Transition from ocean plastic waste to next production loop

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MASTER THESIS

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Abstract

Plastic waste is a growing issue in the world today. Most of all human responsible debris in the oceans consist of different varieties of plastic, with a large part being used fishing equipment such as nets and synthetic lines. If this ocean plastic waste could re-enter the production loop, it could help solve the increasing waste problem and limit new plastics entering the loop. This thesis is written in collaboration with Ocean Tech Hub LDA and will explore how used fishing nets should re-enter the production loop.

The method for this thesis is divided into three parts. A literature study to lay out a groundwork of current knowledge, conducting interviews with company representatives to get a practical perspective and by performing and analyzing material tests to get physical data. The materials tested were compounded together with RISE and consisted of polyamide fishing nets reinforced with either graphene or recycled boat fibers consisting of a mixture of glass fibers and epoxy. To examine the quality of the fishing nets, an industrial recycled polyamide was used as a reference material.

The results from the material testing were not entirely in line with what was anticipated, which can be for several reasons. It could be the quality of the material, issues during compounding or problems during mechanical testing. However, it showed the importance of quality assuring the material. If quality assurance got as established for recycled materials as it is for virgin materials, it would be easier to compare materials and enable recycled materials to re-enter the market.

Keywords: Polyamide, Ocean waste plastics, Recycling, Graphene, Quality assurance

Sammanfattning

Plastavfall är ett växande problem i världen idag. Merparten av allt skräp i haven som kommer ifrån människan består av olika sorters plast, varav en stor del är använd fiskeutrustning såsom nät och syntetiska linor. Om denna havsplast kunde återinföras i production igen, skulle det bade kunna hjälpa till att lösa det ökade avfallsproblemet och samt begränsa användandet av ny plast i produktion. Detta examensarbete är utfört i samarbete med Ocean Tech Hub LDA och kommer att utforska hur använda fiskenät ska återinföras i produktionen.

Metoden för detta examensarbete är uppdelad i tre delar. En litteraturstudie för att lägga en grund av nuvarande kunskap inom området, genomförande av intervjuer med företagsrepresentanter för att få ett praktiskt perspektiv samt genom att utföra och analysera materialtester för att få fysisk data. Materialen som testades kompanderades tillsammans med RISE och bestod av fisknät av polyamid som förstärktes med antingen grafen eller återvunna båtfibrer bestående av en blandning av glasfibrer och epoxi. För att undersöka kvaliteten på fiskenäten användes en industriellt återvunnen polyamid som referensmaterial.

Resultaten från materialprovningen var inte helt i linje med vad som förväntades, vilket kan bero på flera skäl. Det kan vara kvaliteten på materialet, felkällor från kompanderingen eller problem under de mekaniska testerna. Det visade dock vikten av att kvalitetssäkra materialet. Om kvalitetssäkring av återvunnet material blev lika etablerat som det är för jungfruliga material, skulle det vara lättare att jämföra material och möjliggöra för återvunnet material att bli återintroducerat på marknaden igen.

Nyckelord: Polyamid, Havsplast, Återvinning, Grafen, Kvalitetssäkring

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Lund, August 2022

Simon Ölund

Contents

List of acronyms and abbrevations

ABS	acrylonitrile-butadiene-styrene
ALDFG	abandonded, lost or discarded fishing gear
CVD	chemical vapor deposition
FDM	fused deposition modelling
ISCC	International Sustainability and Carbon Certification
LSAM	large scale additive manufacturing
MB	masterbatch
MFI	melt flow index
MFR	melt flow rate
OCT	Ocean Tech Hub LDA
PA	polyamide
PE	polyethylene
PLA	polylactic acid
PP	polypropylene
RISE	Research institute of Sweden
SLA	stereolithography
SLS	selective laser sintering
TPE	thermoplastic elastomer
TPRR	Thermo Plastic Recycled Rubber
UNEP	United Nations Environment Program

1 Introduction

This chapter introduces the project and presents background for the project and establish goals and research questions for the thesis.

1.1 Background

Plastic waste is a growing issue in the world today. A majority of all human responsible debris in the oceans consists of different varieties of plastic, which in turn largely comes from used fishing equipment such as nets and synthetic lines. Plastics have a long lifecycle which lead to a build up of plastic ending up in the environment. It can be hazardous for the marine ecosystem due to ingestion of marine debris and entanglement in synthetic lines and drifting nets. For example, in a study done in the North Pacific, plastic particles was found in 8 out of 11 seabird species caught as bycatch. Plastic waste on the ocean floor can prohibit the gas exchange between the bottom sediment and the overlaying waters, leading to oxygen deprived oceans. (Derraik, 2002)

Figure 1: Ocean waste plastics. Source: Pixabay

To reduce plastic waste and marine litter, the European Union has adapted a strategy for plastics in January 2018. It aims to support a more sustainable and safer consumption and production patterns for plastics by changing the way plastic products are produced, designed, used and recycled in the EU. This strategy plays a key part in Europe's transition towards a carbon neutral and circular economy. (European Commission, n.d.a)

Plastics as materials are quite diverse and can obtain many different qualities such as lightweight, strong, durable and cheap to name a few. Qualities like these are probably one of the reasons why plastics have become such a common material in commercial goods. Waste plastic can often still retain large parts of these qualities and may therefore be an under utilized resource.

1.2 Company introduction

This thesis is written in collaboration with the company Ocean Tech Hub LDA (OCT). Ocean Tech Hub LDA leads an initiative called Peniche Ocean Watch, which aims to unite protagonists from different sectors and backgrounds to pursue innovative solutions related to ocean and societal challenges. Based in the Portuguese coastal town of Peniche, a fishing community one hour north of Lisbon, they run several different blue circular projects and they are converting two warehouses into co-creation and coworking spaces. Their goal is to enable people, regardless of organization affiliation, to learn, create and connect through support and incubation spaces in addition to provide the ability for creating innovative and sustainable prototypes in their workshop areas. (Peniche Ocean Watch, n.d.a)

One of the projects is called Sculptur Ocean, which is a collaboration between Ocean Tech Hub LDA and Sculptur Sweden AB. Sculptur Sweden AB was founded in 2019 and was one of the first companies in the world to use robots for large scale additive manufacturing (LSAM). They offer collaboration with companies interested in exploring 3D-printing as a way to convert waste into valuable product (Sculptur, 2021). This project is focused on developing the local production of products from marine waste with the use of LSAM. They are also exploring the possibility of hybrid nanocomposite materials with graphene to be used in LSAM, to utilize the material properties of graphene such as increased strength, lightweight and wear resistance. (Peniche Ocean Watch, n.d.b)

To develop materials for this project, a collaboration with the research institute of Sweden (RISE), which is a Swedish research institute and innovative partner, was established. RISE strive towards strengthening competitiveness and sustainability for Swedish industry by collaborating with industry, academia and the public sector. (RISE, n.d.)

