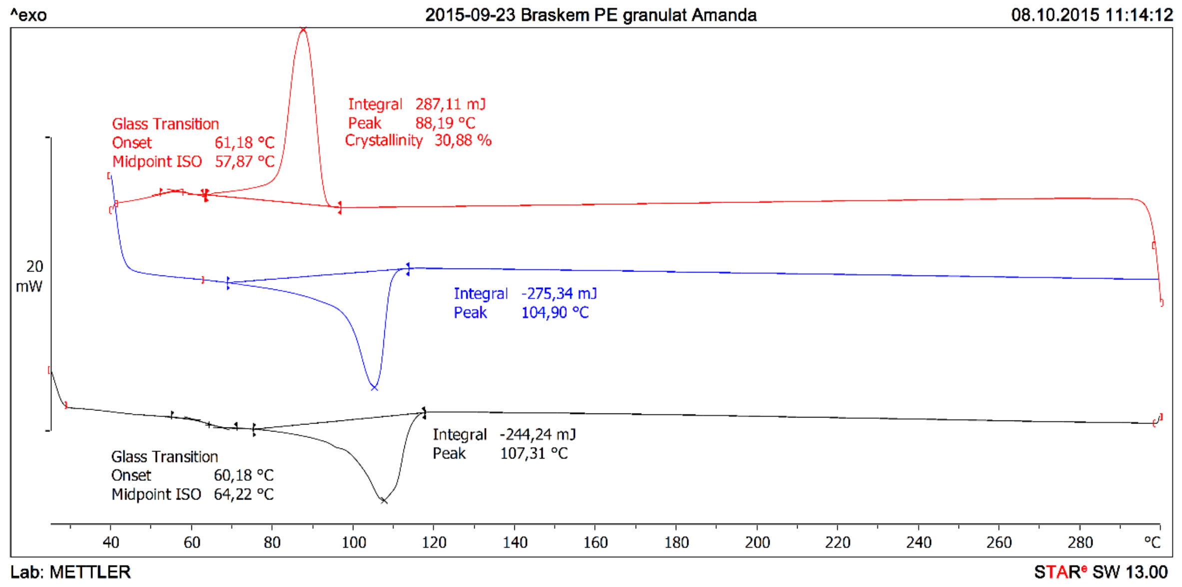

Figure 32. DSC plot for the braskem PE granulates. Slightly askew melt and crystal temperatures compared to the conventional material. The order of curves is Black, red and blue with a heating of 20°C/min.

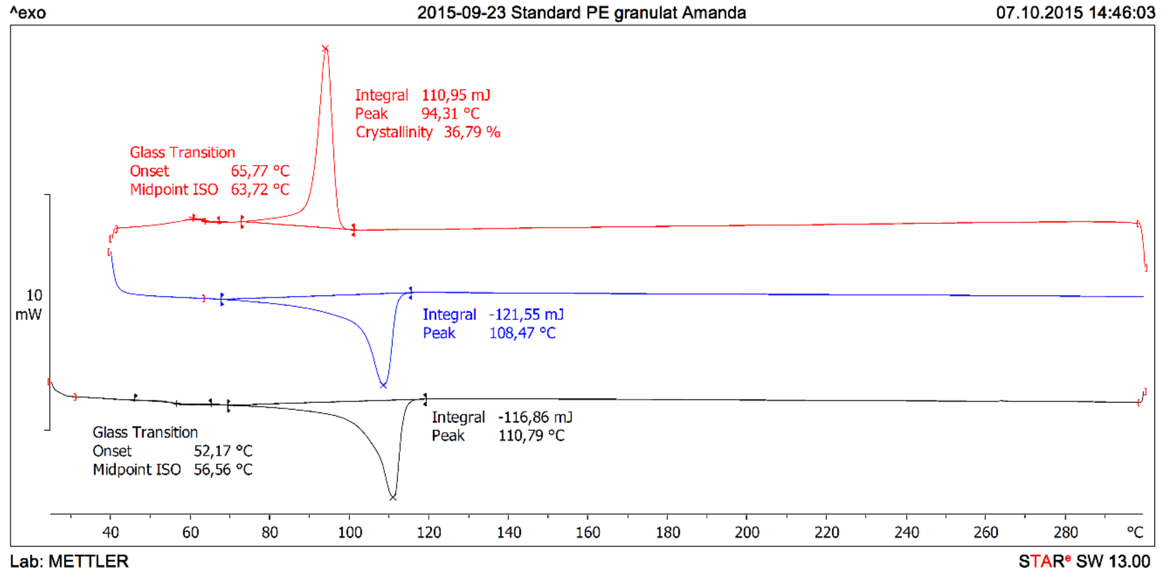

Figure 33. DSC plot for the conventional PE material granulates. The order of curves is Black, red and blue with a heating of 20°C/min.

A DSC plot was made for the delaminated material of Fibercote 50/25 and compared with non-delaminated standard material.

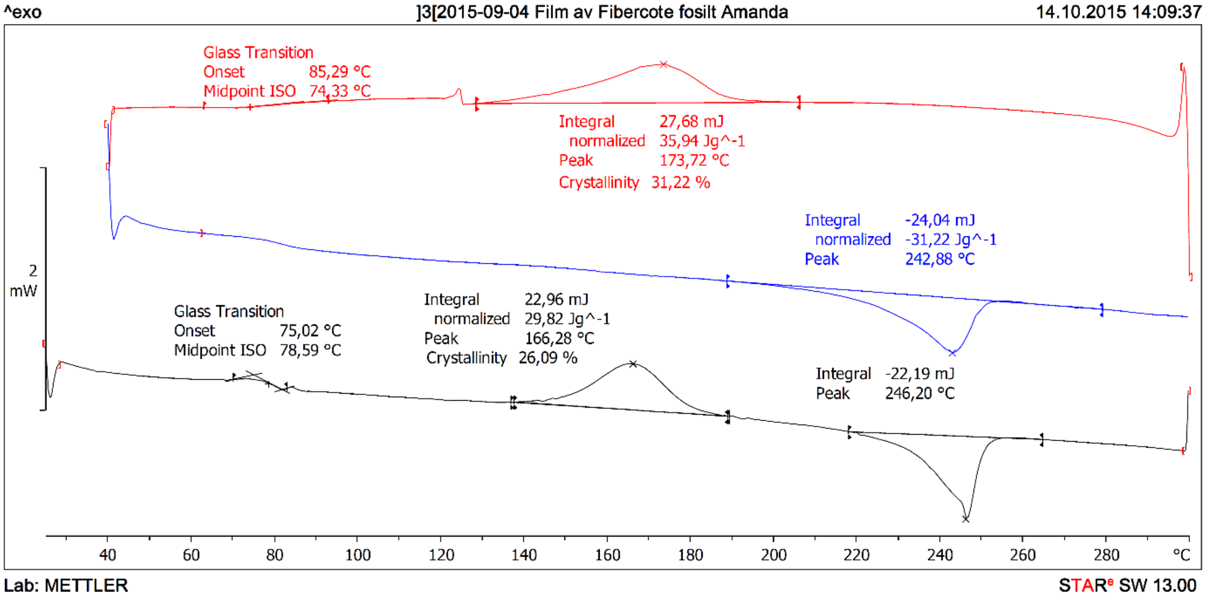

Figure 34. DSC plot for the fossil laminate of Fibercote 50/25. Full crystallization in the cooling curve.

In this case the material did not degrade or show tendency to not crystalize in the cooling curve.

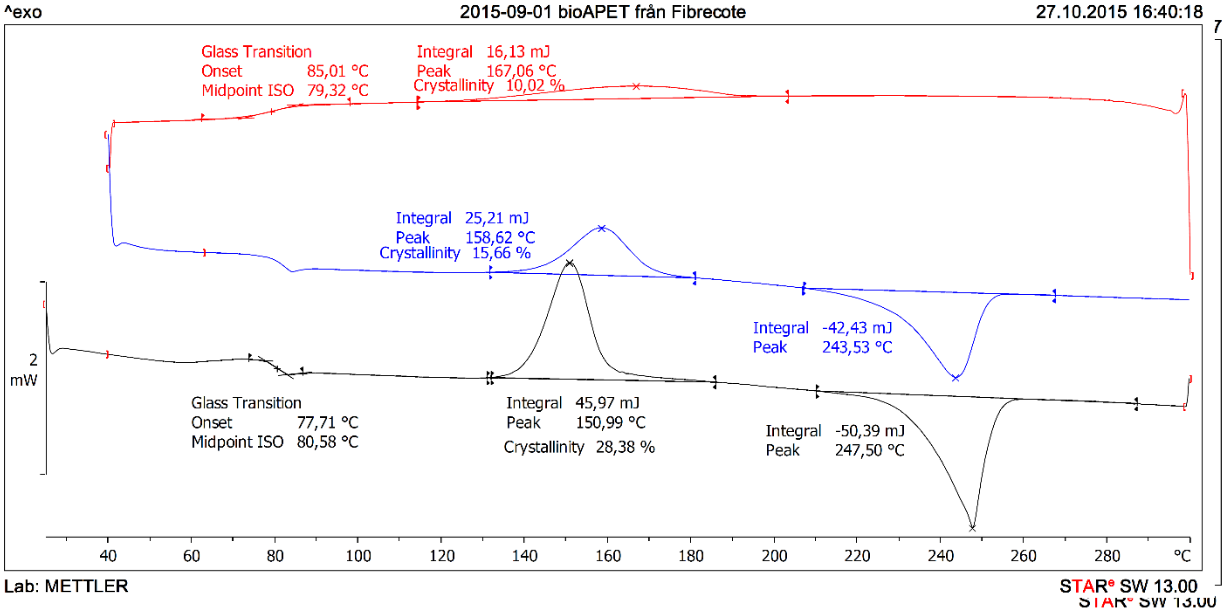

Figure 35. DSC plot of the delaminated PET sheet from Fibercote 50/25 after lane brake. Recrystallization in the second heating cycle all material did not crystalize over the cooling. Otherwise no evident difference.

