Biodegradable replacement for PVC (Polyvinyl Chloride) as a packaging material for skis

Bachelor thesis for Bachelor of Science in Mechanical Engineering

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Department of Industrial and Materials Science
Examiner / Supervisor: Giada Lo Re & Angelica Avella

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Preface

This bachelor thesis was written during the spring semester of 2022 at the Department of Industrial and Materials Science at Chalmers University of Technology.

First of all, we would like to give a huge thank you to Åre Skidfabrik for entrusting us with their search for a new packaging material. We would also like to give thanks to our examiner Giada Lo Re and our supervisor Angelica Avella for all the help and tutoring we have gotten during this semester.

Abbreviations

PVC	Polyvinyl Chloride
PE	Polyethylene
PP	Polypropylene
PBAT	Polybutylene adipate terephthalate
PLA	Polyactid acid
TPS	Thermoplastic starch
PBS	Polybutylene succinate
LCA	Life-cycle assessment

Abstract

On inquiry of Åre Skidfabrik a project was started to find alternatives to their current packaging material, PVC, for skis. Åre Skidfabrik strive to become more environmentally friendly and as a step in that direction all of their production materials are to be sourced from within Europe, the packaging plastic is the last material imported from outside Europe. The company wanted a biodegradable material with comparable properties to their current material and it would also be advantageous if the material is biobased. Alternative materials were found through literature study, interviews, and material testing. With the help of tensile tests, it was determined that PBATC1.6, TPS and PLA were possible replacements for the company but PBATC1.6 was later removed from the list because of the carbon footprint that was calculated.

1 Introduction

1.1 Background

Åre Skidfabrik AB is Sweden's largest ski manufacturer and during the last couple of years the company has focused a lot of their resources into reducing their climate footprint and creating a more sustainable production of skis. Åre Skidfabrik has managed to source all their materials they use in production from within Europe except for their packaging plastic. The company currently uses heat-shrinkable wrap made from PVC plastic to protect the skis from scratches and dust while being stored and during shipping. Not only is PVC considered environmentally harmful but the specific PVC the company uses is imported from China. This is something the company wishes to change as soon as possible. The company is searching for a replacement that is better for the environment and is open for any changes to the current process. If plastic is to be used again, they would strongly prefer biodegradable plastic and the use of a bio-based material is also an advantage. This thesis is written at the Department of Industrial and Materials science at Chalmers University of Technology.

1.2 Aim

The aim of this thesis is to find a more environmentally friendly solution to the packaging of skis at Åre Skidfabrik AB. This includes both the characteristics of the material used, and the climate footprint caused by transport from the material distributor. The characteristics that will be looked at are the potential biodegradability of the material and whether the source of the material is bio- or fossil-based

1.3 Limitations

Potential materials will be limited to biodegradable materials.
Due to lack of time the calculations of carbon footprint will be simplified.
This thesis project will focus on finding a theoretical potential material and will not include any testing by the company due to the location of the factory being so far away.
The cost of potential materials are estimated and only for the raw material at a weight of 100kg, if bought in bigger batches the price would likely decrease..

1.4 Research questions

RQ1: What is the current carbon footprint from the material the company uses today?
RQ2: What materials exist on the market that would better suit the company?

2 Theory

The following chapter is split into different sections that further describes parts of this thesis project. Areas that will be addressed in this chapter include an explanation of the packaging process at Åre Skidfabrik, what PVC is and how different materials have different carbon footprints.

2.1 Packaging process at Åre Skidfabrik

The company currently buys rolls of PVC from China that come in a sleeve shape. The skis are then inserted into the sleeve and the plastic is cut to the right length, after which the ends are sealed using heat. Then the skis are put on a conveyor belt that runs through an oven that is heated to 160 degrees Celsius. The heat from the oven shrinks the PVC so that it wraps tightly around the skis which then are ready to be packaged and sent out to stores.

2.2 Polyvinyl chloride

Polyvinyl chloride, more commonly known as PVC, is the third most produced plastic globally standing for 12% of the worlds plastic production and is only beaten by PE (polyethylene, 36%) and PP (polypropylene, 21%) [1]. PVC is part of the thermoplastic family which gives it the ability to be transformed into a molten state at elevated temperatures and later solidified when cooled. This property makes PVC and other thermoplastics easy to form into desirable shapes and forms. Because of the popularity PVC is produced heavily making it both accessible and cheap which makes it a great material to use in many different industries.

PVC is produced using vinyl chloride as a monomer which has been found to be cancerogenic resulting in huge risks during the manufacturing phase and disposal of the material [2]. Along with chlorine PVC also uses plasticizers and additives such as phthalates and metals. These additives and materials are released into the environment when disposed of at landfills or incineration centres, this creates dangerous compounds such as chlorinated dioxins and hydrochloric acid that are hazardous for humans [3]. Some phthalates, the plasticizer used in PVC, have been banned for use in EU and those that have not been banned are still considered to be a health risk [4].

Although PVC is fully recyclable, which drastically decreases the carbon footprint of the material, data show that the recycling rate of PVC in the Nordic countries is low compared to the rest of Europe. Official reports from Denmark state that their recycling rate of PVC is between 10 to 13% and according to “Overview of polyvinyl chloride (PVC) waste management practices in the Nordic countries” the rest of the Nordic countries likely have a lower recycling rate. The remaining PVC that is not recycled is likely to end up on landfills or incinerated or be exported out of the Nordic countries [5].

2.3 Footprint of materials

The footprint that materials have on the environment is a result of several distinct factors where production and transportation usually is the largest contributors. The carbon footprint is more specifically the amount of CO_2 (carbon dioxide) emitted during a specific activity such as production or transportation.

The plastics industry has been growing steadily and according to "Growing environmental footprint of plastics driven by coal combustion" the carbon footprint of plastic production has doubled between 1995 and 2015 and was then causing 4.5% of the global greenhouse gas emissions, this number has likely increased since 2015 [6].

Embodied energy is also often considered when talking about the footprint of a material. This is the total amount of energy associated with the production of a material and includes the energy used from the beginning of the process to the very end. From the extraction of raw material all the way to when the material is produced. Embodied energy is important to include in footprint calculations because it gives a better picture of the footprint prior to the actual production of the material.

End of life is another expression that describes what happens to the material after it has been used. As mentioned in the sub-chapter above, even though PVC is fully recyclable that is most commonly not the result for its end of life and instead it ends up in landfills or incineration. This also contributes to the footprint of the material due to the effects named previously that PVC has when it is disposed of. The European union has begun a project to decrease the amount of waste that is produced and end up in landfills or incineration facilities. This project defines a hierarchy of what options there are for waste and which ones are preferred and is presented in the figure below. (Figure 1) Biodegradation of a material is considered to be the same level as recycling in this case.

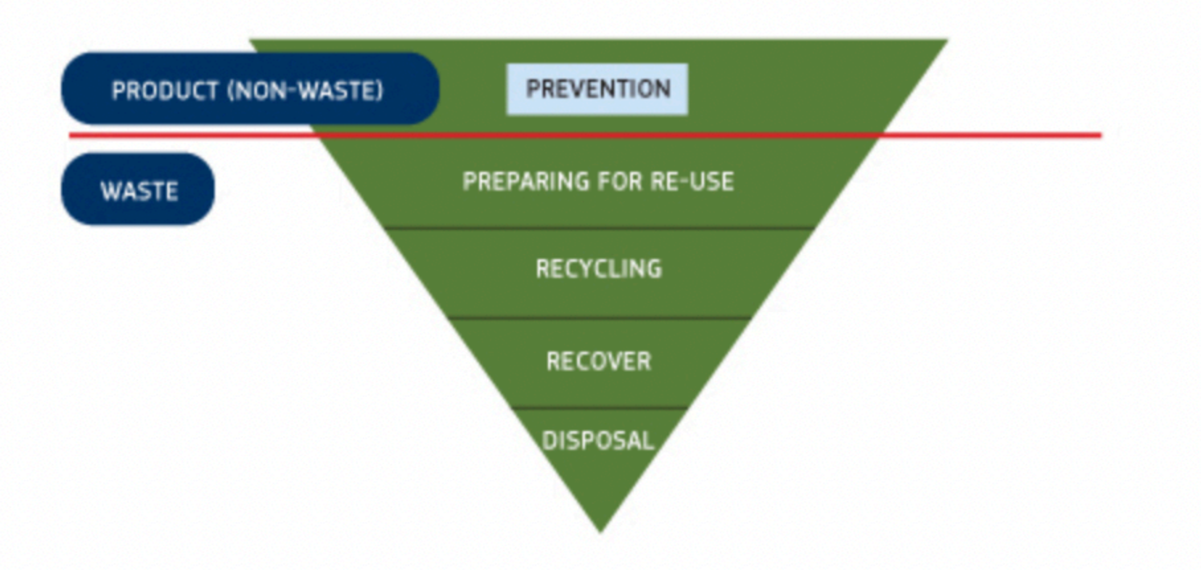

Figure 1, Waste hierarchy [7]

2.4 Biodegradable and Biobased

There is a big misconception that biodegradable and biobased are synonyms although they are actual two vastly different things. A plastic that is biobased does not necessarily mean that it is biodegradable, an example of this are major plastics such as PET and PE. A figure (Figure 2) published by The Nordic bioplastic organization in their article "Bioplastics, it's a better choice" gives a good understanding of the differences.