It is this project which has laid the foundation for this master thesis and sets the basic guidelines for what to be investigated. However, the aim is for the report to target a wider audience and for proposed solutions to be applicable at a larger scale.

1.3 Purpose and overall goals

The overall objective of this degree project is to research how to utilize waste plastics, such as discarded fishing nets, and transform it into new products to try and utilize the entire life-span of the material. The aim is also to investigate the spectrum of limitations when used multiple times.

1.4 Research questions

To fulfill the goals and aim of the degree project, the following three questions will be investigated.

- What affects the quality of discarded fishing nets and what is important in the recycling process?
- How to upgrade the waste material from recycled fishing nets by using additives and how to keep the material properties as good as possible?
- Is 3D-printing a viable manufacturing option for recycled fishing nets?

1.5 Limitations

This study only takes in consideration the chain from collected ocean waste plastic to a material which can be used in additive manufacturing. The plastic studied in this report consists of polyamide 6 (PA6) and polyamide 12 (PA12), so plastic waste of other types will not be taken into consideration. However, a similar approach can hopefully be used when considering other plastic materials. The depth of the material study will be at an application level, therefore a deep analysis at a molecular level will not be carried out. How waste plastic is collected and the logistics behind the production will not be looked into. This report shall cover what parameters that are required for a successful 3D-print but not what printing parameters that shall be used.

2 Methodology

This chapter describes the methodology used for this study and how they were adapted to fit the project

2.1 Literature study

The project began with a literature study to lay out a groundwork of prior knowledge to aid in creating support for interview questions and analysis of material testing. Information was collected from published literature, such as research papers, books and public information on the topic. Literature was gathered from several different sources. Books on compounding were provided by the supervisor from LTH and prior course literature was also used. Research papers and academic journals were gathered by using search databases such as Google scholar and LUBsearch. Keywords such as "compounding", "additive manufacturing", "marine waste" and "polyamide" were used both in combination and separately to both get a deeper understanding of each area and also to see what is currently done in line with this thesis.

Rules and regulations about plastic usage and recycling were retrieved from the European Commission, which covers all countries whom are members of the European Union and creates a legal framework to be followed. This framework means to drive research and development towards a circular approach for plastic products.

2.2 Interviews

Interviews were held with company representatives involved in the field with the aim to get a practical perspective on the research questions. Information about interviewed individuals are presented under **4. Interviews**.

The interviews were held using applications such as Zoom and Microsoft Teams when possible. Some interviews were held over a phone call when there were difficulties in finding time for a scheduled meeting. If permission was given by the interviewee, the meeting was recorded. Research about each company was done before the interviews to be able to ask questions to get specific information about their area of expertise. Questions were created prior to each interview, based on the background research. When reasonable, similar questions such as questions considering quality assurance were asked to get a comparison between the different interviews.

All interviews began with asking the interviewee to talk about their position at the company or institution and giving short summary about the company, to get the conversation started. It was followed up by asking the prepared questions in an order which felt natural to keep a flowing conversation, adding follow up questions when possible. Short notes were taken continuously during the interview in order to better summarize the interview into a transcript.

After the interview, a transcript of the interview was created from the notes and sent to each interviewee for approval. All interviews were held in Swedish but were translated into English in this report. The research questions are presented in Appendix B.

2.3 Compounding of test materials

The test materials was prepared together with Johan Landberg at RISE in Mölndal, Göteborg. Landberg is a laboratory engineer who manage projects regarding material development, compounding, recycling, injection molding, material analysis and mechanical testing.

Two different matrix materials were used, recycled PA6 fishing nets from Peniche, Portugal and Ravamid from the global plastic material supplier Resinex, Jönköping. Ravamid is a recycled PA6 from Resinex of industrial quality. It was delivered in the shape of pellets with average lenght of around 5 mm, see figure 2.

Figure 2: Ravamid pellets from Resinex

The fishing nets arrived pre-shredded and had to be shredded to smaller size on the site. To reduce moisture content, drying of all materials was done over night in a dry-air dryer at 70 °C. Figure 3 shows how the nets looked after shredding and drying. To achieve the desired material ratio in each finished compound, the material was weight using a digital scale with three decimal accuracy.

Figure 3: Shredded and dried fishing nets before compounding

The compounder consisted of a twin-screw extruder inside a heated barrel. Two hoppers was connected to the main extruder with feeding screws, one was a twin-screw and one was a single screw. The compound was extruded into a filament which was cooled in a water bath and feeded into a cutter which cut the filament into pellets. Six different batches was done, which can be seen in the list below. Recycled PA6 from Resinex was used as a reference material.

- Ravamid from Resinex
- Ravamid from Resinex with 20% masterbatch graphene
- Ravamid from Resinex with 20% recycled boat fibers
- Recycled PA6 fishing nets with 10% masterbatch graphene
- Recycled PA6 fishing nets with 20% masterbatch graphene
- Recycled PA6 fishing nets with 20% recycled boat fibres

2.4 Material testing

Two different material tests were performed, melt flow index (MFI) and tensile tests. MFI was tested to check rheology and material degradation. Tensile tests were performed to study mechanical strength of the materials. These two tests give a good indication of material and mechanical properties of the recycled material. Data sheets containing information of material properties of plastic materials often displays data from these two test. The results from these tests can therefore be used in order to easier to compare the recycled material to other available plastics on the market.

2.4.1 Melt flow rate

Melt flow rate (MFR) or melt flow index which it also can be referred as, are measured by inserting test material in melt flow rate machine, which heats up the material and a standardized weight pushes down the melt through a die and the exerted material is weighted to calculate the amount of grams which have passed through the die. Unit used is grams/10 min. Temperature used was 250 °C and the standardized weight was 2,16 kg.