Presented in Figure 35 the delaminated Globio sheet follows the same pattern as the conventional laminate from Figure 34 but instead of crystallizing in the cooling curve the material have a large pre-crystallizing peak right before the melting peak in the second heating curve.

Figure 36 show the graph over a DSC scan for the laminated HiLite 390/40 material with the conventional raw material. At sight it does not differ remarkably more than by a few degrees on some temperatures to HiLite 390/40 Bio presented in Figure 37. The fossil material as seen in previous figures has a bit sharper peaks but in this result it is not as distinct as in the other examples.

In the first (black) melting peak in the conventional material plot there is a separation of the PE peak resulting in two melting temperatures. This could be due to an inefficient cooling inducing a curing time on the material. This effect is not noticed for the bio-material.

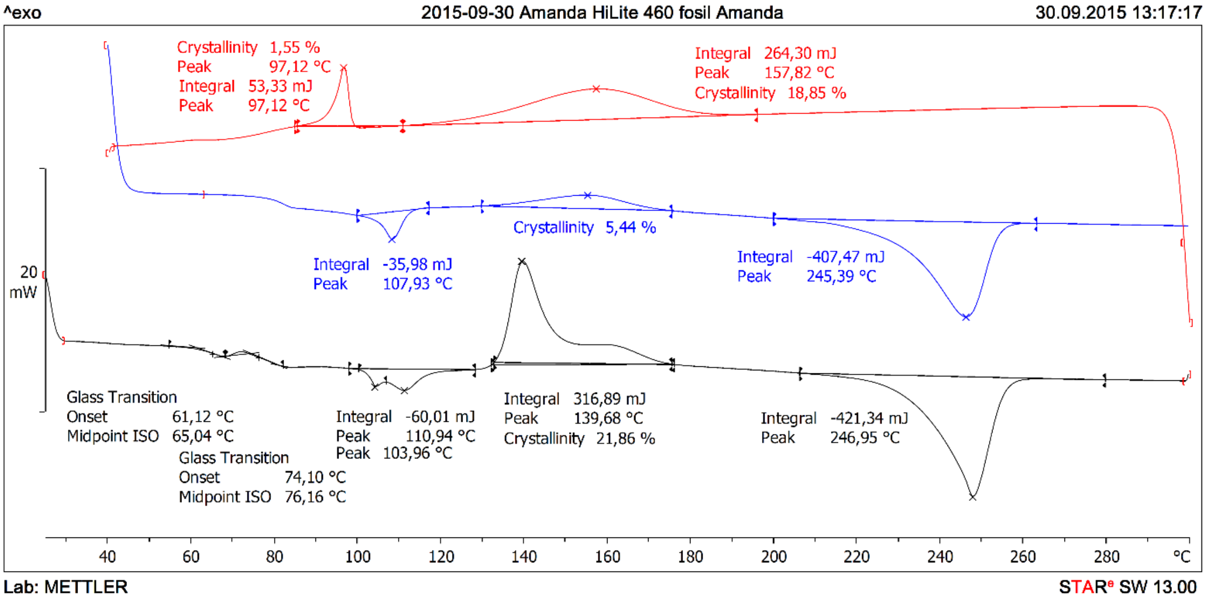

Figure 36. DSC plot for the conventional HiLite 390/40 material

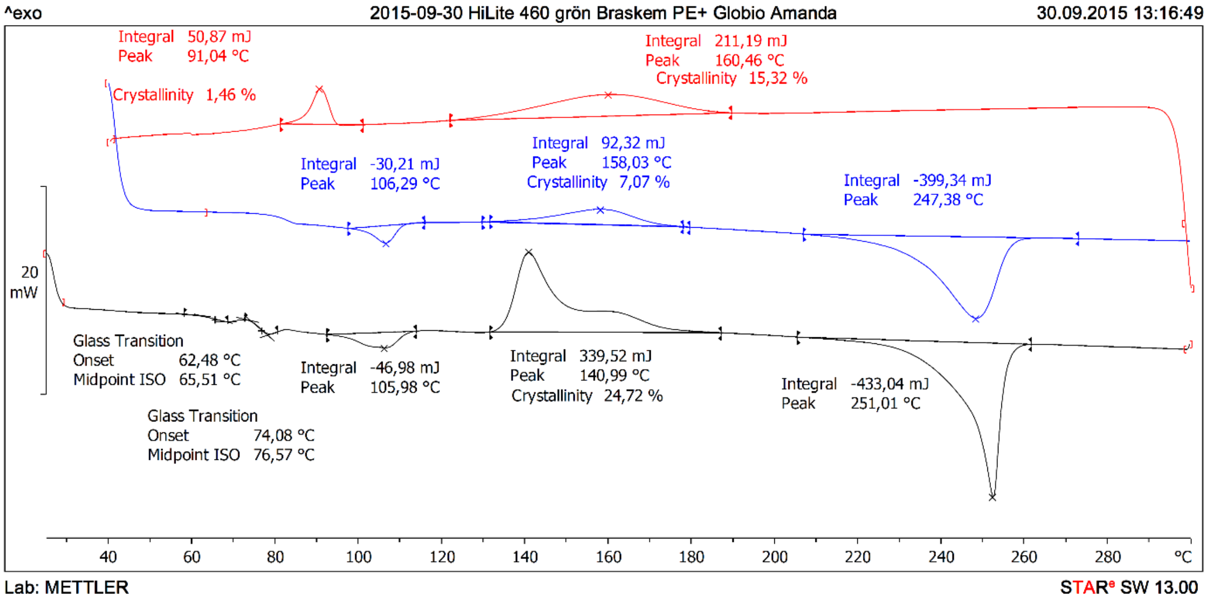

Figure 37. DSC plot for HiLite 390/40 Bio.

6 Discussion

Both materials do show extensive lowering of IV in respect to their starting material but the biomaterial is on the edge of not being quality approved. This limit, set by Flextrus, is at 0.720 and the mean IV for Bio-HiLite 390/40 is just below that figure. Even so, the quality tests performed after production showed approved values which could indicate that some migration of the undried content mistakenly added in the funnel during the set time for the APET casting therefore adding some of the undried material to the extruder before the assumed injection. To further develop this conclusion material further into the produced material would be needed. This material is now coated with PE and therefor further IV-tests are not possible due to the immiscible character of the two plastics. The results from this can there for only be speculative and further production with substantial control of the drying silo with corresponding IV-tests will be needed before we conclude that the bio-material has a larger tendency to degrade during process. Chemically this should not be the case.

Regarding the COF results the difference should not be process related. The friction of APET is normally too great for flexible packaging applications without adding a slipping agent due to the smoothness of the surface. Since the laminates were produced in the same machine under the same properties it is more realistic that the difference is dependent on the qualities them self. Possibly there is some additive in the quality of the Globio material that differ from the ones used in the Ramapet. This was also the suspicion of the supplier. Probably it is a co-polymer used to suppress the crystallization rate that could be different in the two qualities. An NMR-analysis of the two qualities would be interesting to see if there is any peaks not corresponding to the PET. If there was any peaks differing within the qualities a vaster conclusion of an additive difference could be drawn.

Since the friction is directly dependent on the coefficient this decrease would mean a decrease of 30 % for APET-APET friction and 20 % for APET-PE friction comparing with the conventional material. Since no difference could be proved in the case of PE-PE friction it is possible to guess that it in that case would be the PET raw material that differs. Friction of the material is tricky since it should not be too high but neither too low if the customer should be able to incorporate it in their production. Normally, when produced in larger quantity, the material is produced in another line why COF-tests of the material when produced under the thought circumstances would be needed further on. Then it would be possible to say if the lowering of friction coefficient would be an obstacle at customer production sites.

UV-VIS variance is more dependent on the material thickness profile which is further on depending on the processing. At 380 nm where the edges show a decrease in transmission could therefore hint a variating thickness profile in the edges of the produced biomaterial. This was not evident in the thickness measurements for HiLite 390/40. The variation could also relate to some background errors in the spectrometry measurement. Further tests is needed to make this clear.

In the IR-tests similarity by chemical groups were found as expected. Something induce a minimal difference in absorbance towards the bio-HiLite 390/40 which could indicate that there would be a small difference in some incorporated compound in the plastic. Might be an additive that is slowing down the crystallization in the bottle grade assumed by the supplier to be a part of the COF-results. However this difference is not there for the IR-ATR tests where the graphs for the bio materials at each side of the laminate is identical to the conventional. Chemically this is expected since the two plastics both are built up by identical chemical groups but regarding the different additions to the plastics added for processing purposes this should make a difference in an IR-measurement. The lower absorbance at some of the wavelengths is not large so it is probably not something that would affect the final product.

The OTR for Fibercote 50/25 showed a significant difference in the t-test performed on the stabilized values of transmission while it was not possible to prove any differences after stabilization for the HiLite 390/40 material. When performing the thickness profile test on the same samples used in the OTR experiment the results showed little difference on a μm scale for Hilite 390/40 while the Fibercote 50/25 difference was above twice as thick for the bio polymer layer. This would have an impact on the OTR measurements of the Fibercote 50/25 material.