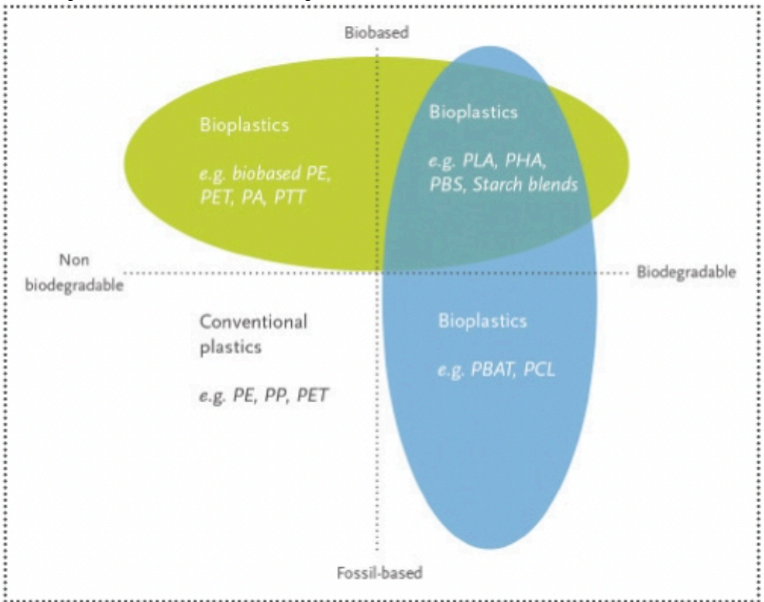

Figure 2, Biodegradable / Biobased [8]

For a plastic to be considered biodegradable it requires to be able to be fully degrade by micro-organisms with or without the use of oxygen. A biodegradable plastic is considered compostable when it is degraded within a specific timeframe, in Europe this timeframe is determined by the European standard EN 13432.

Biobased plastics on the other hand needs to be produced fully by biological resources, examples of these are natural biopolymers such as cellulose or starch, fermentation to create monomers or using bioethanol/methanol in the same way as fossil-based plastics [8].

Bioplastics is the common term for a plastic to be biodegradable, biobased or both.

3 Method

3.1 Literature study

Finding appropriate literature articles about bio-degradable plastics, heatshrink wraps and other relevant subjects helped to further understand the problem the company was having and how to combat and solve it. The literature study was also conducted to see if there are any other companies and or thesis regarding similar problems with packaging materials. This study also gathered information on why the currently used plastic is bad for the environment.

3.2 Interviews with the company

During the thesis interviews has been done with the company to help assess the company's needs and goals with the new material. It was also a chance to get a better understanding of what parameters that the company thought was important for the new material. The interviews also gave more information about how the company's current solution looks and what the current process looks like. Some examples of information given by the company through interviews were pricing of the used material, origin of the material but also certain wishes and demands for the new material from the company.

3.3 Material selection

The materials found in the literature study was further studied in the computer software Granta EduPack. This supplied the thesis group with material properties such as Young Modulus, Elongation at break, density, and cost for some of the materials. Information not found through Granta EduPack was found through the literature study or interviews.
The results from the material research immediately addressed the research question RQ2 but also helped when assessing the carbon footprint of the current material used by the company.

3.4 Material testing

The tests were performed at the department of Industrial and Materials Science at Johanneberg. A sample of the PVC that the company currently use was sent to be tested, while the other potential replacement materials already existed at the department. The PVC that the company uses is made using an extrusion film blowing process, therefore the PVC was divided into two different versions by cutting the sample with the direction of the blow moulding process (PVC-L) and against the direction (PVC-T) to see if there is any difference in parameters. The materials at the department were shaped into squared films of around 1 mm thickness using a compression moulder Buscher-Guyer KHL 100 at 120 °C for 3 min at 40 bar and 1 min at 500 bar, followed by quenching to room temperature under pressure. The tensile tests were performed on Dumbbell's specimens cut from compression moulded flat sheet. 3-5 specimens were tested for each material, with a Zwick Z 2.5 Instron machine, with a load cell of 2 kN and 100 % strain rate. The software Zwick testXpert was used to record force and crosshead travel data. Tests were performed according to the standard ASTM D638-14 (Standard Test Method for Tensile Properties of Plastics).

3.5 Plotting of material data

The values that were received from the tensile tests were plotted using OriginPro. OriginPro is a software that is used to graph, analyse and interpret data. After plotting stress (MPa) and strain (%) graphs for the different plastics the values of Young's modulus (E) were calculated as the slope of the elastic region in the tensile curves. Ultimate tensile stress (UTS) was extracted as the highest value of stress. Strain (ε_f) at break were extracted as the coordinates of the breaking point and σ_y was extracted as the stress of the yield point. The figure shows how all the parameters are extracted from the graphs (Figure 3).

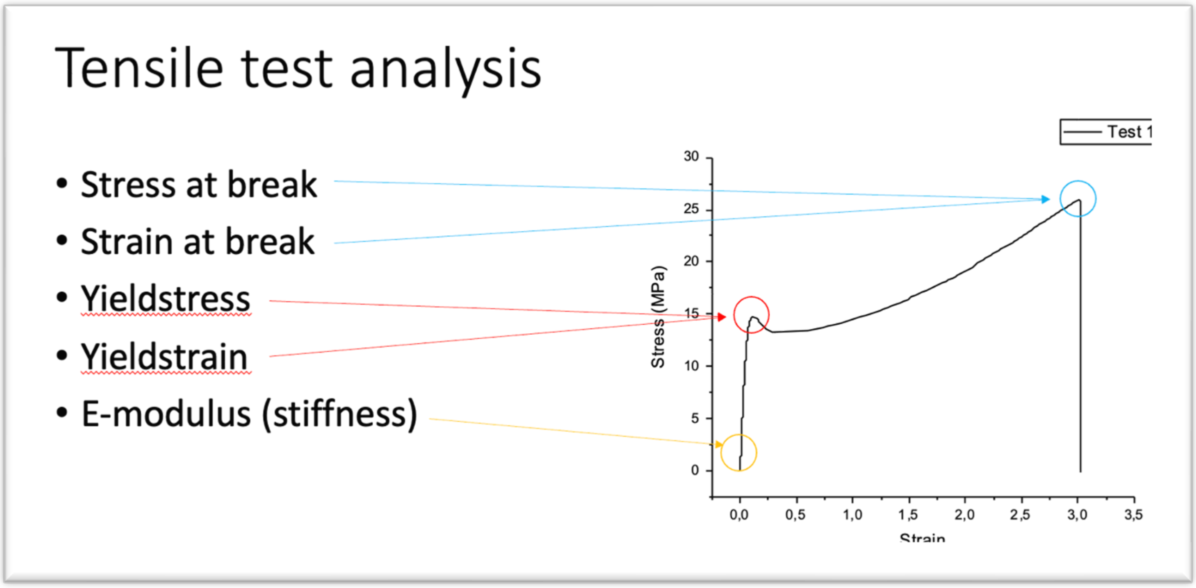

Figure 3, Values that was extracted from the graphs

To get a better picture of how the different materials will compare to each other a few Ashby graphs will be created. An Ashby graph is essentially a scatter graph that is useful for comparing different material properties in an easy to read way.

3.6 Calculation of carbon footprint

To answer RQ1 two methods were used. Granta EduPack was used to find the amount of kgCO_2/kg PVC produced. Another part of the carbon footprint comes from the fact that the PVC that the company currently uses is imported from China, to calculate the environmental impact from this transportation the DHL carbon calculator was used [9]. In this calculator two different transportation legs were inputted, one from Shanghai, China to Stockholm, Sweden by sea and one from Stockholm, Sweden to Åre, Sweden by road.