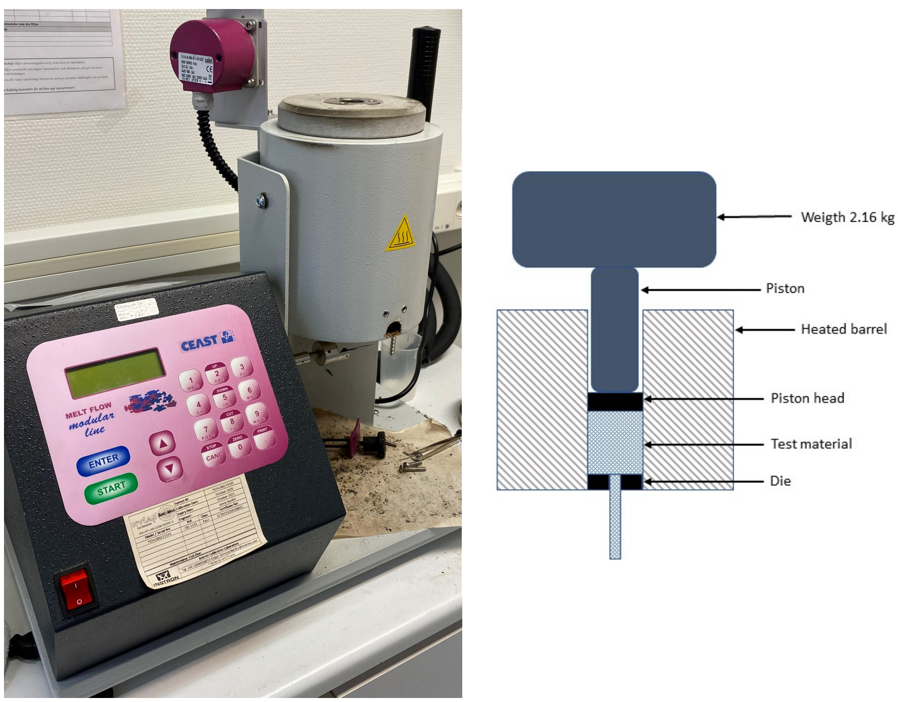

Figure 4: Equipment with corresponding schematic to test MFI

2.4.2 Tensile tests

Tensile tests of the different compounds are done with equipment at LTH. Six different batches are tested according to ISO-standard 527-1/2. The test specimens are conditioned in room temperature at 21 °C at 40% humidity for four days. Five specimens are tested from each batch, see figure 5a. The specimens are checked for imperfections prior to testing and any damaged specimen are replaced. Measuring of gauge length, width and thickness is done with the use of a caliper.

(a) Prepared specimens

(b) Tensile testing machine

Figure 5: Equipment for performing tensile tests

The tensile testing machine, see figure 5b, is connected to a computer which automatically collects and calculate data during each test. No extensometer was used to measure change in length of specimens during each test. Grip displacement was used instead. Strain calculated is therefore nominal strain and not actual strain for each specimen. The difference is however very minor and nominal strain is considered good enough for these test results.

3 Theory

This chapter covers research gathered from the literature study.

3.1 Ocean waste plastics

Abandoned, lost or otherwise discarded fishing gear (ALDFG) represents one of the largest parts of marine waste in the oceans. Entanglement of marine life, smothering of the seafloor and plastic degradation into microplastics which can enter the marine food web are a few of the harmful impacts caused by ALDFG. (Weißbach et al., 2021) Another occuring issue is ghost fishing, where abandoned, lost or discarded fishing gear such as gillnets, trammel nets, seines, trawls and pots, continues to catch fish, crustaceans and other animals. This problem has risen rapidly over past decades, both due to expansion of fishing grounds and due to transition to synthetic more fishing gear which is more durable and does not break down as quickly. (Deshpande et al., 2020)

Since the 1960s, fishing gear has been produced from oil-based polymers because of their long-lasting properties, and contributes to between 30-50% of plastic items found in the world's oceans. Reliable information about exact quantities of fishing gear lost at sea every year is not yet available. However, in a study commissioned by the European Commission, it is estimated to be between 1700-12000 tons of fishing gear lost in European seas from active fishing. An earlier estimate done shows that around 25000 tons of fishing nets are used in the North Atlantic region each year. In a pilot study done by WWF Poland, it is estimated that between 5000 and 10000 net fragments are lost each year in the Baltic Sea. It is hard to estimate the exact weight of potentially lost ALDFG, since different fishing gear such as for example gillnets and trawls, have very different fibre structures, densities and amount of material. The size of torn fragments can even vary between tens of centimeters to several hundred meters in length. This is especially true for gillnets, in where 10-20 net segments are attached to each other to form a single net which can be 500-1000 meters in length. (Weißbach et al., 2021)

Since commonly used fishing nets and especially gillnets are produced from long-lasting, highly strain and stress-resistant thermoplastics, the material is in theory well-suited for recycling. Polymers originating from fishing gear can be processed in all classical waste management pathways, including re-use, mechanical recycling, chemical recycling and energy recovery. If the material can be recycled using some of these methods, it would allow to establish a more circular economy around fishing gear. (Weißbach et al., 2021)

3.1.1 Quality of fishing gear

Depending on what state the fishing gear is found and retrieved in, the initial quality can vary drastically. For example, fishing nets which have been left at the docks are not as contaminated by sediments, mussel chalk and other inorganic minerals as nets which have drifted or lays at the sea bed.

3.2 Recycling

Out of all plastic waste globally in 2016, about 40 million tons or 16% was collected for recycling, 25% was energy recovered, up to 40% was properly landfilled and up to 19% was disposed of in an unregulated manner. For comparison, post-consumer packaging waste collected in Europe in recent years is 16,7 million tons, where 40,9% was directed to recycling, 38,8% was energy recovered and 20,3% went to landfills. (Feil & Pretz, 2020, Chapter 11)

Fiskereturen is an initiate launched by Båtskroten, Sotenäs kommun, Håll Sverige Rent and Fiskareföreningen Norden, funded by the Swedish Agency for Marine and Water Management. It is a collection service which offers to collect worn-out fishing gear which are unusable or no longer needed in commercial fishing. They believe that, to proactively retrieve and take care of fishing gear, is an effective way to minimize the risk of lost fishing gear in nature which poses a threat towards wildlife and the environment. (Fiskereturen, n.d.)

Items they accept include:

- Cages, tins and fyke nets
- Worn-out fishing nets
- Ghost nets
- Fishing related equipment, such as different type of ropes and floating balls

They do not accept smaller fishing equipment, such as lures, rods and lines or boat related waste like buoys and fenders. Those items are ,together with household waste, instead sent to local recycling centers. Nets which are treated with impregnating agents can contain environmentally hazardous substances, and complicate recycling. Fiskereturen aids in ensuring these impregnated nets are taken care of correctly. (Fiskereturen, 2020)

3.2.1 Types of recycling

Recycling of plastics can generally be divided in to four categories going from mechanical recycling to chemical recycling to energy recovery and lastly landfill. Going from mechanical recycling, each step utilized the mechanical properties left in the material less and less, with landfill being the worst.

Re-use Re-use implies the use of used polymer materials to exploit their existing material properties. Commonly used production methods are often complex, energy-intensive and costly which makes re-using materials both economically and ecologically desirable. This can also contribute to decrease the amount of virgin materials produced. (Weißbach et al., 2021)

Mechanical recycling In a mechanical recycling process, waste plastics is converted into new materials without significantly changing the chemical structure of the material. (Jeswani et al, 2021) Mechanical recycling involves two separate processes. First a physical process to create single material streams, to remove contaminations by washing and to reduce the size of the material by shredding. Then the material is melted, where the waste is compounded into a functional material. After a mechanical recycling process, the recycled compound can replace original plastics with similar properties as of the recycled compound. In general, this method is only applicable to thermoplastic materials with certain thermoplastics being easier to process than others. (Adelodun, 2021) For example, polyamide is suitable for mechanical recycling (Bruder, 2014).