Since the production of this material did not go by plan and it was hard to produce in the right speed. It is possible that this is the reason why the profile is thicker than the conventional material produced only hours before. Any material specific conclusions can therefore not be drawn by these results. The same analysis is valid for the WVP results. Probably the results are more related to the varying thickness caused by the lower speed in the production Bio-Fibercote 50/25 run.

This theory is confirmed when relating the OTR values to the thickness with help of the permeability coefficient. Still it would be wise to repeat this on a normal product than placing any truth in this results. Probably the decreased values of OTR for the bio material is only related to thickness.

The heat and relative humidity increase in the WVP analysis did for Fibercote 50/25 not show the same tenfold increase as for the HiLite 390/40. In the latter case, the PE-layer was placed towards the humid side in the experimental set up. The steady state value of the PE-layer would thus decide the concentration gradient over the PET-layer. For the Fibercote 50/25 the PET-layer was kept against the humid side. Since PE has a lower glass transition temperature, seen in 5.2.10 DSC, the increased chain vibrations would induce the mass transport of water vapor in larger extent at lower temperature than for PET. In HiLite 390/40, this might have increased the concentration gradient over the PET layer which could be the reason why this material is more sensitive to a temperature and humidity raise. This could be an indication why Fibercote 50/25, only including PET, does not show the same large increase in water vapor transport as HiLite 390/40 at raised parameters.

Why the production of Fibercote 50/25 did not go well enough to produce any material in the same class as the conventional one can only be speculated. No moisture tests were taken on the granulates at this test production but the IV results of the delaminated APET sheet, the sample collected after the lane break, at 0.65 indicate some degradation within the production. It could be an indication that the drying was insufficient which was also one of the suspicions in the later APET casting.

When trying to perform benchmarking IV-tests on the conventional Fibercote 50/25 with Ramapet N180 the IV dropped and the outgoing material threads were brittle and brown. The observations was connected to residual paper fibers by putting a small piece of the paper inside another IV-test gaining the same brittleness and brown feature. Even if the delaminated material coming out of the capillary viscometer was not showing these effects it is possible that a small amount of paper fibers was left on the delaminated material. If that would be the case the IV result would be influenced by those remaining fibers and thus give a wrong impression about the degree of degradation within the production.

In the sealing strength experiments it would be interesting to investigate a lower sealing temperature. The biomaterial sealed at 124°C in the sealing temperature experiment, 6°C under the target value. Investigating a lower sealing temperature could therefore vary the seal strength so it would be measurable before stretching the top-film out. The HiLite 390/40 however are above target value for both qualities.

Why the sealing temperature is 6°C lower than for the conventional material is difficult to see by looking at the results. The difference in melting temperature found in the DSC experiments is limited to 3 degrees. It is possible that the sealing temperature is in the interval of 124-130°C since there is 4-6°C between the welding points in the temperature analysis. The welding of a seal is also dependant on the heat transfer within the material since the seal, in this temperature is during 2 seconds and at 250 kPa it is possible that there is some difference in additive that allows more heat through the material and thus allow sealing at lower temperatures. It would be interesting to narrow the temperature interval between the welding points to try to lower the difference and see if it is similar to the melting point difference in the DSC-experiments. Further discussions with the supplier to try to get more information on the additives and their influence would also be of interest. A possibility to seal at lower temperatures are often positive since it limit the temperature used in production near the package containment.

Narrowing the temperature difference between the measuring points in the temperature seal test would also be interesting. Since everything seals above the lowest sealing temperature it is hard to say the exact when it differ 4°C between the different sealing points. The sealing strength results show one important quality: When sealing, the strength to open that seal is hard enough to either rip the paper in the Fibercote 50/25 material or to stretch out the top film used for analysis. This was not different between the materials. In the company interest this feature would ensure customer food and medical security from contaminations by packages open before usage in for example transportation.

As for the tendency to get statically charged the materials show significant difference in the Fibercote 50/25 case while an equality not could be discarded in the case of the HiLite 390/40 materials. These measurements varied a lot between the samples and it would be difficult to draw any conclusions further than that both materials and their different qualities show tendency to charge. If there would be a difference between the materials after processing the results are also contradicting. The Fibercote 50/25 samples show a higher resistivity for the bio material while for the HiLite 390/40 the results are reversed, reading the mean values gained by the data series. To see any trends a larger data collection would be needed. Since the materials were produced under the same properties in the same machine the production dependence of this tendency might be ruled out if it has nothing to do with the pre-treatment of the raw material which was the only differing factor except the shift of operational staff between the two HiLite 390/40 qualities.

The differential scanning calorimetry may be the most valid method to conclude if there is a significant difference between the materials that might be raw material-dependent since the thermal behavior of the polymer correspond to the chemical bonds in the repeating units. The scans look similar and only some of the crystallization temperatures are differing. When confronting the biomaterial suppliers about this difference the thought was that this might be additive dependent. What additives used by the producers are confidential but they use copolymers to suppress the crystallization process to achieve a clearer end product. This would be the reason why the PET does not crystallize in the cooling cycle but not before the next heating cycle when the polymer had more time to get ordered.

Some of the peaks are broader for the bio-PE raw material granulates is not influencing the production since the PE coating was the smooth part during the test production. Since the polymer structure of LDPE is dependent on pressure and temperature in the autoclave production it would be likely to assume that the broader peaks in the DSC diagram is due to a difference in polymer branching.

What can be concluded by the DSC results is that the qualities are mainly the same and the widths of the peaks do not differ greatly. This would indicate that with the right treatment they would behave the same in production and any differences seen in the materials tests would be related to additives, production or pre-treatment.

By the look of it, with some more investigation of the stability of the dryer oven it would be possible to state weather these materials are directly exchangeable. The question asked if that would be the case is if it is a valid investment in the corporation. The reason why those two specific products were chosen was of the assumed market interest. In Fibercote 50/25's case this was not validated during the project but because of its renewability properties in combination with a partly renewable plastic it is thought to be a package marketable with added value. It is also economically feasible to directly exchange the PET quality in this case. For HiLite 390/40 the interest was investigated from a customer perspective where the response was positive. It perform well in the carbon footprint analysis and is produced in a large variety and the possibilities to extend the production to other products and customers is therefore large. Since the amount of PET is large in the laminates the carbon dioxide reduction is lowered mainly to the lower emissions related to the raw material where the carbon sinks is involved in the figure. The carbon footprint evaluation is only a cradle to gate evaluation why this is harder to promote as a marketing aspect. The end customer is possible to grasp some aspects easier than others as when comparing environmental aspects and innovations related to a package. Also when regarding the packaged goods in the sector where Flextrus materials are used, the emissions related to the package is so low comparing the whole product system that it is hard to communicate the actual impact.

It is also important to consider the raise of the cost of HiLite 390/40 when using the new bio-produced qualities. An increase of 90 % must be taken into consideration and most likely this cost will be paid by the end customer. When considering a price raise of the consumer product it is even more important to figure out a way to communicate the added value of the new package as a nearly half as large carbon footprint. If communicated right and the material is considered for the right product a packaging cost of a few Swedish öre could be valid but should follow substantial customer evaluations.

A possibility in the PET case it is also possible that in a near future there will be a quality from 100 % renewable material produced and commercial. Already now investing and connect to interested customers with this 30 % biomass grade could be an advantage since it probably would be easier to in the future switch towards the fully bio-produced quality.

7 Conclusion and future work

The general conclusion drawn from the previous section is that a clear material difference, independent on processing properties, is difficult to see. Even though the materials where processed with the same parameters, limitations can have had impact on some of the results. Limitations were for example the difference in dryer function, method and size. Examples results where this could have had an impact are OTR/thickness profile for Fibercote 50/25, UV-VIS, COF and essentially IV. IV is indirectly connected to molecular weight. The lowering of IV after production of the APET sheet could therefore indicate a degradation during the production. This degradation process is, as mentioned in the background section 2.2.2 PET, induced by a low water content performing a chain scission when reacting with the terephthalate monomers' double bonded oxygens.

Fibercote 50/25 met some difficulties during production. Why is hard to tell. The material performs very well in renewability which could induce an added value while the gain in saved carbon emission annually is limited by the small amount of plastic incorporated. A customer survey to reveal the real demand for this product, and further test productions to investigate if it really is process able, is interesting future work.

A survey of market interest would also be valid to perform for HiLite 390/40. When it comes to performance, the most important aspect would be looking further into if there is a degradation issue. The economics should also be further investigated and negotiated. If these products would gain interest on the market it would also be interesting to look into the possibilities to create a top film with a higher degree of renewable material. Finding new special components delivering the same barrier properties. This would improve the total environmental performance on the full package.

Over all it would be important to perform larger data sets on all the experiments done in this report to support the speculative aspects and assumptions drawn by these results. Based on this study there is no evident difference between the materials and they should perform basically the same in the production at Flextrus.

8 Bibliography

[1] T. Iwata, “Biodegradable and Bio-Based Polymers : Future Prospects of Eco-Friendly Plastics,” *Angew. Chemie Int. Ed.*, vol. 54, no. 11, pp. 3210–3215, 2015.

[2] J. A. C. E. I. W. S. Rahimifard, “A Holistic Approach to Design Support for Bio-polymer Based Packaging,” *J. Polym. Environ.*, vol. 20, no. 4, pp. 1112–1123, 2012.