4 Results and discussion

4.1 Literature study

An article that gave a good ground on what materials that would be of interest to look at was "Packaging related properties of commercially available biopolymers" [10]. As potential alternatives to the neat polymers, in the case of PBAT (Polybutylene adipate terephthalate) two variants already produced at Chalmers were considered. One is PBAT1.6 which consists of PBAT melt crosslinked with 1.6 phr of peroxide. The second is PBATC1.6, which is PBAT + 13 vol% of pulp fibres melt crosslinked with 1.6 phr of peroxide. The crosslinking is a common method to increase the mechanical strength of materials while pulp fibres can increase the mechanical properties and improve the bio-based content of PBAT. Moreover, both PBAT alternatives are heat shrinkable. A table was then made with the most interesting materials from the article and the PBAT variants (Table 1). The table also includes the current packaging material used by the company (PVC).

Table 1, Potential materials

POTENTIAL MATERIALS
PVC (Currently used)
PLA (Polylactide)
TPS (Thermoplastic Starch)
PBAT
PBAT1.6
PBATC1.6
PBS (Polybutylene succinate)

PLA, TPS and PBS are all both biobased and biodegradable while the three PBAT variants are fossilbased but fully biodegradable. A demand from the company is that the new plastic needs to be biodegradable and therefore all the named materials above fit the criteria.

4.2 Study of materials

A closer study of materials was performed resulting in the properties cost and density of the potential materials displayed in the table below (Table 2). Most of the data of the cost were provided by the examiners through receipts and knowledge from previous purchases.
As stated above PBAT1.6 and PBATC1.6 are crosslinked variants of regular PBAT. PBATC1.6 has slightly lower density compared to regular PBAT and PBAT1.6 due to the 13wt.% of pulp and the density of pulp being 1.2g/cm^3 [11]. In this thesis the difference in density because of the peroxide is not considered, however the difference in price is.

Table 2, Potential materials with cost and density

POTENTIAL MATERIALS	COST kr/kg	DENSITY kg/m^3
PVC (Used currently)	50 [12]	1290-1460 [13]

PLA	22,3-28,4 [14]	1240 [10]
TPS	45.4 [15]	1500 [15]
PBAT	34.15 [15]	1250-1270 [10]
PBAT1.6	36.96 [15]	1250-1270 [10]
PBATC1.6	34.1 [15][16]	1243-1260 [10][11]
PBS	127 [15]	1240 [10]

In order to compare all the potential materials, it was important to have tensile properties for all materials. The best way to gather that data was decided to be by conducting tensile tests on the materials since the conditions would be the same for every material resulting in the most accurate data.
The parameters for all the different specimens that were extracted from all the OriginPro plots (Attachment 1-8) was noted in a table. Then calculations of the average parameters for each plastic were done (Table 3). The values of yieldpoint stress/strain for PBATC1.6 is N/A because the graphs did not display any value that was readable.

Table 3, Average properties for each plastic

Plastics	Yield Stress (MPa)	YieldStrain (%)	Stress at break (MPa)	Strain at break (%)	E-Modulus (GPa)
PVC-L	55.36	3.74	41.98	34.52	21.36
PVC-T	65.08	3.83	55.37	38.48	23.32
TPS	9.13	5.52	8.58	30.16	3.19
PLA	57.75	3.88	53.83	5.20	17.93
PBAT	7.87	34.91	13.12	676.08	0.63
PBAT1.6	8.22	33.69	14.90	207.19	0.54
PBATC1.6	N/A	N/A	10.17	40.39	1.10
PBS	13.53	19.80	23.58	1100.68	1.52

The values that were gathered from material selection and testing were then put into a few Ashby graphs with the help of Granta EduPack. The graphs that were considered to be the most important were: Density/Price (Figure 4), Density/Young modulus (Figure 5) and Density/Elongation (Figure 6). A fourth graph was also made (Figure 7) with Elongation/Density over Price to get a good overview of the materials.