Chemical recycling Chemical recycling is done by reducing the polymer to its original monomeric form for reprocessing into a brand new plastics. Thermal or catalytic depolymerization can be used to break long polymer chains into building blocks which can be deployed solely or used as a complement to mechanical recycling. Methods of depolymerization include for example glycolysis, gasification, methanolysis and pyrolysis. In general, this process works in two stages. The first step is to describe and identify chemical reactions to be carried out, and adding the right chemical agents to degrade the polymer. The second step is to speed up the chemical reaction with the use of a catalyst.(Frisa-Rubio et al, 2021) This method is more expensive than mechanical recycling though it maintains a certain level of quality and is widely used in for example recycling of PET. (Wu et al, 2022)

Energy recovery Energy recovery refers to the recovery of the inherent energy of a material. The waste plastics are incinerated and heat from the process is used to drive a steam generator which generates electrical energy. In this process, the only property which is utilized is the stored energy in the material. Energy recovered from this process depends on the material, but since most plastics are oil-based the energy recovered is higher than for example incineration of organic waste. (Adelodun, 2021)

3.2.2 Regulations and policies

According to the European Commission almost 26 million tonnes of plastic waste is generated in Europe every year and around 80% or marine litter is plastic. (European Commission, 2020) EU policies on plastics aim to protect the environment and human health by reducing marine litter, emission of greenhouse gases and dependence of imported fossil fuels. Further goals the EU aims to achieve are:

- Change the way plastic products are designed, produced, used and recycled in Europe
- Transition to a more sustainable plastics economy
- Support more sustainable and safer consumption and production patterns for plastics
- Create new opportunities for innovation, competitiveness and jobs
- Induce change and set an example at a global level

Currently there is no international instrument in place specifically designed to prevent plastic pollution throughout the entire lifecycle of plastics. Some countries are taking actions to increase recycling or reduce plastic consumption, with for example awareness-raising measures and campaigns. Other countries have laws in place to oblige producers and manufacturers to minimise waste, adopting recycling targets, or phasing out plastic products which are most problematic such as single use plastics. According to the European commission, recent studies show that with the current measures, reduction of marine plastic pollution will be around 7%. Because of this, more than 100 countries are inclined to establish a global agreement on plastics, under the United Nations Environment Program (UNEP). This agreement intends to tackle the global discharge and mismanagement of plastics, by reducing the amount of plastic leaking into the environment and the impact of plastic production and consumption on resources.(European Commission, n.d.)

Landfill According to the EU's waste hierarchy *Waste Framework Directive*, (Directive 2008/98/EC), disposal to landfills should be the least preferable option and limited to the necessary minimum. Landfills generate leachate which can contaminate groundwater and methane is produced released into the atmosphere. To reduce the amount of waste being disposed in landfills, The EU introduced restrictions on landfilling of all waste which is suitable for recycling or energy recovery from 2030.(*on the landfill of waste*, Directive 1999/31/EC)

3.2.3 Recycling of ocean waste plastics

According to Ellen MacArthur foundation (n.d.), three criterion must be met to fulfill a circular economy for plastic products. All unnecessary and problematic plastic products must be eliminated, innovation must take place to ensure that the plastic materials we do need are re-usable, recyclable or compostable and that the plastic items we use are circulated so they are kept in the economy and out of the environment. These criterion are the foundation for the New Plastic Economy Initiative, which elaborate these criterion into six key points:

- There should be a priority to eliminate all problematic and unnecessary plastic packaging through redesign, innovation and new delivery models
- Reducing the need for single-use plastics by applying reuse models where relevant.
- All plastic packaging is 100% reusable, recyclable or compostable
- All plastic products are actually reused, recycled or composted in practice
- Plastic usage is fully decoupled from the consumption of finite resources
- All plastic packaging is free of hazardous chemicals, and the health, safety and rights of all people involved are ensured.

These key points try to limit the use of plastic where it is not needed, as in single use packaging. Where no suitable options to plastics exist, plastics used should not be fossil based and recycling should be ensured. The main point is that no plastics should end up in the environment. Even if energy recovery and to some degree landfill are short term solutions, more long term options must be established which strive towards a circular economy. Governments are essential in creating effective infrastructure for collection, facilitating the establishment with self-sustaining mechanisms and providing an enabling regulatory and policy landscape. Businesses which produce and/or sell plastic products have a responsibility to ensure that their products are re-usable, recyclable or compostable. (Ellen MacArthur foundation, n.d.)

3.2.4 Usage of recycled ocean waste plastics

DSM launched a material series named Akulun RePurposed in 2018 which is a compound consisting of at least 80% recycled PA6. It is based on worn-out fishing nets from the Indian Ocean. DSM have during the recent years developed a wide range of technical compounds to support a sustainable circular economy, and have committed to provide recycled or bio-plastic alternatives for their entire portfolio by 2030. Akulun RePurposed is used today in Samsung Electronic latest smartphone Galaxy 22 and tablet Tab S8. It is used for the inner casing and in the key holder of the smartphone as wel as the internal support bracket of the tablet. (Folkesson, 2022)

IKEA launched a collection called MUSSELBLOMMA in 2019 which was made out of recycled plastic, partly collected by fishermen in the Mediterranean Sea. The polyester fabric used in MUSSELBLOMMA is partly made out of PET which was caught in fishing nets. After collection the material is aggregated in containers onshore, washed, sorted and then mechanically recycled. It is then made into yarn and fabric together with recycled PET bottles. (IKEA, 2019)

3.3 Matrix materials

A composite material is a union of two or more materials to get a new material with increased properties, such as mechanical or electrical conductivity. Composites usually consists of one continuous phase known as a matrix and one or more discontinuous phases which are referred to as reinforcements. In polymer composites, the matrix material is a polymer which gives the composite its net shape, determines surface quality and transfer loads between reinforcement fibers. It is the main component of a composite. (Sharma er al., 2019)

3.3.1 Plastic classification

Plastics can be divided into two different categories, thermosets and thermoplastics. Thermosets are defined by having cross-linking between the polymer chains which are very strong and do not break when heated. This make it so thermosets cannot be melted, which makes them difficult to recycle. Thermoplastics on the other hand can be melted and are easy to process with a variety of production methods. Most plastics used today are thermoplastics. (Bruder, 2014)

Thermoplastics are generally divided into three categories which are commodities, engineering plastics and high performance plastics. Commodities are accountable for about 90% of all thermoplastics in use today. They are readily available, easy to process and also fairly cheap. Examples of commodities are polypropylene (PP) and polyethylene (PE). Engineering plastics are designed with to have properties for improved performance in more demanding applications. They are more expensive than commodities and include plastics such as polyamide (PA) and thermoplastic elastomer (TPE). High performance plastics are engineered to have exceptional mechanical and thermal properties in order to fulfill high performance requirements. They are the most expensive plastics and are often used in low volumes in speciality applications. (Gemini group, 2022)