[3] L. Fitzpatrick, K. Verghese, and H. Lewis, *Packaging for Sustainability*. Springer Science & Buissuness media, 2012.

[4] H. Williams, “Food Packaging for Sustainable Development Food Packaging for Sustainable Development,” Karlstad Universty Studies, 2011.

[5] M. Wallman and K. Nilsson, “Klimatpåverkan och energianvändning från livsmedelsförpackningar,” 2011.

[6] Plastics Europe, “PLastics - the facts 2014/2015,” 2015. [Online]. Available: http://issuu.com/plasticseuropeebook/docs/final_plastics_the_facts_2014_19122. [Accessed: 24-Jul-2015].

[7] D. Jeremic, “Polyethylene,” *Ullmann’s Encyclopedia of Industrial Chemistry*. Verlag GmbH & Co., pp. 1–41, 2012.

[8] L. Shen, E. Worrell, and M. Patel, “Present and future development in plastics from biomass,” *Biofuels, Bioprod. Biorefining*, vol. 4, no. 1, pp. 25–40, 2010.

[9] OECD, “Biobased Chemicals and Bioplastics,” *OECD Sceience, Technol. Ind. Policy Pap.*, vol. 17, pp. 21–25, 2014.

[10] H. Köpnick, M. Schmidt, W. Brügging, J. Rüter, and W. Kaminsky, “Polyesters,” *Ullmann’s Enncyclopedia of Industrial Chemistry*. pp. 623–646, 2012.

[11] S. Rebsdat and D. Mayer, “Ethylene Glycol,” *Ullmann’s Encyclopedia of Industrial Chemistry*. pp. 531–544, 2012.

[12] Z. (Linde E. D. Hienz and W. (Linde engineering D. Roland, “Ethylene,” *Ullmann’s Encyclopedia of Industrial Chemistry*. Wiley-VCH Verlag GmbH & Co. KGaA, pp. 547–572, 2012.

[13] K. M. Sundaram, M. M. Shreehan, and E. F. Olszewski, “Ethylene,” in *Kirk-Othmer Encyclopedia of Chemical Technology*, John Wiley & Sons, Inc., 2000, pp. 1–39.

[14] Y. Kikuchi, M. Hirao, K. Narita, E. Sugiyama, S. Oliveira, S. Chapman, M. M. Arakaki, and C. M. Cappra, “Environmental Performance of Biomass-Derived Chemical Production : A Case Study on

Journal of Chemical Engineering of Japan , Advance Publication," *J. Chem. Eng. Japan*, vol. 46, no. 4, pp. 319–325, 2013.

[15] E. De Jong, A. Chemicals, P. Walsh, C. Gmit, M. Wellisch, and A. Canada, "Product developments in the bio-based chemicals arena†," *Biofuels, Bioprod. Biorefining*, vol. 6, no. 6, pp. 606–624, 2012.

[16] Braskem, "I'm Green - Life Cycle Assesment," 2015. [Online]. Available: http://www.braskem.com.br/site.aspx/Research-and-Development. [Accessed: 20-Jul-2015].

[17] C.-M. Park and R. J. Sheehan, "Phthalic acids and other benzenepolycarboxylic acids," *Kirk-Othmer Encyclopedia of Chemical Technology*. pp. 17–18, 2000.

[18] A. Soroudi and I. Jakubowicz, "Recycling of bioplastics , their blends and biocomposites : A review," *Eur. Polym. J.*, vol. 49, no. 10, pp. 2839–2858, 2013.

[19] K. Molen veld, M. van den Oever, and H. Bos, "Biobased Packaging Catalogue," 2015.

[20] Y. Tokiwa and B. P. Calabia, "Biodegradability and biodegradation of poly (lactide)," *Appl. Microbiolgy Biotechnol.*, vol. 72, no. 2, pp. 244–251, 2006.

[21] A. (nova-I. Florence and C. (nova-I. Mechael, "Bio-based Building Blocks and Polymers in the World," 2015.

[22] A. Lundgren and T. Hjertberg, "6 Ethylene from Renewable Resources," in *Surfactants from renewable resources*, M. Kjellin and I. Johansson, Eds. John Wiley & Sons, Inc., 2010, pp. 111–126.

[23] Coca-Cola, "Coca-Cola 2013/2014 Sustainability Report," 2014.

[24] Braskem, "Research and Development," 2015. [Online]. Available: http://www.braskem.com.br/site.aspx/Research-and-Development. [Accessed: 08-Jun-2015].

[25] C. Ludlow-palafox and H. A. Chase, "Microwave-Induced Pyrolysis of Plastic Wastes," *Ind. Eng. Res.*, vol. 40, no. 22, pp. 4749–4756, 2001.

[26] N. Lagerwall, *Data from PolymerFront AB*. 2014.

[27] FTI (Förpacknings och tidningsinsamlingen), "Återvinningsstatistik," 2014. [Online]. Available: http://www.ftiab.se/180.html. [Accessed: 24-Jun-2015].

[28] FTI (Förpacknings och tidningsinsamlingen), "En plastmolekyls livsresa." [Online]. Available: http://www.ftiab.se/download/18.3107745f13dfb3b423e1335/1367237276362/En+plastmolekyls+livsresa.pdf. [Accessed: 24-Jun-2015].

[29] L. Dahlén, "Återvinning av plast från hushållsavfall," 2009.

[30] M. Machiels, "Ampere newsletter," *Electr. Eng.*, no. 48, pp. 1–6, 2006.

[31] C. Ludlow-Palafox and H. A. Chase, "Microwave Induced Pyrolysis Reactorr and Method," US 7,951,270.

[32] Enval, "Enval's Beginnings." [Online]. Available: http://www.enval.com/history.php. [Accessed: 20-Jul-2015].

[33] Lunds renhållningsverk, "Vad händer sen? - om återvinning," 2009. [Online]. Available: http://www.lund.se/Global/F%C3%B6rvaltningar/Lunds renh%C3%A5llningsverk/Broschyrer/Sedanbroschyrww.pdf.

[34] TetraPak, "Plast och Aluminium." [Online]. Available: http://edit.tetrapak.com/se/miljo/atervinning/polyal. [Accessed: 11-Aug-2015].

[35] Fiskeby Board, "Hållbarhet en naturlig del i verksamheten." [Online]. Available: http://www.fiskeby.com/h%C3%A5llbarhet-en-naturlig-del-i-verksamheten-0. [Accessed: 11-Aug-2015].

[36] B. K. Verghese, H. Lewis, S. Lockrey, and H. Williams, "Packaging ' s Role in Minimizing Food Loss and Waste Across the Supply Chain," *Packag. Technol. Sci.*, vol. 28, no. 7, pp. 603–620, 2015.

[37] Z. Berk, "Food Packa," in *Food Process Engineering and Technology*, Elsevier inc., 2009, pp. 545–559.

[38] B. K. Grönman, R. Soukka, T. Järvi-kääriäinen, J. Katajajuuri, M. Kuisma, H. Koivupuro, M. Ollila, M. Pitkänen, O. Miettinen, F. Silvenius, R. Thun, H. Wessman, and L. Linnanen, "Framework for Sustainable Food Packaging Design," *Packag. Technol. Sci.*, vol. 26, no. 4, pp. 187–200, 2013.

[39] M. J. Franchetti and D. Apul, "Definitions of Carbon Footprint Analysis and Related Concepts 1.1," in *Carbon Footprint Analysis*, CRC Press, 2012, pp. 3–24.

[40] G. Bruntland, "Our common future, Chapter 2: Towards Sustainable Development," 1987.

[41] European Bioplastics, "Industrial Use of Agricultural Feedstocks," 2015.

[42] M. Carus and L. Dammer, "Food or Non-Food: Which Agricultural Feedstocks Are Best for Industrial Uses?," *Ind. Biotecnol.*, vol. 9, no. 4, pp. 171–176, 2013.

[43] M. Carus and A. Raschka, "Agricultural Resources for Bioplastics," *Bioplastics Mag.*, vol. 6, no. 6, pp. 44–46, 2011.

[44] J. Baffes and T. Haniotis, "Placing the 2006 / 08 Commodity Price Boom into Perspective," 2010.

[45] A. Müller, J. Weigelt, A. Götz, O. Schmidt, I. Alva, Lobos, I. Matuschke, U. Ehling, and T. Beringer, "The Role of Biomass in the Sustainable Development Goals : A Reality Check and Governance Implications," Postdam, 2015.

[46] A. Azapagic, “Assessing Environmental Sustainability : Life Cycle Thinking and Life Cycle Assessment,” in *Sustainable Development in Practice: Case Studies for Engineers and Scientists*, 2nd ed., 2011, pp. 56–80.

[47] C. Naden, “Greenhouse gas standard reaches voting stage,” *ISO News*, 2015. [Online]. Available: http://www.iso.org/iso/home/news_index/news_archive/news.htm?refid=Ref1643. [Accessed: 13-Aug-2015].

9 Appendix

9.1 IV

Table 25 present all raw data collected for the IV-measurements.

Table 25. All raw data collected in the IV-experiment.