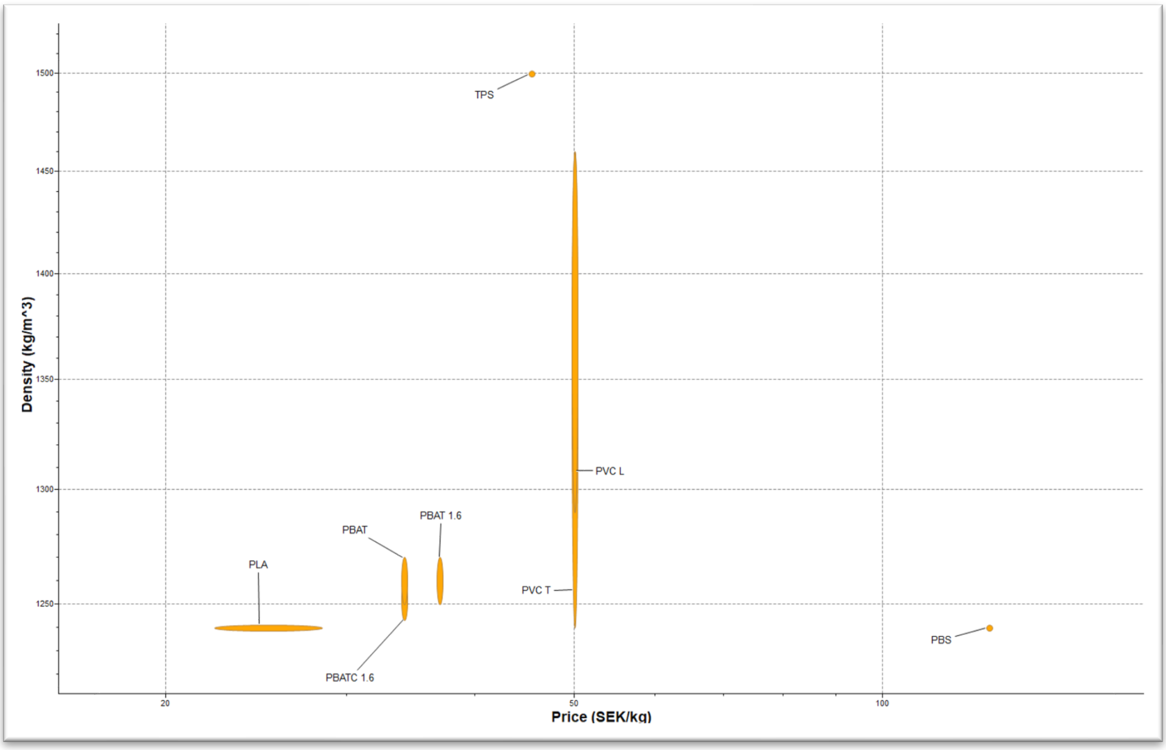

Figure 4, Ashby plot density over price

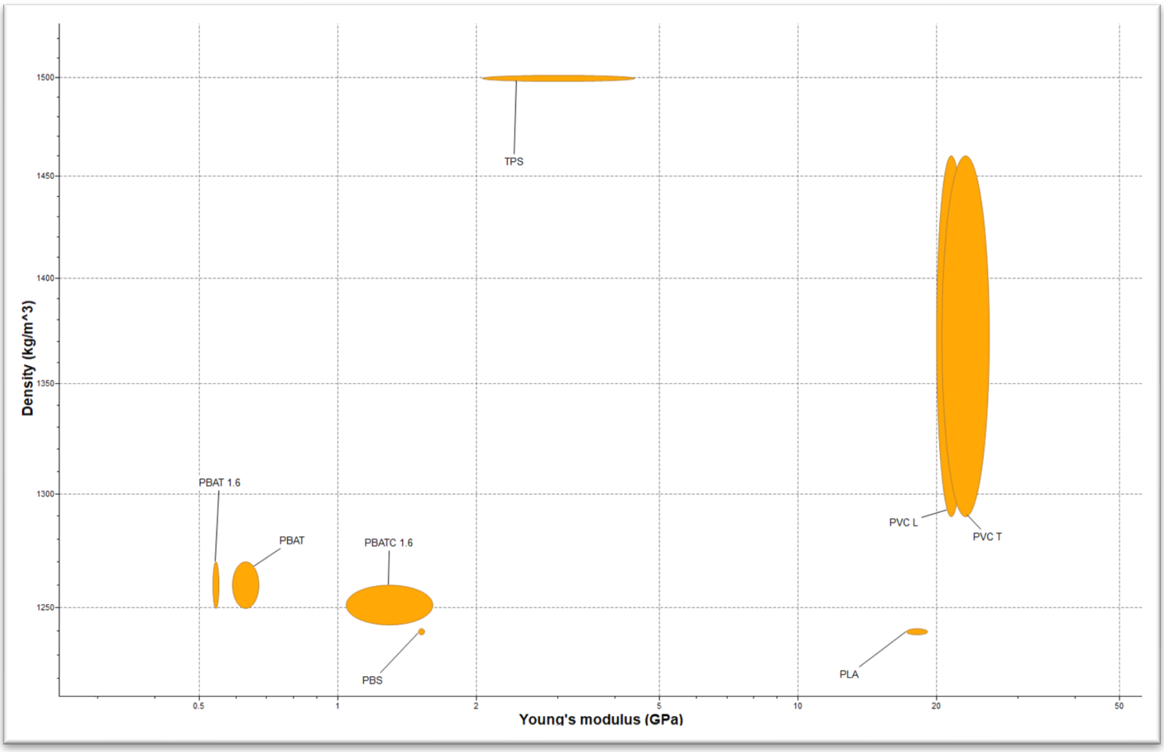

Figure 5, Ashby plot density over young modulus

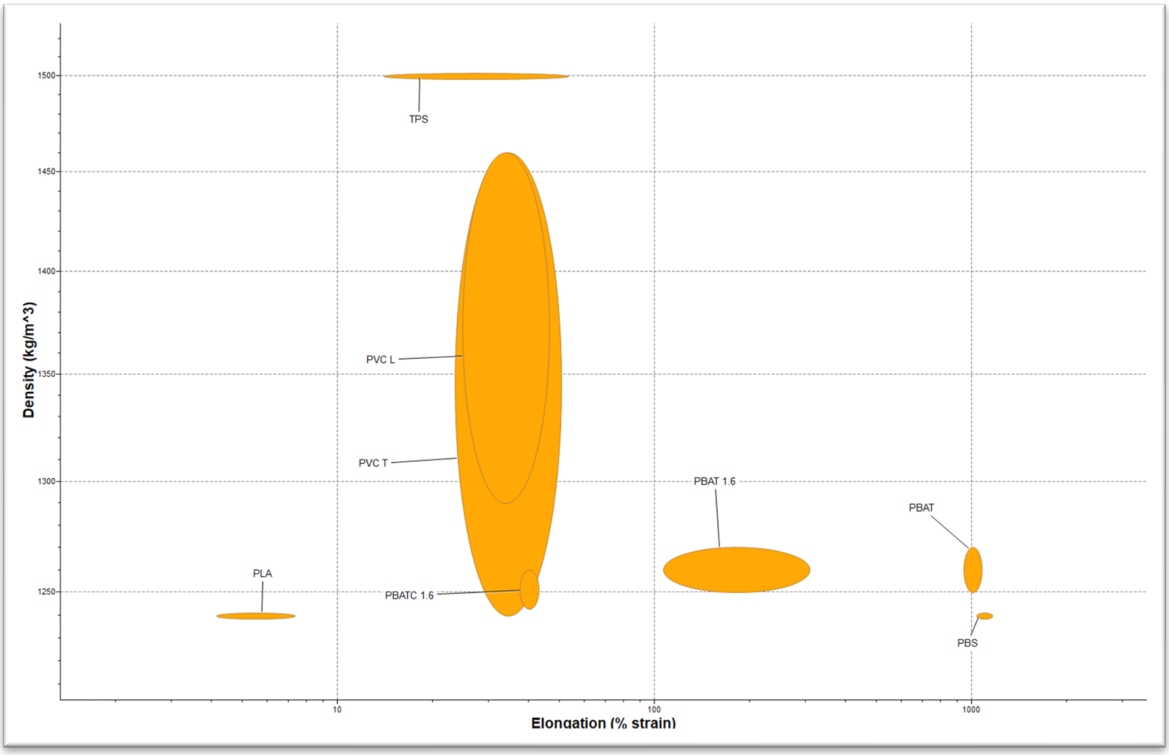

Figure 6, Ashby plot density over elongation

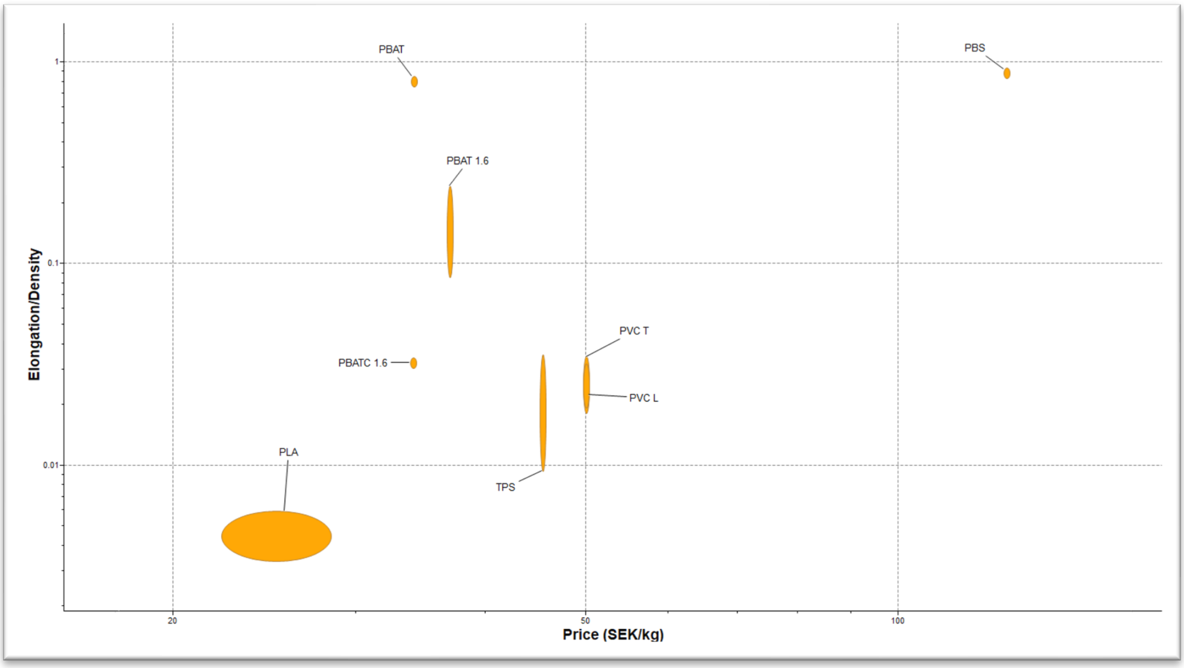

Figure 7, Ashby plot elongation/density over price

After some discussions with the Åre Skidfabrik, it is noticeably clear that material cost is a highly prioritised parameter. After that the company would like the elongation to be similar to the currently used material (PVC). This is because they want the distributors to be able to remove the plastic by hand to reduce the risk of damaging the skis.
When looking at the first Ashby graph (Figure 4) it is clear that PBS is far too expensive to be a viable alternative to PVC and is therefore no longer considered as a potential plastic.

Out of the three PBAT variants both PBAT1.6 and PBAT have a breakpoint strain over 100% which could lead to problems when manually removing the plastic from the ski. Meanwhile PBATC1.6 has more equivalent properties to PVC in both strain and is also the cheapest alternative of the PBAT variants. Because of this both PBAT1.6 and PBAT are also not to be considered as a potential plastic for this thesis project.
This leaves three potential materials, PLA, TPS and PBATC1.6 that all have reasonably comparable properties to PVC as shown in the figures (Figures 4-7). All of these materials are cheaper than PVC. Looking at elongation PBATC1.6 and TPS almost have the same properties as PVC while PLA is slight lower. Where the materials start to differ quite a lot from PVC is in the Young's modulusbut since the materials will not be enduring much stress when being used as packing material, it is not as important as the other properties.
From the last Ashby plot (Figure 7) it is easy to see that both TPS and PBATC1.6 have a similar elongation/density ratio to PVC while remaining cheaper. Although PLA is significantly cheaper than PVC, the material has a very low elongation/density ratio. Even though not all the properties of PLA match the standard of the PVC it will still remain as a potential material due to its very attractive price and similar stress (Figure 8).