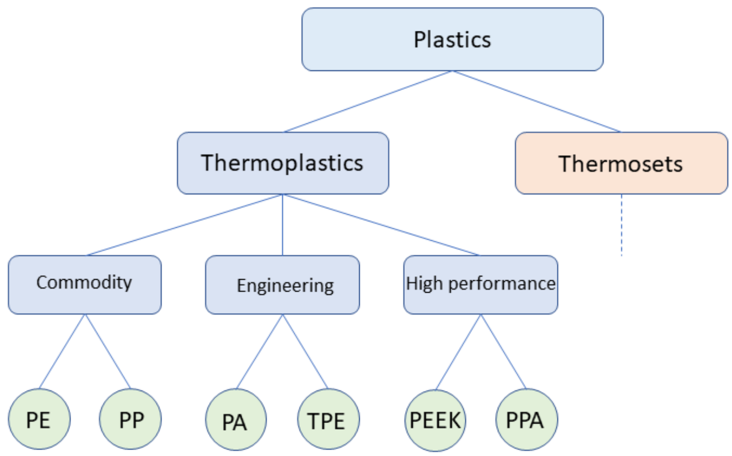

Figure 6: Classification of plastics

Thermoplastics can also be classified by molecular structure. They can be amorphous, semi-crystalline or a combination of both. Examples of other materials which have these molecular structures are glass which is amorphous and metals which are crystalline. The amorphous molecular structure is completely disordered while semi-crystalline plastics have molecular chains which align themselves in orderly layers called lamellae. Amorphous plastics do not have a specific melting point. They are instead defined by a glass transition temperature (Tg) when the molecular chains begin to move. Semi-crystalline plastics do not soften in the same way and are more similar to metals, where they change from solid form to liquid form at the melting point (Ts). (Bruder, 2014)

3.3.2 Polyamide

Polyamide is a semi-crystalline plastic, and was the first engineering polymer which was available on the market. It is commonly used in the automotive industry and is the largest in volume used engineering plastic. Polyamide was invented by DuPont in 1934 as a fibre in parachutes and women's stockings under the trade name Nylon, which is how it is commonly referred to today. Polyamides are classified by the amounts of carbon atoms in each monomer which makes up the polymer. PA6 has the simplest molecular structure and is together with PA66 the most commonly used polyamides. PA66 consists of two different monomers, one amide group and one acid group, each containing six carbon atoms. (Bruder, 2014)

New polyamide grades which are not fossil based have been introduced to the market over the recent years. They are often referred to as biopolyamides. Examples of these new grades are PA410, PA610, PA1010, PA10 and PA11. These materials offer an alternative to PA12, which is petroleum-based. Biopolyamides consist in general of raw material extracted from castor oil which is derived from castor bean plants grown in the tropics. Compared to fossil based polyamides such as PA6 and PA66, these materials have better dimensional stability, better resistance to chemicals and lower water absorption. (Bruder, 2014)

General properties of PA6 can be seen in figure 7. It is the simplest of polyamides due to its molecular structure both show high stiffness and strength. It has a high service temperature but can be brittle at lower temperatures if not impact modified. This is a difference compared to PA12, which can be studied in figure 8, which can withstand lower temperatures much better compared to PA6. However, both grades are susceptible to moisture absorption from the environment which alters the mechanical properties, even if it is worse for PA6.

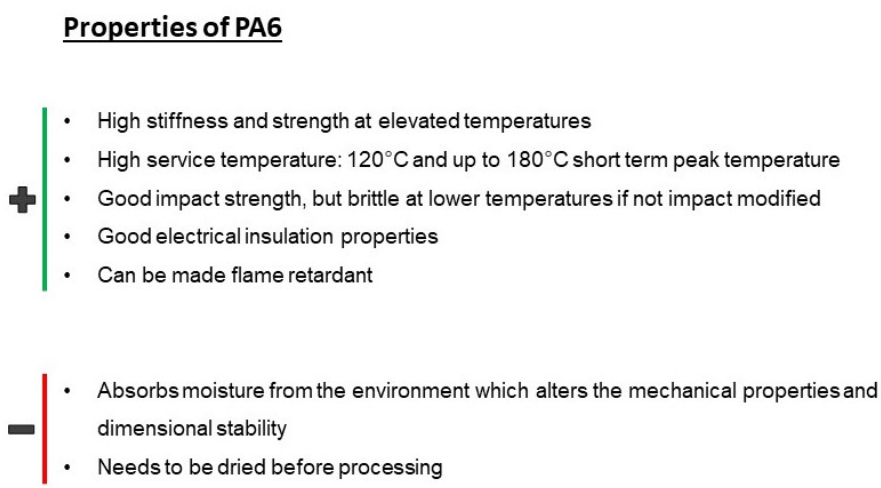

Figure 7: Properties of PA6 (Omnexus, n.d.)

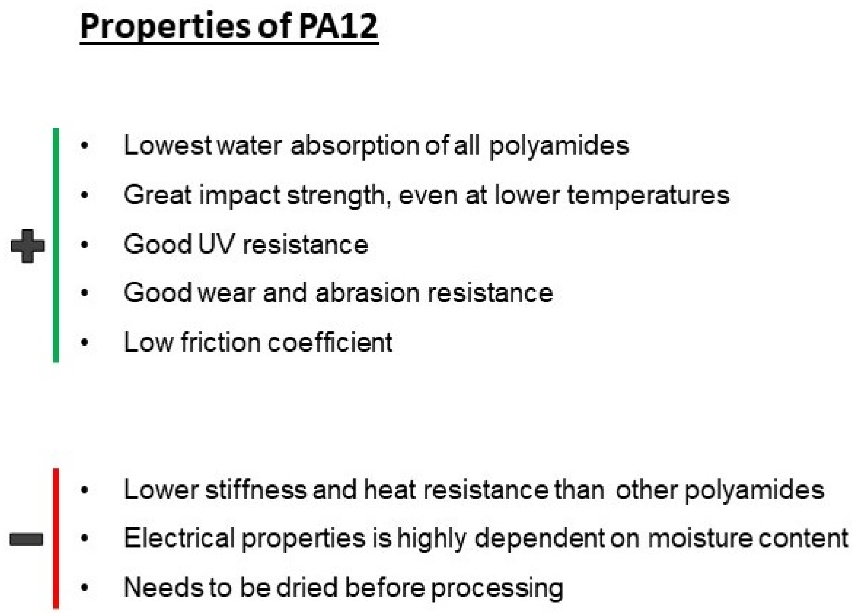

Figure 8: Properties of PA12 (Omnexus, n.d.)