Material	Sample ID	Iv at zero
Globio Fibercote delam	1	0,66
Globio Fibercote delam	2	0,64
Globio granulates	1	0,783
RAMAPET N180 granulates	1	0,79
Globio APET-set-up reel	1	0,733
Globio APET-set-up reel	2	0,736
Globio APET-set-up reel	3	error
Globio APET-product reel	1	0,721
Globio APET-product reel	2	0,723
Globio APET-product reel	3	0,714
RAMAPET N180 product-reel	1	0,737
RAMAPET N180 product-reel	2	0,732
RAMAPET N180 product-reel	3	0,739
Globio APET-product reel	left edge	0,722
Globio APET-product reel	left center	0,712
Globio APET-product reel	middle	0,714
Globio APET-product reel	right center	0,718
Globio APET-product reel	right edge	0,722
RAMAPET N180 product-reel	left edge	0,74
RAMAPET N180 product-reel	left center	0,744
RAMAPET N180 product-reel	middle	0,739
RAMAPET N180 product-reel	right center	0,745
RAMAPET N180 product-reel	right edge	0,743
	IV mean [η]	**standard deviation**
GLOBIO BCB80	0,724846154	0,009450275
Ramapet N180	0,7422	0,002588436
GLOBIO BCB80 including quality tests	0,7176	0,004560702
Ramapet N180 including quality tests	0,7422	0,002588436

9.2 Sealing strength

As in the IV-tests the sealing strength was only referred to with mean values in the results in Table 26 and Table 27 the raw data collected is presented.

Table 26. Raw data of Fibercote 50/25 sealing strength analysis.

Material	Seal direction	sample row	Position	Force
Fibercote Ramapet N180	CD	1	Left	20,76
Fibercote Ramapet N180	CD	1	Left	20,51
Fibercote Ramapet N180	CD	1	middle	16,73
Fibercote Ramapet N180	CD	1	middle	20,63
Fibercote Ramapet N180	CD	1	right	18,68
Fibercote Ramapet N180	CD	1	right	16,85
Fibercote Ramapet N180	CD	2	Left	20,27
Fibercote Ramapet N180	CD	2	Left	20,76
Fibercote Ramapet N180	CD	2	middle	20,73
Fibercote Ramapet N180	CD	2	middle	20,51
Fibercote Ramapet N180	CD	2	right	20,27
Fibercote Ramapet N180	CD	2	right	16,61
Fibercote Ramapet N180	CD	3	Left	20,39
Fibercote Ramapet N180	CD	3	middle	16,73
Fibercote Ramapet N180	CD	3	middle	14,46
Fibercote Ramapet N180	CD	3	right	20,39
Fibercote Ramapet N180	CD	3	right	20,27
Fibercote Globio	CD	1	Left	25,52
Fibercote Globio	CD	1	Left	24,42
Fibercote Globio	CD	1	middle	28,21
Fibercote Globio	CD	1	middle	21,61
Fibercote Globio	CD	1	right	24,3
Fibercote Globio	CD	1	right	22,59
Fibercote Globio	CD	2	Left	24,91
Fibercote Globio	CD	2	Left	26,62
Fibercote Globio	CD	2	middle	26,25
Fibercote Globio	CD	2	middle	22,59
Fibercote Globio	CD	2	right	26,86
Fibercote Globio	CD	2	right	23,08
Fibercote Globio	CD	3	Left	24,91
Fibercote Globio	CD	3	Left	24,66
Fibercote Globio	CD	3	middle	26,25

Fibercote Globio	CD	3	middle	24,18
Fibercote Globio	CD	3	right	24,66
Fibercote Globio	CD	3	right	22,22

Table 27. Raw data of HiLite 390/40 sealing strength analysis.

Material	Seal direction	sample row	Position	Force
HiLite conventional	CD	left	1	37,48
HiLite conventional	CD	middle	1	37,24
HiLite conventional	CD	right	1	37
HiLite conventional	CD	left	2	40,42
HiLite conventional	CD	middle	2	30,89
HiLite conventional	CD	right	2	36,26
HiLite conventional	CD	left	3	37,48
HiLite conventional	CD	middle	3	30,53
HiLite conventional	CD	right	3	35,53
HiLite Bio	CD	left	1	38,58
HiLite Bio	CD	middle	1	40,05
HiLite Bio	CD	right	1	40,05
HiLite Bio	CD	left	2	37,48
HiLite Bio	CD	middle	2	36,02
HiLite Bio	CD	right	2	36,26
HiLite Bio	CD	left	3	40,05
HiLite Bio	CD	middle	3	32,6
HiLite Bio	CD	right	3	37,97

9.3 Sealing temperature

In Table 28 the raw data for temperature evaluation of the Fibercote 50/25 qualities are presented. Why the MD have four sample rows are since there was two ways of folding to get this seal. Samples MD 3 was excluded since that folding of the laminate counted for broader part of the laminate. The Sample MD s4 is the one used in the report analysis.

Table 28. Fibercote 50/25 values of sealing temperatures for the different qualities.

Material	Direction	Position	Sample	Temperature at breaking seal
Fibercote GLOBIO	MD	left	1	112
Fibercote GLOBIO	MD	left	2	112
Fibercote GLOBIO	MD	left	3	124
Fibercote GLOBIO	MD	left	4	116
Fibercote GLOBIO	CD	left	1	124
Fibercote GLOBIO	CD	left	2	124
Fibercote GLOBIO	CD	left	3	124
Fibercote GLOBIO	MD	middle	1	116
Fibercote GLOBIO	MD	middle	2	116
Fibercote GLOBIO	MD	middle	3	124
Fibercote GLOBIO	MD	middle	4	124
Fibercote GLOBIO	CD	middle	1	124
Fibercote GLOBIO	CD	middle	2	124
Fibercote GLOBIO	CD	middle	3	124
Fibercote GLOBIO	MD	right	1	112
Fibercote GLOBIO	MD	right	2	116
Fibercote GLOBIO	MD	right	3	116
Fibercote GLOBIO	MD	right	4	116
Fibercote GLOBIO	CD	right	1	124
Fibercote GLOBIO	CD	right	2	124
Fibercote GLOBIO	CD	right	3	124
Fibercote RAMAPET	MD	left	1	116
Fibercote RAMAPET	MD	left	2	116
Fibercote RAMAPET	MD	left	3	124
Fibercote RAMAPET	MD	left	4	116
Fibercote RAMAPET	CD	left	1	124
Fibercote RAMAPET	CD	left	2	124
Fibercote RAMAPET	CD	left	3	116
Fibercote RAMAPET	MD	middle	1	116
Fibercote RAMAPET	MD	middle	2	124
Fibercote RAMAPET	MD	middle	3	116
Fibercote RAMAPET	MD	middle	4	116
Fibercote RAMAPET	CD	middle	1	124
Fibercote RAMAPET	CD	middle	2	124
Fibercote RAMAPET	CD	middle	3	124
Fibercote RAMAPET	MD	right	1	116
Fibercote RAMAPET	MD	right	2	116
Fibercote RAMAPET	MD	right	3	116

Fibercote RAMAPET	MD	right	4	116
Fibercote RAMAPET	CD	right	1	124
Fibercote RAMAPET	CD	right	2	116
Fibercote RAMAPET	CD	right	3	116

In Table 29 the corresponding values for HiLite is presented. Here the seal was made with a top wed and the above mentioned folding issue was not an obstacle.

Table 29. The HiLite 390/40 measurements of sealing temperature.

HiLite conventional	**MD**	**left**	**1**	**130**
HiLite conventional	MD	middle	1	130
HiLite conventional	MD	right	1	130
HiLite conventional	MD	left	2	130
HiLite conventional	MD	middle	2	130
HiLite conventional	MD	right	2	130
HiLite conventional	MD	left	3	130
HiLite conventional	MD	middle	3	130
HiLite conventional	MD	right	3	124
HiLite conventional	CD	left	1	130
HiLite conventional	CD	middle	1	130
HiLite conventional	CD	right	1	130
HiLite conventional	CD	left	2	124
HiLite conventional	CD	middle	2	130
HiLite conventional	CD	right	2	130
HiLite conventional	CD	left	3	130
HiLite conventional	CD	middle	3	130
HiLite conventional	CD	right	3	130
HiLite Bio	MD	left	1	124
HiLite Bio	MD	middle	1	124
HiLite Bio	MD	right	1	124
HiLite Bio	MD	left	2	124
HiLite Bio	MD	middle	2	124
HiLite Bio	MD	right	2	124
HiLite Bio	MD	left	3	124
HiLite Bio	MD	middle	3	124
HiLite Bio	MD	right	3	124
HiLite Bio	CD	left	1	124
HiLite Bio	CD	middle	1	124
HiLite Bio	CD	right	1	124
HiLite Bio	CD	left	2	124
HiLite Bio	CD	middle	2	130
HiLite Bio	CD	right	2	124
HiLite Bio	CD	left	3	124
HiLite Bio	CD	middle	3	124
HiLite Bio	CD	right	3	124

9.4 COF

The COF-values of the Fibercote 50/25 qualities are presented in Table 30. Both the dynamic and static friction coefficient is presented. Sample achieving static COF values >1 was excluded in this study why the whole series of Fibercote values is not in the report. Only the Out-Out measurements received static COF-values <1. Since the paper quality is the same in both laminates this series of data points were not relevant as results. The effect of COF-values >1 is measurement dependent since this method show difficulties to measure values if the material surface is too smooth.

Table 30. Fibercote 50/25 values of COF.