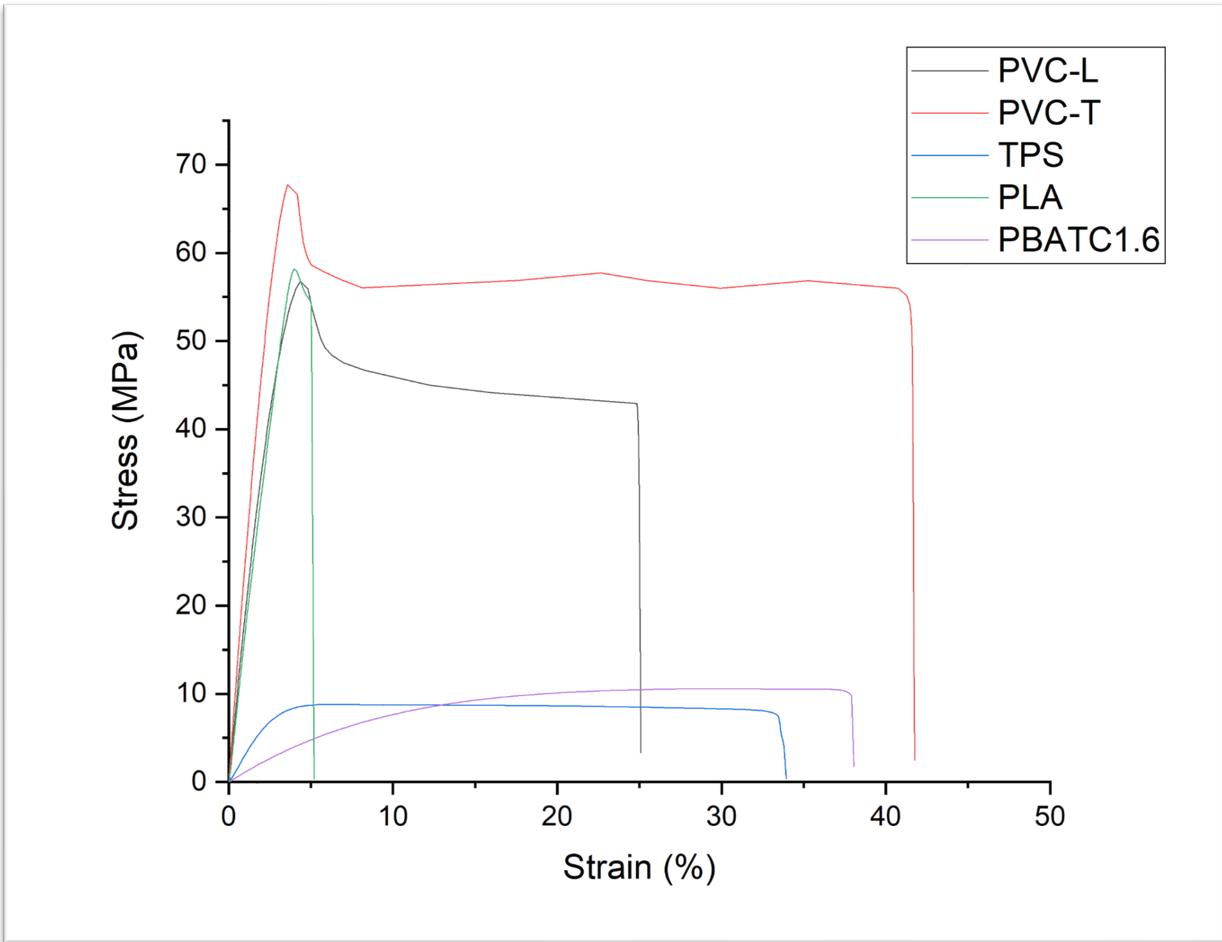

Figure 8 – Potential materials Stress/Strain

4.3 Calculation of carbon footprint

When studying PVC in the Granta EduPack database the carbon footprint of the material was estimated to be 2.57-2.83 kgCO_2 / kg PVC produced with the embodied energy of 61.8-68.2 MJ/kg PVC produced. This is the carbon footprint of the material when it has been produced in China and a substantial portion of the lifelong footprint remains due to the transportation from China to Sweden. The amount of CO_2 emission from the transportation was calculated using DHLs' carbon calculator [9]. The company usually orders batches of 100 kg PVC plastic at roughly one cubic metre of package. This results in 111.29 $kgCO_2$ emitted during transport. The transportation is split into different legs of the journey, the first part is from Xinjiang to Shanghai by truck resulting in 58 $kgCO_2$ as shown in figure 9. Xinjiang is where the company buys their PVC from. The second part is by boat from Shanghai, China to Stockholm, Sweden and emits roughly 43.15 $kgCO_2$ as shown in figure 10 and is the major contributor. The third part is from Stockholm, Sweden to Åre, Sweden by road and emits around 10.13 $kgCO_2$ shown in figure 11.

Figure 9, Xinjiang to Shanghai

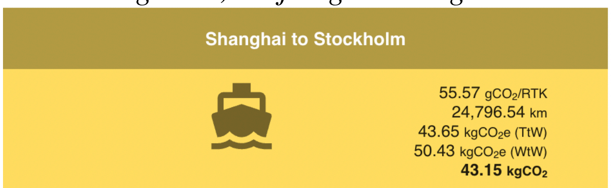

Figure 10, Shanghai to Stockholm

Figure 11, Stockholm to Åre

This answers RQ1, what is the current carbon footprint from the material the company uses today? The material is estimated to be emitting between 310,28 and 336.28 $kgCO_2$ per 100 kg PVC the company uses.

All of the potential materials are considered to be sourced from within Europe which drastically decreases the length of the travel and therefore also lowers the carbon footprint from transportation. TPS can be sourced from Novara outside Milano in Italy resulting in 43,10 $kgCO_2$ emitted through transportation calculated using the DHL carbon calculator as presented in figure 12. [9]. Production of TPS is estimated to be around 1,48-1,64 $kgCO_2$/kg according to Granta EduPack. Combined the use of TPS would roughly emit 191,1-207,1 $kgCO_2$/ 100 kg TPS [13].

Summary 2,915 km I 2,019 km (GCD)		
43.10 kgCO 2	100 kg	1.00 cbm
43.81 $kgCO_2e$ (TtW)		52.10 $kgCO_2e$ (WtW)

Figure 12, Novara, Italy to Åre, Sweden

PLA is produced outside Frankfurt in Germany and the transportation using trucks emits 31,73 $kgCO_2$. (Figure 13) [9]. The carbon footprint of PLA is 1,34 $kgCO_2$/kg [17] which would result in 165,73 $kgCO_2$/ 100kg PLA the company uses.

Summary 2,146 km I 1,510 km (GCD)		
31.73 kgCO 2	100 kg	1.00 cbm
32.25 $kgCO_2e$ (TtW)		38.36 $kgCO_2e$ (WtW)

Figure 13, Frankfurt, Germany to Åre, Sweden

Calculating the carbon footprint of PBATC1.6 proved to be a little bit more difficult due to lack of reliable sources and several different values. PBAT is a mixture of 1.4 Butanediol (0,41kg/kgPBAT), Adipic acid (0,37kg/kgPBAT) and Terepthalic acid (0,33kg/kgPBAT). Through different sources it was found that 1.4 Butanediol has a carbon footprint of 1,6$kgCO_2$/kg [18], Adipic acid emits 7,84 $kgCO_2$/kg [19] and Terephtalic acid 2,4 $kgCO_2$/kg [20]. Knowing both the mixture and the different emission from the different parts the calculation was made and resulted in roughly 4,3 $kgCO_2$/kg. PBAT has the same production location as PLA and therefor the same transportation emissions, this resulted in 464,73 $kgCO_2$/ 100kg PBAT. This value is higher than the one of PVC and as the aim of this thesis is to lower the carbon footprint from plastic uses at Åre Skidfabrik PBATC1.6 is no longer an option. Further calculations would be needed at end-of-life emissions from both PVC and PBAT to ensure which one would better suit the company. The acids and butanediol in PBAT have bio-based variants that are currently being tested in use for PBAT which would potentially decrease this carbon footprint making it a viable option in the future.

This leaves the result of two possible suitable material alternatives, TPS and PLA, that both would decrease the carbon footprint of the packaging material from its production and transport by more than 100$kgCO_2$/100kg material used. This would equal to roughly decreasing the carbon footprint by 40 to 50 % depending on what material the company would choose.

Worth noting is that the petrol-based materials have been stuck under the earth for millions of years while the bio-based materials can sometimes be considered "carbon neutral" due to the fact that it recently was collecting carbon dioxide through its growth process that it is now returning to the atmosphere. This would further strengthen the reasons as to why the company should chose a bio-based option.

5 Conclusion

Through the research and work that has been done two different alternatives to PVC for a more suitable material has been provided to Åre Skidfabrik, PLA and TPS. The method that was used has answered both research questions in the following way:

- RQ1: What is the current carbon footprint from the material the company uses today? It is estimated that the company currently emits between 310,28 and 336,28 kgCO_2 per 100 kg PVC they use.
- RQ2: What materials exist on the market that would better suit the company? Two materials were found that already exist on the market that would better suit the company, PLA and TPS. The choice now lies at the company's hands on the decision on whether to go with the cheaper option, PLA, or the option that better resembles PVC in its elongation and density properties, TPS.

6 Recommendations

For future developments of the thesis project, it would be beneficial to perform a full LCA (Life-cycle assessment) on the current packaging material (PVC) to get an even more realistic view of the carbon footprint.

It would also be helpful to take a look at more composites *i.e.* looking at materials that are mixed with fillers, fibres, powders and other substances that change the materials properties like the PBAT variants.

Testing could also be improved by using more samples for each material, this would give more accurate data for the material properties.