Depending on if the material is to be used in injection molding or in extrusion, certain criterion have to be met. For injection molding, it is usually required for a material to have low viscosity and high fluidity. Viscosity describes a materials resistance to motion under an applied force. A high viscosity correlates to a slower flowing material and vice versa. Viscosity is also related to temperature, when the temperature increases the plastic flows easier. This is true until a certain point when the material starts to degenerate and breakdown. (SEA-LECT plastics, 2021)

The injection molding process is quick and it is important to ensure the entire mold is filled. If the viscosity of the material is too high, the shear forces applied to the material during the injection molding process can introduce defects in the final product. Polymer grades designed for extrusion are instead generally characterized by having a higher molecular weight and high viscosity. This allows for better dimension control of the material during extrusion and avoids the extruded profile collapsing. Polyamides can be modified to fit both grades. (Gemini group, 2022)

3.4 Additives/Reinforcement

Additives are often used to enhance the properties of the matrix material, to ease the production process or to add color to name a few applications. This report will focus on additives which increases mechanical strength of a material, in other words reinforcements. The two additives which are investigated are glass fiber and graphene. Glass fibers are one of the most common used reinforcement additives in polymers today and graphene is a newly researched material with excellent qualities and high potential. The reason additives are investigated in this report is to study possibilities of upgrading the material to compensate for loss of material properties from the recycling process.

3.4.1 Graphene

Graphene was first isolated in 2004 by Andre Geim and Konstantin Novoselov for which they were awarded the Nobel Prize in Physics 2010. It is a form of carbon, and in its purest form it consists of layers only one atom thick. Geim and Novoselov successfully extracted graphene by using adheisive tape to rip of flakes of graphene from a larger piece of graphite. They were then able to perform tests with this new material and found it to have excellent material properties. (Nobel Prize, 2010)

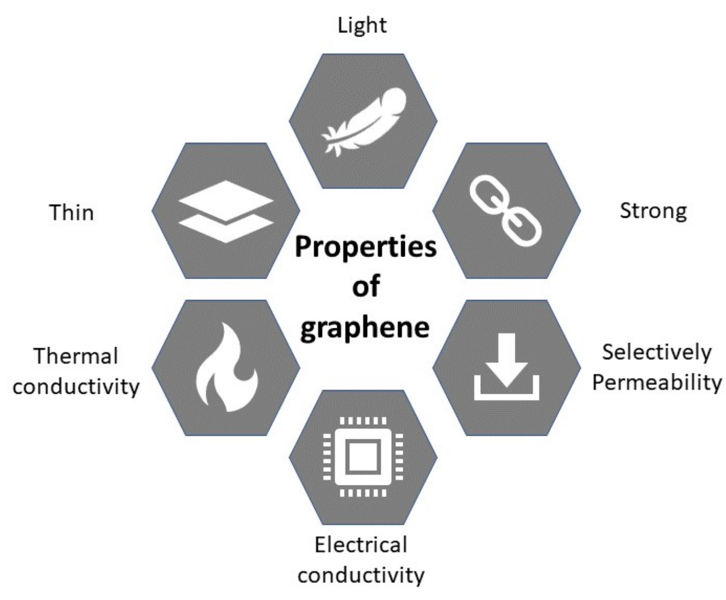

Figure 9: Properties of graphene

In figure 9 some of these material properties are displayed. It is already established that graphene is a very thin material due to layers only being one atom thick, which is also why it is light. Its atomic structure, which is similar to that of diamond makes graphene very strong. The atomic structure enables permeability and it can act as a barrier for gases. It is also an excellent conductor of electricity and heat which enables applications in electrical components. (Nobel Prize, 2010)

Graphene can be subdivided into three different groups; Single-layered graphene, double-layered graphene and multi-layered graphene. Single-layered graphene is the purest form and consists of a single layer of carbon atoms bound in a hexagonial honeycomb lattice. With a thickness of 0,34 nanometers it is currently the thinnest material known to man.(Bauhuis, 2020) It is an allotrope of carbon and stacked layers of graphene form graphite, with an interplanar spacing of 0,335 nanometers. The graphene layers in graphite are held together by van der Waals forces, which need to be overcome during exfoliation of graphene from graphite. (De La Fuente, n.d.)

Graphene can be produced using several different methods, but can largely be divided into top-down and bottom-up methods. Top-down methods, are cheaper and has the potential for larger scale production, but produces a lower quality graphene material compared to bottom-up methods. Since graphene is a single or a few layers of graphite, the main difference between the two methods is if layers of graphene are removed from graphite or if it is build from the bottom up. (Peleg, 2021)

In top-down methods graphene flakes can either be seperated from graphite flakes through mechanical cleavage or by exfoliation of graphite oxide prepared from graphite through oxidation and reduction. The latter process has a larger risk of introducing structural defects with functional groups containing oxygen, which is not as prevalent if mechanical cleavage is used. Mechanical cleavage is therefore a more optimal top-down process in producing higher quality graphene, but is harder to bring to large scale production. (Takai et al., 2020)

Bottom-up methods, with chemical vapor deposition (CVD) being the most widely used bottom-up method today, produces single-layered graphene of higher quality but is quite time consuming. In CVD, metals sheets of for example copper or nickel, are placed in a vacuum chamber. A mixture of gases containing carbon are passed through the vacuum chamber and single-layered graphene are formed on the metal sheets. It has the potential to create graphene with high structural perfection but it is difficult to produce large quantities of graphene. (Rudrapati, 2020)

Practical applications today are still in an early stage. Due to the excellent material properties of graphene, being very mechanical strong and experiencing great conductivity of heat and electricity, it has the possibility to be used in touch screens, light panels and solar cells, where it can replace Indium-Tin-Oxide which is rather fragile and expensive. There is also a possibility to utilize the mechanical strength in new light-weight composite materials for satellites and aircrafts. (Nobel Prize, 2010)

Graphamatech AB is a tech startup based in Uppsala, Sweden which has started to develop graphene compounds with metals and polymers. It is important when using graphene as an additive to disperse it well in the matrix material and ensure that it does not return back to graphite. They have a patented graphene hybrid material technology, called Aros Graphene, which claims to solve this issue with agglomeration in graphene applications. To ease the application of graphene they have developed ready to use compounds, both in the form of masterbatches and regular compounds. The graphene masterbatch used in this project is supplied by Graphamatech AB. (Graphmatech AB, 2022)

3.4.2 Glass fiber

Glass fibers are formed from melts of different raw materials depending on which type of glass fiber which is produced. This can for example be sand for silica based glass fibers or clay for alumina based. Since different raw materials can be used to produce glass fibers, the fibers can show different performances such as resistance to alkaline substances or high mechanical properties. Glass fibers are classified according to which composite it is utilized in. Glass fiber products are mainly categorized in four groups; chopped strands, direct draw rowings, assembled rowings and mat products. Out of these four product groups, chopped strands is the group which is most used as a reinforcement for polymer compounds. (Cevahir, 2017)

Glass fibers primary application area is in reinforcement of polymer matrices. The leading types of glass fibers are E-glass, high-strength glass and corrosion resistant glass. E-glass, which is the most widely used fibre reinforcement today, was also the first major synthetic composite reinforcement. It was originally developed for insulation in electrical applications which is where the origin of ("E") derives from. The primary reason why glass fibers are frequently used as fiber reinforcements are due to their low cost in combination with good mechanical strength. (Zweben, 2005)

E-glass fibers have a relatively low elasticity compared to other fibre reinforcements. In addition, E-glass fiber are receptive to creep and creep rupture. High-strength glass fibers are stiffer and stronger than E-glass, and exhibit better resistance to fatigue and creep. Glass fibers have low thermal and electrical conductivity, which is the reason why they are often used as thermal and electrical insulators. (Zweben, 2005)

The glass fibers which was used during this project originated from a recycled boat hull. It was an epoxy matrix reinforced with glass fibers at a ratio of 2:1, which can be seen in figure 10 .