Material	Position	Side combination	Sample row	Friction type	COF
fibercote GLOBIO	left	In-in	1	static	>1
fibercote GLOBIO	middle	In-in	1	static	>1
fibercote GLOBIO	right	In-in	1	static	>1
fibercote GLOBIO	left	In-in	1	dynamic	>1
fibercote GLOBIO	middle	In-in	1	dynamic	>1
fibercote GLOBIO	right	In-in	1	dynamic	>1
fibercote GLOBIO	left	In-in	2	static	>1
fibercote GLOBIO	middle	In-in	2	static	>1
fibercote GLOBIO	right	In-in	2	static	>1
fibercote GLOBIO	left	In-in	2	dynamic	>1
fibercote GLOBIO	middle	In-in	2	dynamic	>1
fibercote GLOBIO	right	In-in	2	dynamic	>1
fibercote GLOBIO	left	out-out	3	static	0,363
fibercote GLOBIO	middle	out-out	3	static	0,372
fibercote GLOBIO	right	out-out	3	static	0,413
fibercote GLOBIO	left	out-out	3	dynamic	0,308
fibercote GLOBIO	middle	out-out	3	dynamic	0,333
fibercote GLOBIO	right	out-out	3	dynamic	0,335
fibercote GLOBIO	left	out-out	4	static	0,343
fibercote GLOBIO	middle	out-out	4	static	0,392
fibercote GLOBIO	right	out-out	4	static	0,409
fibercote GLOBIO	left	out-out	4	dynamic	0,37
fibercote GLOBIO	middle	out-out	4	dynamic	0,32
fibercote GLOBIO	right	out-out	4	dynamic	0,342
fibercote GLOBIO	left	in-out	5	static	>1
fibercote GLOBIO	middle	in-out	5	static	>1
fibercote GLOBIO	right	in-out	5	static	>1
fibercote GLOBIO	left	in-out	5	dynamic	0,959
fibercote GLOBIO	middle	in-out	5	dynamic	>1
fibercote GLOBIO	right	in-out	5	dynamic	>1
fibercote GLOBIO	left	in-out	6	static	>1

fibercote GLOBIO	middle	in-out	6	static	>1
fibercote GLOBIO	right	in-out	6	static	0,909
fibercote GLOBIO	left	in-out	6	dynamic	0,816
fibercote GLOBIO	middle	in-out	6	dynamic	0,972
fibercote GLOBIO	right	in-out	6	dynamic	0,609
Fibercote RAMAPET	left	In-in	1	static	>1
Fibercote RAMAPET	middle	in-in	1	static	>1
Fibercote RAMAPET	right	in-in	1	static	>1
Fibercote RAMAPET	left	in-in	1	dynamic	>1
Fibercote RAMAPET	middle	in-in	1	dynamic	>1
Fibercote RAMAPET	right	in-in	1	dynamic	>1
Fibercote RAMAPET	left	in-in	2	static	>1
Fibercote RAMAPET	middle	in-in	2	static	>1
Fibercote RAMAPET	right	in-in	2	static	>1
Fibercote RAMAPET	left	in-in	2	dynamic	>1
Fibercote RAMAPET	middle	in-in	2	dynamic	>1
Fibercote RAMAPET	right	in-in	2	dynamic	>1
Fibercote RAMAPET	left	out-out	3	static	0,392
Fibercote RAMAPET	middle	out-out	3	static	0,9
Fibercote RAMAPET	right	out-out	3	static	0,382
Fibercote RAMAPET	left	out-out	3	dynamic	0,335
Fibercote RAMAPET	middle	out-out	3	dynamic	0,33
Fibercote RAMAPET	right	out-out	3	dynamic	0,331
Fibercote RAMAPET	left	out-out	4	static	0,401
Fibercote RAMAPET	middle	out-out	4	static	0,411
Fibercote RAMAPET	right	out-out	4	static	0,386
Fibercote RAMAPET	left	out-out	4	dynamic	0,346
Fibercote RAMAPET	middle	out-out	4	dynamic	0,351
Fibercote RAMAPET	right	out-out	4	dynamic	0,338
Fibercote RAMAPET	left	in-out	5	static	>1
Fibercote RAMAPET	middle	in-out	5	static	>1
Fibercote RAMAPET	right	in-out	5	static	>1
Fibercote RAMAPET	left	in-out	5	dynamic	0,92
Fibercote RAMAPET	middle	in-out	5	dynamic	0,664
Fibercote RAMAPET	right	in-out	5	dynamic	0,881
Fibercote RAMAPET	left	in-out	6	static	>1
Fibercote RAMAPET	middle	in-out	6	static	>1
Fibercote RAMAPET	right	in-out	6	static	>1
Fibercote RAMAPET	left	in-out	6	dynamic	0,976
Fibercote RAMAPET	middle	in-out	6	dynamic	>1
Fibercote RAMAPET	right	in-out	6	dynamic	0,974

Only the dynamic COF was used in the study since the material is incorporated in moving lines at customer production this is the value of most interest. Still presented in table is all the measured values presented for the HiLite experiments. The samples giving rise to static values >1 was excluded from analysis. As example the static COF-value for HiLite Conventional APET-APET sample 1 right is >1 then the dynamic COF-value for that sample was excluded for further analysis.

Table 31. COF-values for the HiLite 390/40 qualities.

Material	Position	Side combination	Sample row	Friction type	COF-value
HiLite Bio	left	APET-APET	1	dynamic	0,2
HiLite Bio	left	APET-APET	2	dynamic	0,26
HiLite Bio	left	APET-APET	1	static	0,341
HiLite Bio	left	APET-APET	2	static	0,347
HiLite conventional	left	APET-APET	1	dynamic	0,4
HiLite conventional	left	APET-APET	2	dynamic	0,283
HiLite conventional	left	APET-APET	1	static	0,48
HiLite conventional	left	APET-APET	2	static	0,347
HiLite Bio	middle	APET-APET	1	dynamic	0,23
HiLite Bio	middle	APET-APET	2	dynamic	0,271
HiLite Bio	middle	APET-APET	1	static	0,299
HiLite Bio	middle	APET-APET	2	static	0,515
HiLite conventional	middle	APET-APET	1	dynamic	0,434
HiLite conventional	middle	APET-APET	2	dynamic	0,359
HiLite conventional	middle	APET-APET	1	static	0,511
HiLite conventional	middle	APET-APET	2	static	0,529
HiLite Bio	right	APET-APET	1	dynamic	0,271
HiLite Bio	right	APET-APET	2	dynamic	0,195
HiLite Bio	right	APET-APET	1	static	0,32
HiLite Bio	right	APET-APET	2	static	0,253
HiLite conventional	right	APET-APET	1	dynamic	0,806
HiLite conventional	right	APET-APET	2	dynamic	0,268
HiLite conventional	right	APET-APET	1	static	>1
HiLite conventional	right	APET-APET	2	static	0,401
HiLite conventional	left	APET-PE	1	dynamic	0,595
HiLite conventional	left	APET-PE	2	dynamic	0,505
HiLite Bio	left	APET-PE	1	dynamic	0,417
HiLite Bio	left	APET-PE	2	dynamic	0,435
HiLite conventional	left	APET-PE	1	static	0,699
HiLite conventional	left	APET-PE	2	static	0,602
HiLite Bio	left	APET-PE	1	static	0,49
HiLite Bio	left	APET-PE	2	static	0,542

HiLite Bio	left	APET-PE	1	static	0,49
HiLite conventional	middle	APET-PE	1	dynamic	0,491
HiLite conventional	middle	APET-PE	2	dynamic	0,519
HiLite Bio	middle	APET-PE	1	dynamic	0,382
HiLite Bio	middle	APET-PE	2	dynamic	0,399
HiLite conventional	middle	APET-PE	1	static	0,656
HiLite conventional	middle	APET-PE	2	static	0,613
HiLite Bio	middle	APET-PE	1	static	0,478
HiLite Bio	middle	APET-PE	2	static	0,488
HiLite conventional	right	APET-PE	1	dynamic	0,553
HiLite conventional	right	APET-PE	2	dynamic	0,616
HiLite Bio	right	APET-PE	1	dynamic	0,515
HiLite Bio	right	APET-PE	2	dynamic	0,505
HiLite conventional	right	APET-PE	1	static	0,633
HiLite conventional	right	APET-PE	2	static	0,696
HiLite Bio	right	APET-PE	1	static	0,671
HiLite Bio	right	APET-PE	2	static	0,613
HiLite Bio	left	PE-PE	1	dynamic	0,83
HiLite Bio	left	PE-PE	2	dynamic	0,676
HiLite Bio	left	PE-PE	1	static	>1
HiLite Bio	left	PE-PE	2	static	0,779
HiLite conventional	left	PE-PE	1	dynamic	0,482
HiLite conventional	left	PE-PE	2	dynamic	0,465
HiLite conventional	left	PE-PE	1	static	0,554
HiLite conventional	left	PE-PE	2	static	0,536
HiLite Bio	middle	PE-PE	1	dynamic	0,805
HiLite Bio	middle	PE-PE	2	dynamic	0,436
HiLite Bio	middle	PE-PE	1	static	0,941
HiLite Bio	middle	PE-PE	2	static	0,513
HiLite conventional	middle	PE-PE	2	dynamic	0,785
HiLite conventional	middle	PE-PE	1	dynamic	0,473
HiLite conventional	middle	PE-PE	1	static	0,566
HiLite conventional	middle	PE-PE	2	static	>1
HiLite Bio	right	PE-PE	1	dynamic	0,61
HiLite Bio	right	PE-PE	2	dynamic	0,83
HiLite Bio	right	PE-PE	1	static	0,716
HiLite Bio	right	PE-PE	2	static	0,6
HiLite conventional	right	PE-PE	1	dynamic	0,538
HiLite conventional	right	PE-PE	2	dynamic	0,597
HiLite conventional	right	PE-PE	1	static	0,588

HiLite conventional	right	PE-PE	2	static	0,727

9.5 Resistivity

In Table 32 the resistivity for static charging of the Fibercote laminate is presented in GΩ.