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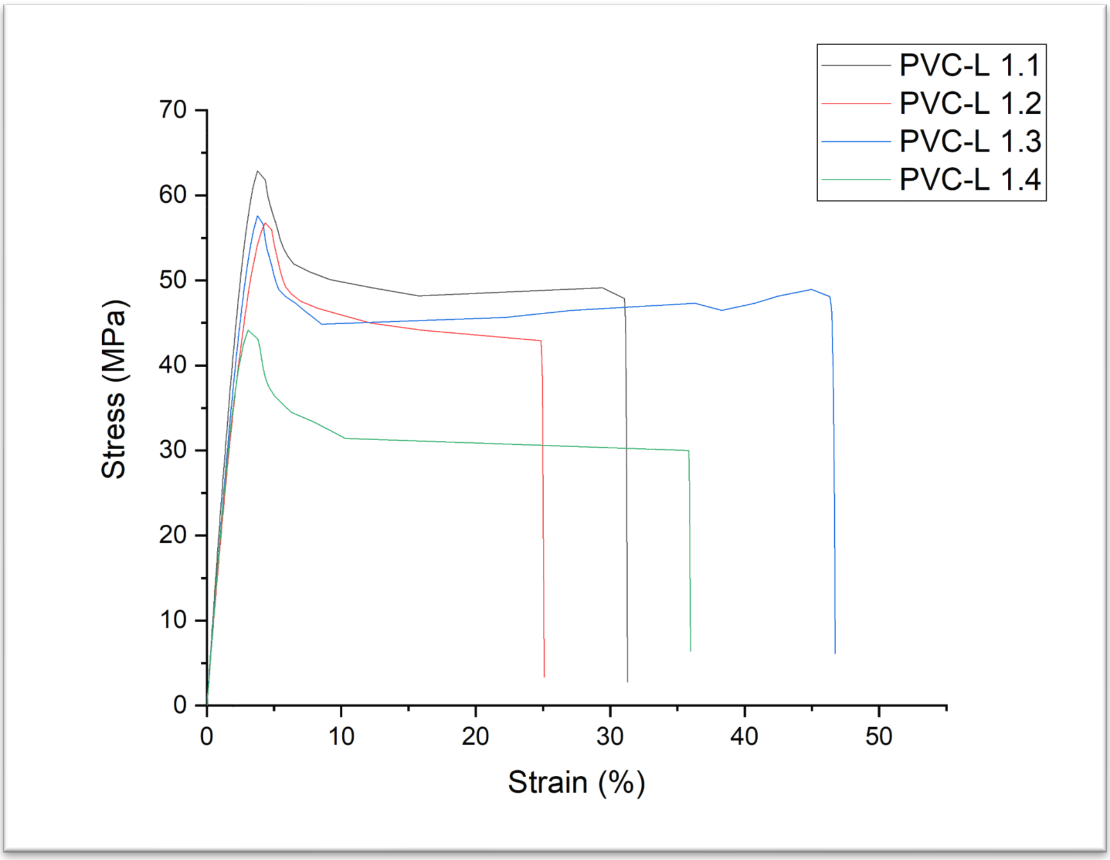
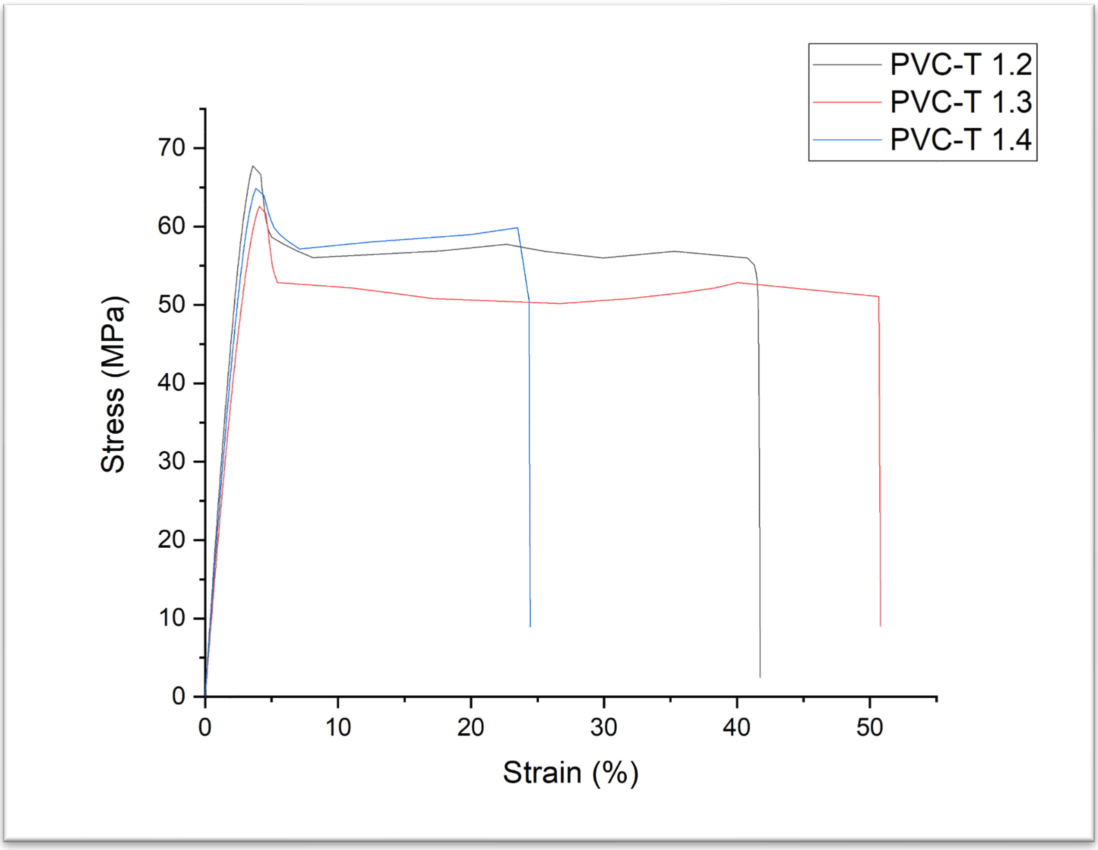
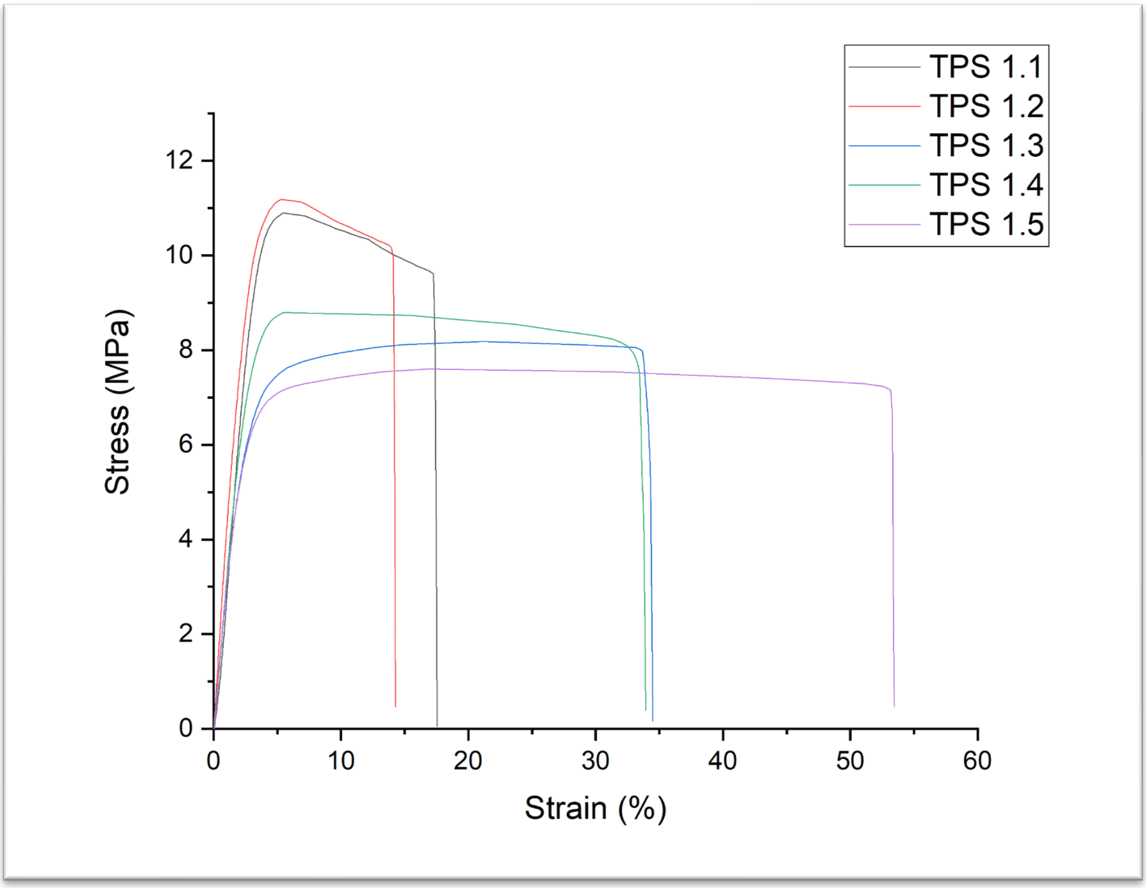
8 Attachments