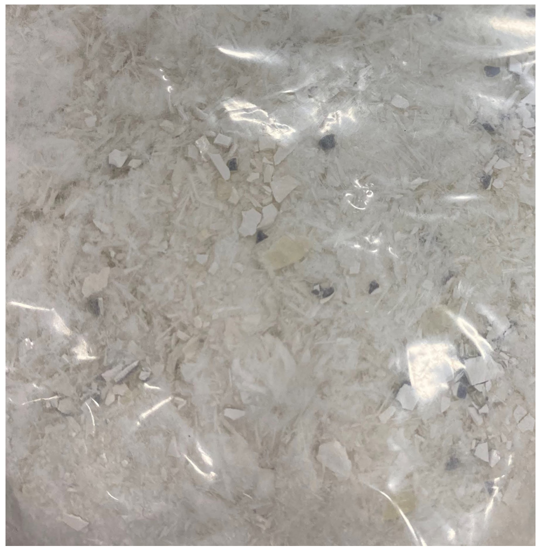

Figure 10: Shredded boat fibers consisting of 33% glass fiber and 66% epoxy.

3.5 Compounding

By definition from the dictionary, compounding is a process of combining a number of different components into one. The components which are combined form a new material with material properties which can be different from the original materials. Industrially, compounding can mean either optimizing ingredients to create an end product with desired properties, or to optimize the process of combining those ingredients. This report will focus more on the latter.

Optimizing compounding equipment and optimizing ingredients are not always independent tasks. There is often a processing window, or a range of compounding conditions, which yield a material with optimal material properties. While this interdependence can exist, one of these optimizations are often dominated in the industry due to economic circumstances. This can for example be if a company uses a limited set of ingredients, they may be more encouraged to optimize their equipment. Material properties to be optimized are defined by the customer and the final application. For polymers, this includes for example flow, impact resistance, tensile strength and color stability to name a few. (Wildi & Maier, 1998)

3.5.1 Basic concepts

To better understand compounding, some key concepts about material behavior must be explained first.

Melting Melting occurs when the temperature of a solid polymer rises and it turns into a fluid. Polymers which have a crystalline molecular structure shows a distinct melting point, similar to a metal. Amorphous polymers, which can be described as more "rubbery", are lacking the crystalline structure and the transition from solid to fluid is instead gradual. This temperature interval is called glass transition temperature, and an exact value when this occurs can sometimes be difficult to define. Semicrystalline polymers, such as polyamide, are partly crystalline and partly amorphous. These semicrystalline polymers show similar melting behavior as amorphous polymers, and also displays a glass transition temperature.(Todd, 1998)

Rheology Rheology describes how a material behaves when subjected to factors causing it to flow. The rheology of fluid polymers are particularly complex because these materials exhibit many unusual features. Polymers are often viscoelastic, meaning they show both elastic and viscous behavior. Flow is imposed on a fluid either by elongational or shear forces. Purely shear flow occurs when a fluid is located between two parallel plates and one plate moves faster than the other. An example of this is when a fluid is used to lubricate metal parts. Only elongational flow occurs when a fluid descends from an opening and thins into a smaller diameter.

Shear-thinning, meaning faster flow results in less resistance to flow, is a behavior shown by many polymers. Some examples are molten plastic, polymer solutions and ketchup. The opposite of shear-thinning is shear-thickening, which is a behavior that is quite rare to see in polymers. When polymers exit from a hole, such as when passing through a die, large changes in cross-sectional area compared to the cross-section area of the die may occur. While contraction sometimes can occur, most polymers show an expansion of cross-section area by as much as eight times. This phenomenon is called die swell. (Wildi & Maier, 1998)

Residence time Residence times, which some times also is referred to as dwell time, is the amount of time an arbitrarily selected small volume element spends inside the compounder during a compounding operation. This can be tested during a compounding operation by adding colored pellets when an all white material is being processed. The time it takes for the material to change the color intensity at the exit to match the intensity as the added pellets is the residence time. It is important to be aware of and control the residence time so that the material does not degenerate too much due to applied heat and shear forces. (Todd, 1998)

3.5.2 Equipment and preparation

Depending on what type of feeders the compounder has, batches are prepared in different ways. Feeders can either be volumetric och gravimetric, meaning it feeds material either by volume or by weight into the compounder.(Wildi & Maier, 1998)

Drying Drying the material before compounding is a requirement for most polymer resins. This is because many polymers are hygroscopic, meaning the material absorbs moisture from the atmosphere due to polarization in polymer molecules. Water is an highly polar substance and is therefore absorbed at higher content at increased polarization levels of the polymer. The amount of water absorption therefore depends on the polarization and a saturated material can have a moisture content of around 0,07% for certain blends of PPE (Polyphenyl ether) and as high as 8-9% for PA. (Sepe, 2014)

If a material is dried for too long, there is a risk of unnecessary breakage of the polymer chains due to thermal degradation. This increases the risk of producing parts of lesser quality. (Kulkarni, 2007)

Figure 11: Equipment for drying material

If these materials are not dried properly, down to about 0,02% moisture content, the risk of hydrolysis is high due to the pressure and heat in the compounder. This can lead to degradation of the polymer or create air pockets when the moisture evaporates which can compromise the structural integrity. (Hamm & Benjamin, 2017)

Preparing batches Depending on the type and number of feeders connected to the compounder and what type of material and additives used, batches can are prepared in different ways. First each material component is measured, either by weight or volume depending on the feeders, to achieve a compound with the right proportions of ingredients.