Table 32. Resistivity towards static charging of the Fibercote 50/25 qualities.

Material	Sample position	sample row	Resistivity gigaohm
Fibercote GLOBIO	Left	1	1,01E+07
Fibercote GLOBIO	Left	2	4,73E+06
Fibercote GLOBIO	Left	3	5,82E+06
Fibercote GLOBIO	Left	4	1,30E+06
Fibercote GLOBIO	Middle	1	9,28E+06
Fibercote GLOBIO	Middle	2	6,72E+07
Fibercote GLOBIO	Middle	3	4,21E+08
Fibercote GLOBIO	Middle	4	1,40E+07
Fibercote GLOBIO	Right	1	1,90E+09
Fibercote GLOBIO	Right	2	1,14E+07
Fibercote GLOBIO	Right	3	3,25E+06
Fibercote GLOBIO	Right	4	1,12E+07
Fibercote Ramapet N180	Left	1	1,64E+07
Fibercote Ramapet N180	Left	2	2,54E+07
Fibercote Ramapet N180	Left	3	3,06E+07
Fibercote Ramapet N180	Left	4	1,15E+07
Fibercote Ramapet N180	Middle	1	2,77E+06
Fibercote Ramapet N180	Middle	2	6,63E+06
Fibercote Ramapet N180	Middle	3	1,26E+07
Fibercote Ramapet N180	Middle	4	1,24E+08
Fibercote Ramapet N180	Right	1	2,33E+07
Fibercote Ramapet N180	Right	2	1,84E+06
Fibercote Ramapet N180	Right	3	2,30E+07
Fibercote Ramapet N180	Right	4	5,82E+08

The corresponding values for the HiLite 390/40 qualities are presented in Table 33 for both sides of the laminate.

Table 33. HiLite 390/40 test results for resistivity of both sides of the laminates.

Material	Sample Position	Sample row	Sample side	Resistivity [GΩ]
HiLite conventional	Left	1	APET	2,94E+07
HiLite conventional	Middle	1	APET	2,24E+08

HiLite conventional	Right	1	APET	7,73E+06
HiLite conventional	Left	2	APET	3,16E+07
HiLite conventional	Middle	2	APET	1,38E+07
HiLite conventional	Right	2	APET	2,60E+07
HiLite conventional	Left	3	APET	1,79E+07
HiLite conventional	Middle	3	APET	4,17E+07
HiLite conventional	Right	3	APET	2,02E+07
HiLite conventional	Left	4	APET	8,05E+07
HiLite conventional	Middle	4	APET	2,46E+07
HiLite conventional	Right	4	APET	3,11E+07
HiLite Bio	Left	1	APET	2,01E+06
HiLite Bio	Middle	1	APET	4,69E+06
HiLite Bio	Right	1	APET	7,43E+06
HiLite Bio	Left	2	APET	3,38E+06
HiLite Bio	Middle	2	APET	2,08E+06
HiLite Bio	Right	2	APET	1,78E+06
HiLite Bio	Left	3	APET	1,12E+08
HiLite Bio	Middle	3	APET	6,74E+06
HiLite Bio	Right	3	APET	1,50E+06
HiLite Bio	Left	4	APET	2,56E+06
HiLite Bio	Middle	4	APET	5,82E+06
HiLite Bio	Right	4	APET	2,14E+06
HiLite conventional	Left	1	PE	1,32E+07
HiLite conventional	Middle	1	PE	3,30E+07
HiLite conventional	Right	1	PE	6,65E+06
HiLite conventional	Left	2	PE	3,32E+07
HiLite conventional	Middle	2	PE	1,19E-09
HiLite conventional	Right	2	PE	3,57E+06
HiLite conventional	Left	3	PE	1,47E+07
HiLite conventional	Middle	3	PE	3,37E+07
HiLite conventional	Right	3	PE	2,74E+06
HiLite conventional	Left	4	PE	7,95E+06
HiLite conventional	Middle	4	PE	1,48E+07
HiLite conventional	Right	4	PE	3,11E+07
HiLite Bio	Left	1	PE	1,28E+06
HiLite Bio	Middle	1	PE	8,06E+04
HiLite Bio	Right	1	PE	8,91E+04
HiLite Bio	Left	2	PE	7,30E+04
HiLite Bio	Middle	2	PE	1,23E+05
HiLite Bio	Right	2	PE	1,19E+05
HiLite Bio	Left	3	PE	7,85E+04

HiLite Bio	Middle	3	PE	2,25E+05
HiLite Bio	Right	3	PE	2,28E+05
HiLite Bio	Left	4	PE	1,96E+05
HiLite Bio	Middle	4	PE	4,45E+05
HiLite Bio	Right	4	PE	1,36E+05

9.6 Permeability- OTR

Below in Table 34 Table 35 the values of oxygen transmission after stabilization are presented for Fibercote 50/25 respective HiLite 390/40.

Table 34. OTR values after steady state for Fbiercote qualities.

Material	Sample ID	cc/(24 h,sqm) - 100%ox
Fibercote GLOBIO	5	28,5
Fibercote GLOBIO	4	30,3
Fibercote GLOBIO	3	29,2
Fibercote GLOBIO	2	29,2
Fibercote GLOBIO	1	29,6
Fibercote Ramapet	1	46,5
Fibercote Ramapet	2	51,7
Fibercote Ramapet	3	54,9
Fibercote Ramapet	4	54,8
Fibercote Ramapet	5	53,8

Table 35. OTR values after steady state for HiLite 390/40 qualitites.

Material	**Sample ID**	**cc/(24 h,sqm) - 100%ox**
HiLite Bio	1	8,6
HiLite Bio	2	6,45
HiLite Bio	3	8,72
HiLite Bio	4	8,73
HiLite Bio	5	8,63
HiLite Conventional	5	8,42
HiLite Conventional	4	8,4
HiLite Conventional	3	8,5
HiLite Conventional	2	8,34
HiLite Conventional	1	8,56

9.7 Laminate thickness

In table the thickness of the samples used in the OTR measurements are presented.

Table 36. Fibercote 50/25 results of the thickness measured on the OTR samples.

Material	Sample ID	thickness
Fibercote GLOBIO	5	90
Fibercote GLOBIO	4	91
Fibercote GLOBIO	3	88
Fibercote GLOBIO	2	88
Fibercote GLOBIO	1	89
Fibercote Ramapet	5	63
Fibercote Ramapet	4	64
Fibercote Ramapet	3	62
Fibercote Ramapet	2	63
Fibercote Ramapet	1	66

Table 37. The results of thickness measurements on the HiLite 390/40 samples used in the OTR-experiments.

Material	Sample ID	thickness
HiLite Bio	1	434
HiLite Bio	2	437
HiLite Bio	3	425
HiLite Bio	4	430
HiLite Bio	5	437
HiLite Conventional	5	442
HiLite Conventional	4	442
HiLite Conventional	3	438
HiLite Conventional	2	445
HiLite Conventional	1	436