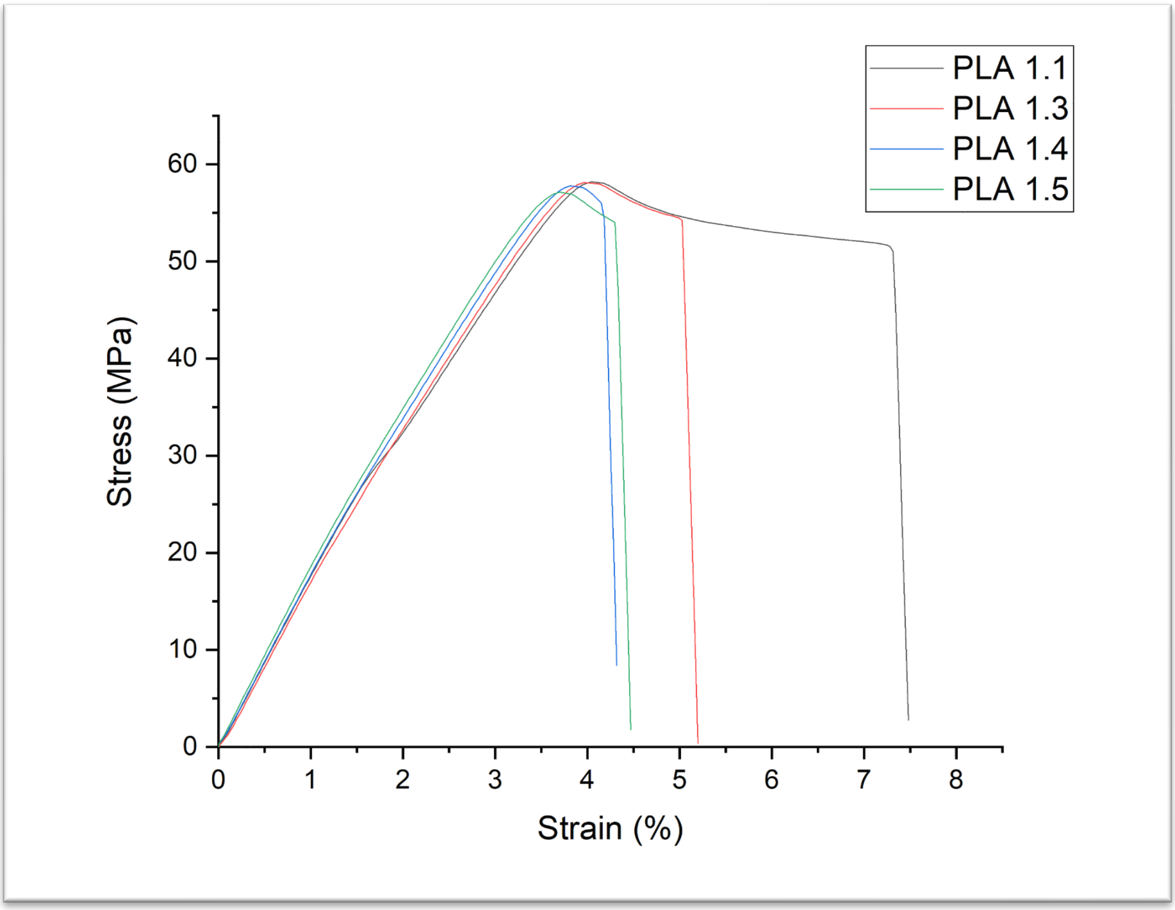
Attachment 1, Graph of PVC-L



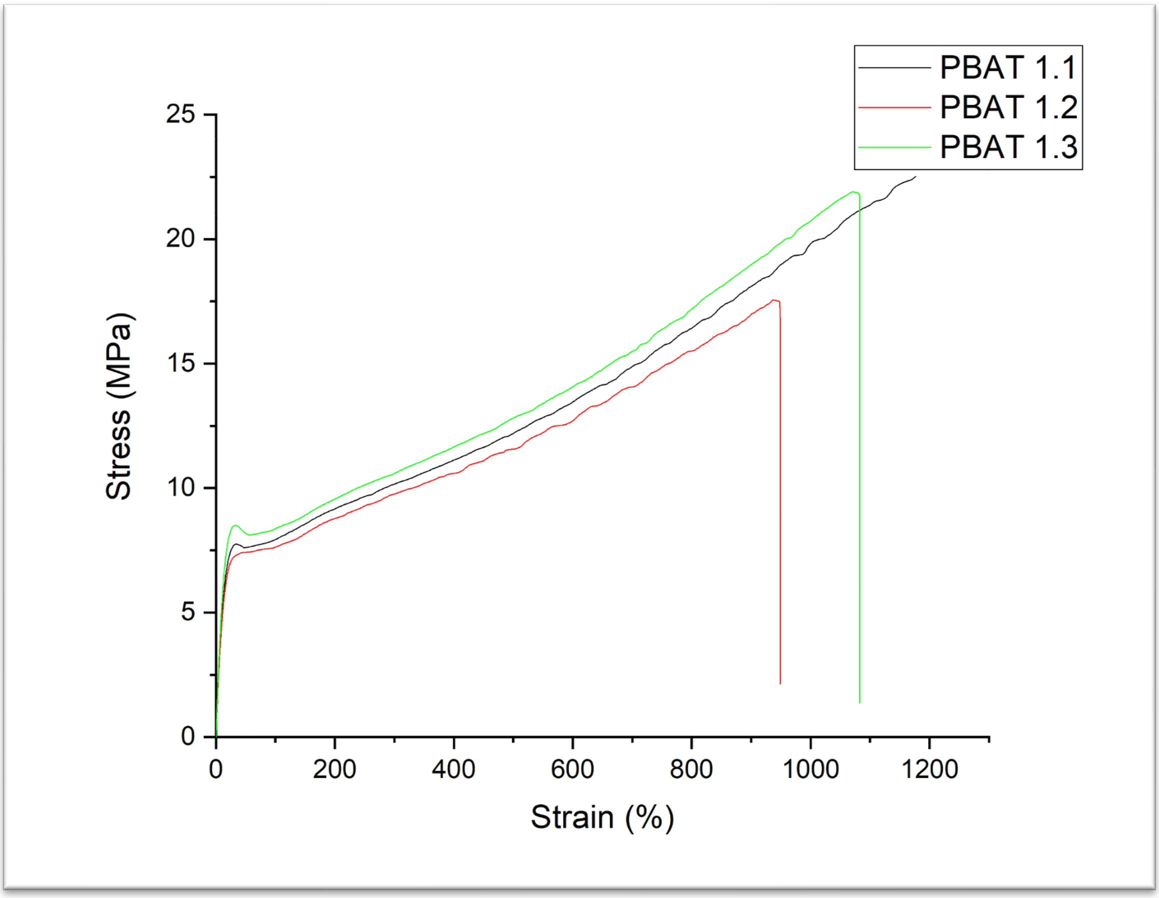
Attachment 2, Graph of PVC-T



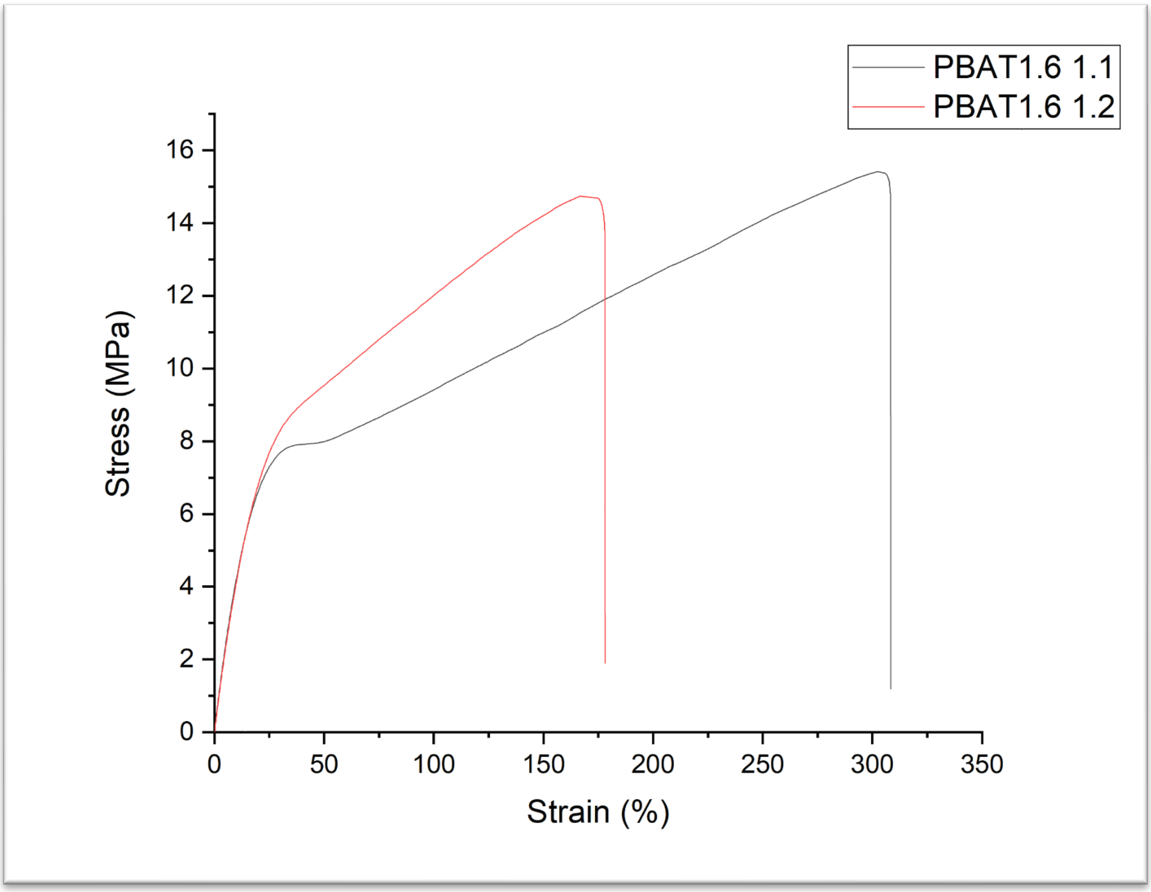
Attachment 3, Graph of TPS



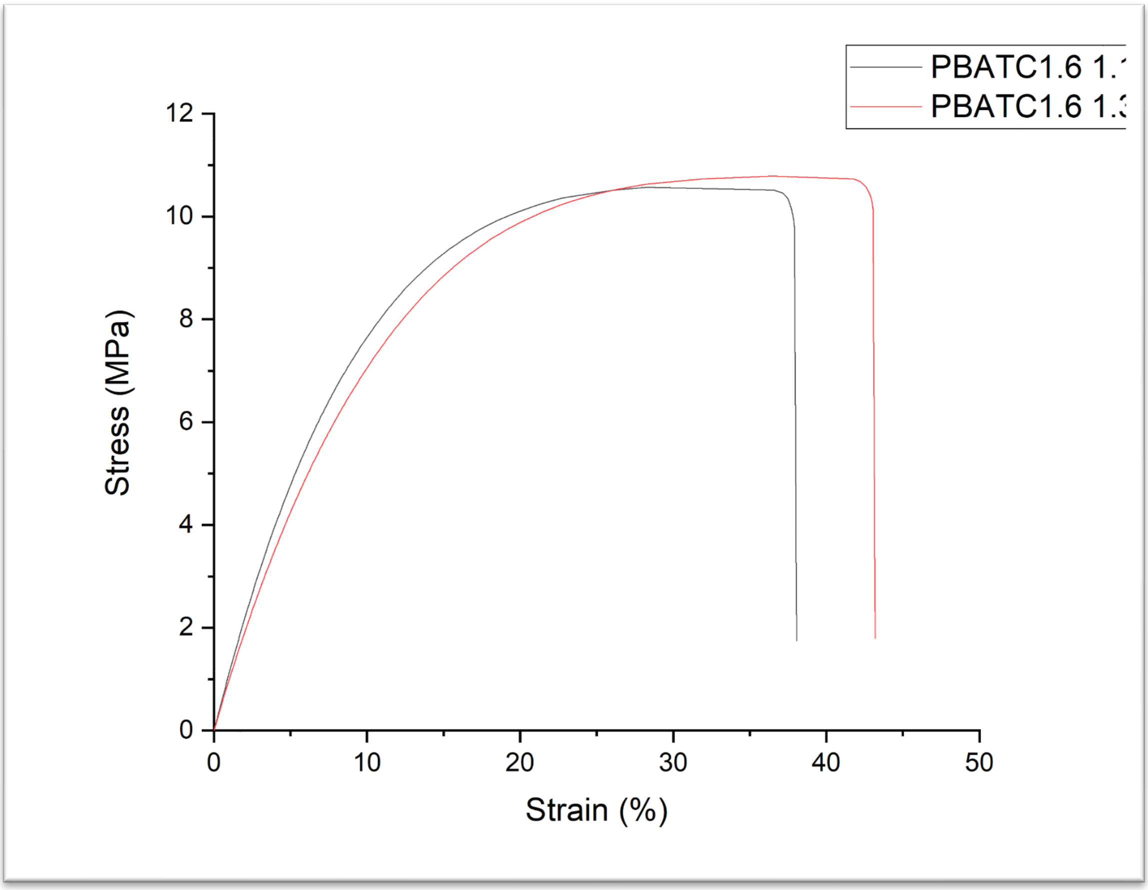