9.8 IR

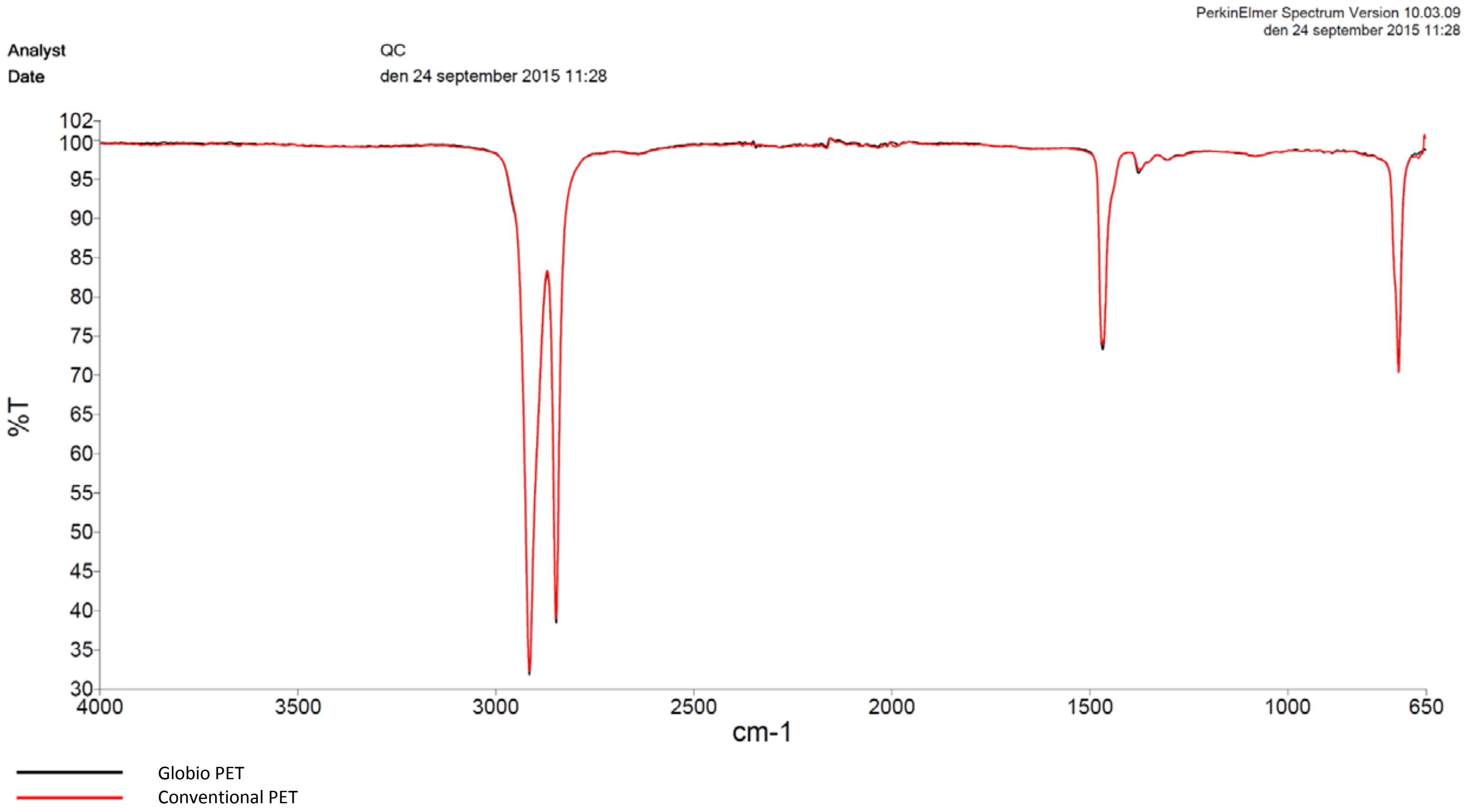

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Figure 38. Larger image of the ATR measurements of the PE side showing no molecular difference to the fossil material.

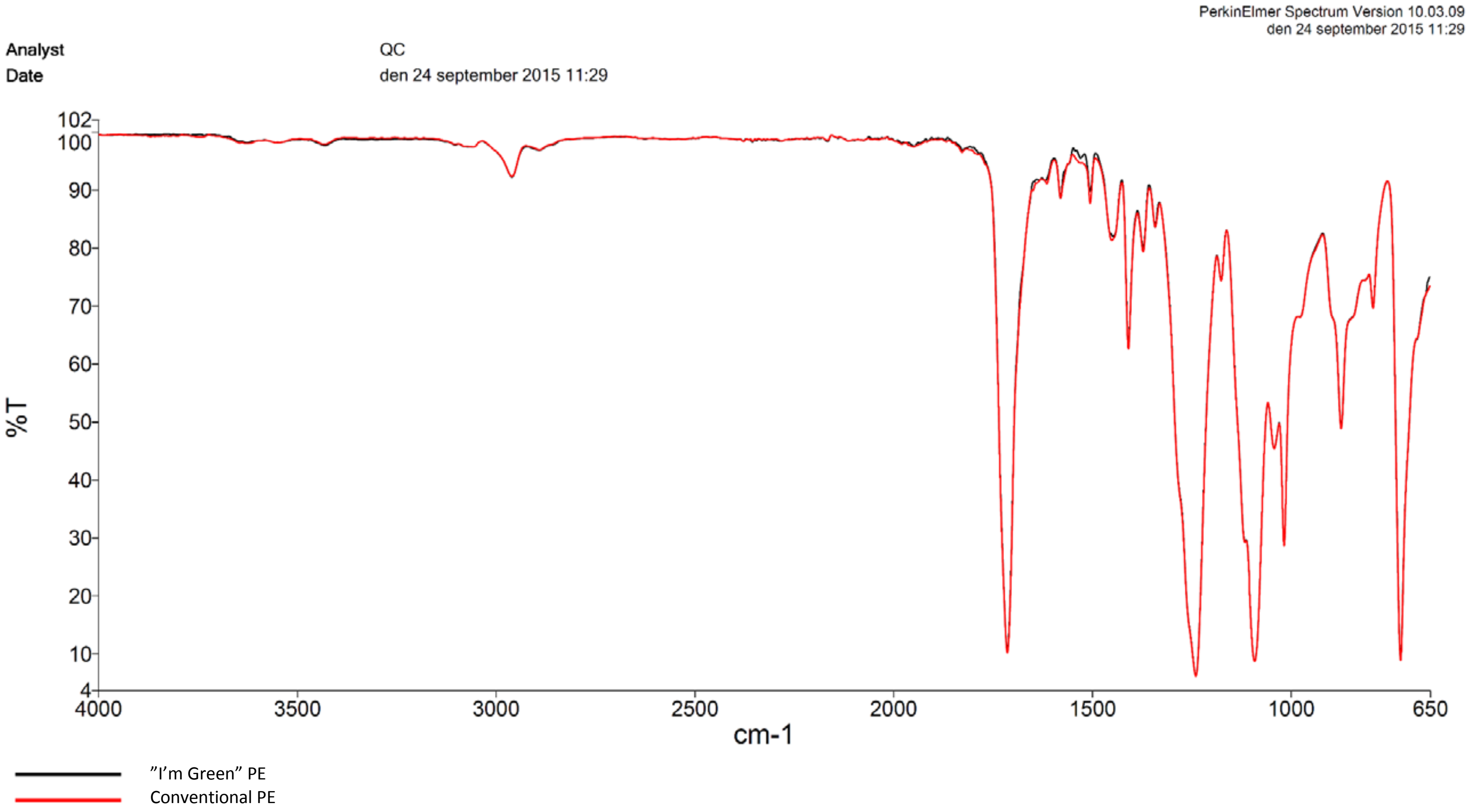

Figure 39. Larger image of the ATR measurements for the APET side of both the materials showing equal transmission in the infrared scan.

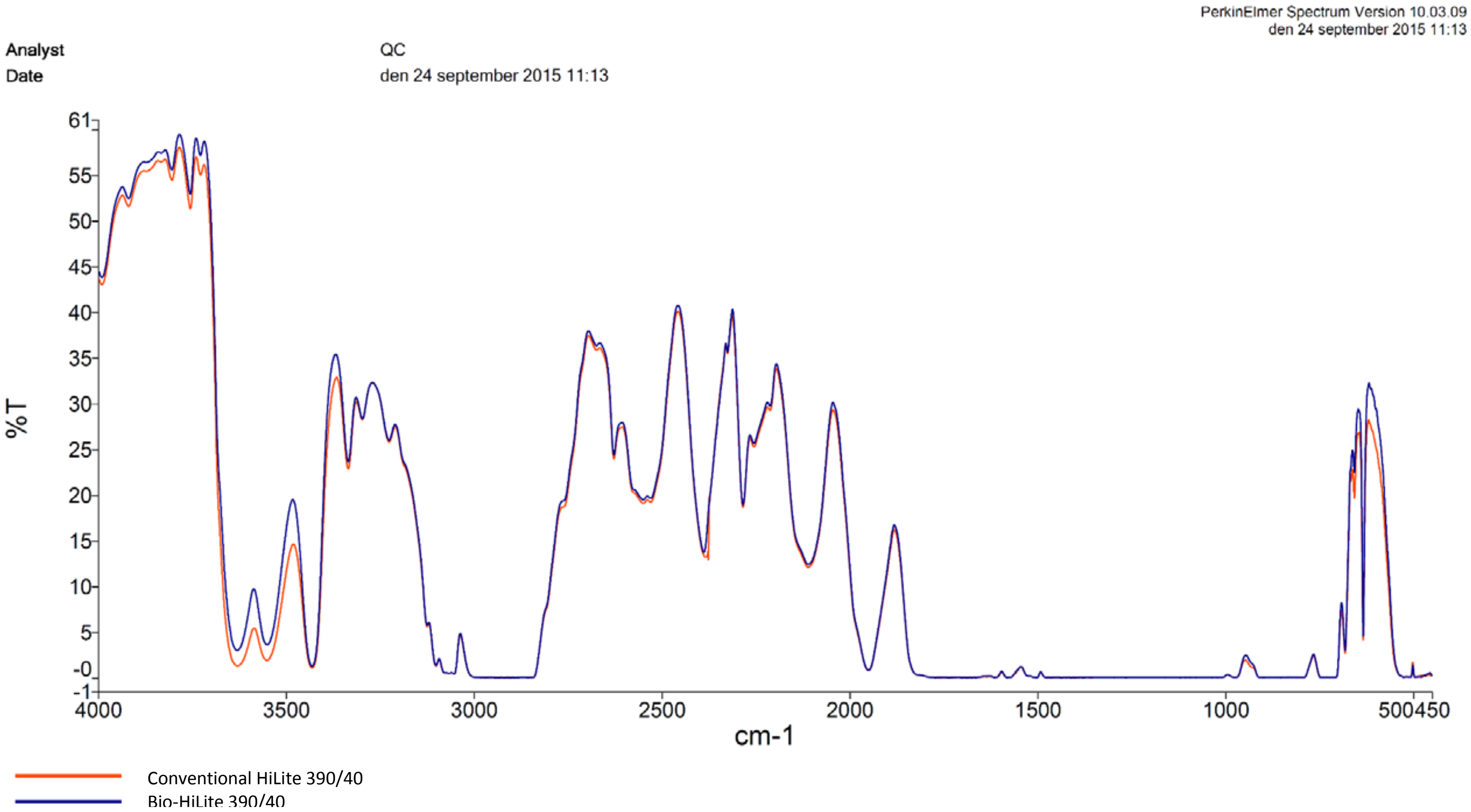

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Figure 40. Larger image of the FTIR for both the laminates. The Bio-HiLite 390/40 is marginally less absorbing at some of the absorption peaks.

9.9 UV-VIS

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