Attachment 4, Graph of PLA



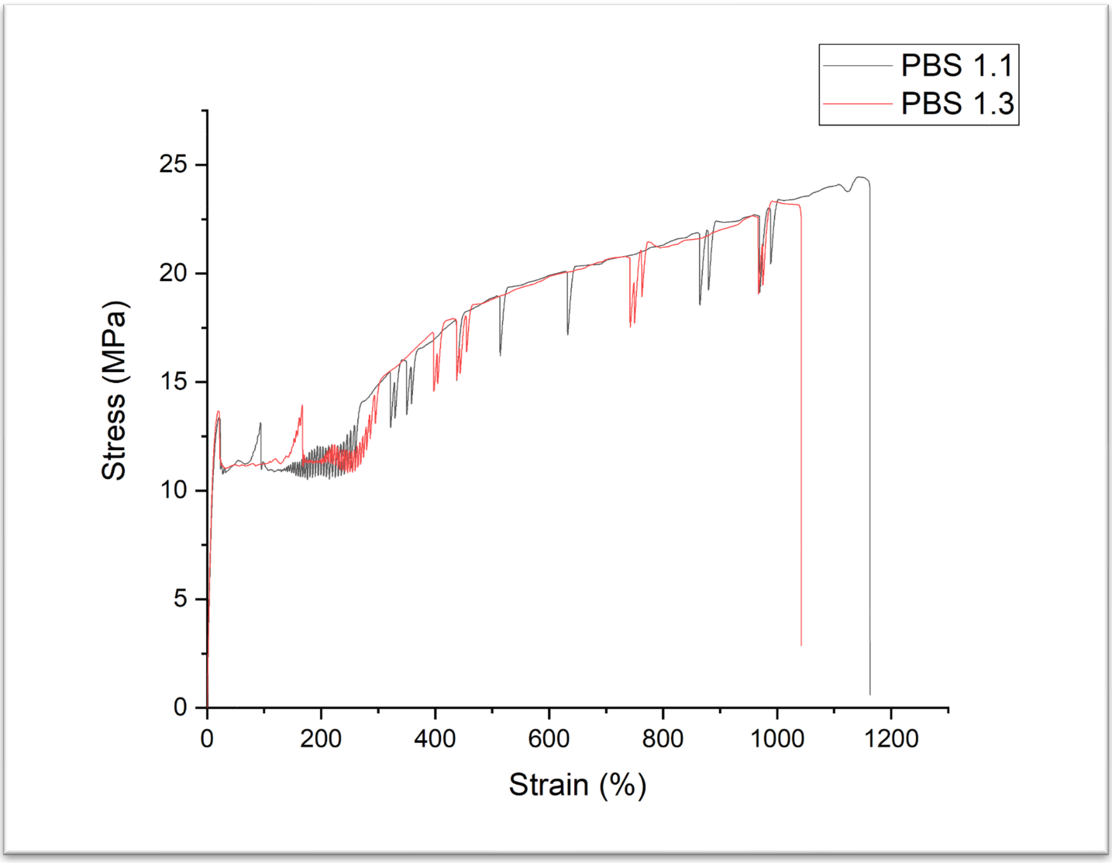
Attachment 5, Graph of PBAT



Attachment 6, Graph of PBAT1.6



Attachment 7, Graph of PBATC1.6



Attachment 8, Graph of PBS

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