To ensure good dispersion of the ingredients, two different approaches can be taken. Either by using feeders for each ingredient which feeds the desired amount or by preblending the ingredients. During preblending, all components are weighed in a single container and mixed without melting. It can be a more economical option but it is important that all ingredients are of similar density, geometry and size so segregation does not occur. (Wildi & Maier, 1998)

3.5.3 Extruders

Material is fed through the compounder by rotating screw extruders. Extruder types can generally be divided into two categories, single-screw extruders and twin-screw extruders. The screws can either by left-handed or right-handed and turn in a clockwise or counter-clockwise rotation, see figure 12. Single-screws

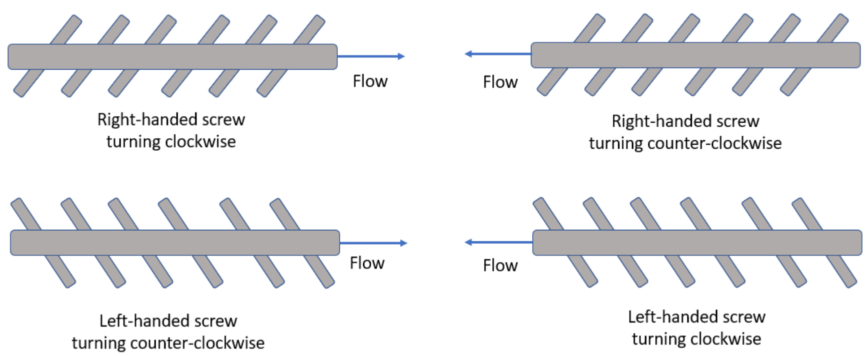

Figure 12: Screw orientation of left- and right-handed screws

are the simplest type and consists of a rotating screw inside a fixed cylinder, called a barrel, with openings for feed channels and optional venting. Material exits at the end of the barrel where a die is attached. The temperature inside the barrel is controlled in multiple zones along the length of the barrel.

The other main category of extruders are twin-screw extruders. They operate in a similar way as the single-screw extruder but instead used two rotating screws which rotates together. If both screws rotate the same way, the extruder is said to be co-rotating. If one screw turns in the opposite direction, it is said to be counter-rotating. If the counter-rotating screws are intermeshing, see figure 13, one screw must be left-handed and the other right handed. (Todd, 1998)

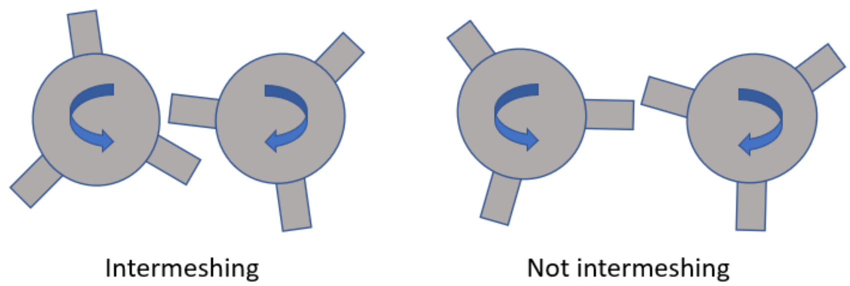

Figure 13: Intermeshing of counter-rotating screws

The main difference between the two screw types is that single-screw extruders are simpler and cheaper, but twin-screw extruders are better in mixing the material and have better self-cleaning properties. In some applications single-screw extruders can suffice but twin-screw extruders are generally preferred due to better and gentler mixing. (Useon, 2021).

3.5.4 Post compounding operations

The melt at the end of the compounding operation must be turned into solid form. Depending of the application of the compound, the shape and size of the solidified compound must be decided. The melt is cooled down by immersion in water at a continuous speed to ensure a string with a homogeneous diameter. If made into a filament, the string is then rolled up on a coil. The material can also be turned into pellets and the string is then led into a pellitizer which cuts the material in desired shape and size. (Wildi & Maier, 1998)

3.6 Part production with additive manufacturing

Additive manufacturing, also known as 3D-printing, is a production method which builds up parts layer by layer. It was first introduced in the late 80s by the use of a process called stereolithography (SLA), where UV lasers are used to cure layers of a light hardening photo-polymer into three-dimensional shapes. (Bruder, 2014)

Today, several different methods of additive manufacturing are available and prints can be made with a range of different material grades of metals, polymers and composite parts. The most common used polymers today are PLA and ABS. Applications of parts manufactured with 3D-printing are very flexible and can used in everything from prototypes to production equipment and end products. (Gibson et al., 2015)

Melt flow index is an important parameter for a material to be a functional material in a 3D-print. It is used to measure melt viscosity under a constant load and low shear rates. Higher melt flow index correlates with a material with lower viscosity. As the viscosity of the material decreases, the flow per unit time increases. Therefore, lower melt flow index relates to a higher viscosity. (Giles Jr et al., 2005) Too high flow rate leads to poorer accuracy in printing and worse dimension control. If the flow rate is too low it can affect the adhesion between printed layers which affects the structural strength of the finished print. According to Kumar et al.(2020), a composite should lay in the range of 20-30 g/10 min to work well in commercial 3D printers.

3.6.1 Fused filament deposition

Fused filament deposition (FFD) uses thermoplastic filaments which are fed through a nozzle, melted and extruded to build up layers in the horizontal direction. The nozzle is controlled by a computer, often with the use of a STL-file, and the nozzle moves a layer thickness vertically each time a new layer is printed. If available, a second nozzle can be utilized to either make supporting layers to reduce the risk of collapsing, or to add details with a different material to the part. When making supporting layers, it can be advantageous to use a material which does not melt together with the part. This is so the supports can be removed after a finished print. (Carolo, 2022)

FDM is a versatile printing technique. It can create small scale parts with high accuracy and but can also prioritize print speed if quality is not as important. However, FDM-printers are dependent on good quality feedstock material. A poor dimension accuracy of the filament can lead to several extrusion issues. Filaments of hygroscopic polymers also need to be stored appropriately to avoid water absorption which affects the printing process. (Carolo, 2022)

3.6.2 Large scale additive manufacturing

Large scale additive manufacturing (LSAM) uses similar principles as FDM, but pellets are used instead of filament. It is a fairly new additive manufacturing technique, gaining traction around five years ago. During operation, pellets are heated and extruded onto the base plate where it solidifies into the first layer. The extruder then moves in a pre-programed pattern, building adding layer by layer until the entire object is built. The extruder can either be mounted to an industrial robot or to a larger gantry system. (Redwood et al., 2017)

Parts printed with LSAM will always have a layered surface, which results in a rough texture. If there are requirements for smooth surfaces and high tolerances, post processing operations are required. The process are often better suited for organic and complex shapes rather than large flat surfaces, which are often easier produced by using a different production method. It is suitable for lower production volumes since the lead time is quite long. Performing smaller alterations from print to print is also easy, which makes it easier to create tailor-made products without large costs in changing tools and equipment or to optimizing the design by fixing minor errors. (Gibson et al., 2015)

Suitable applications for LSAM

- Complex and organic shapes
- Low volume production
- Layered surface texture
- Design optimization and rapid prototyping
- Parametric design

In theory, most thermoplastics could be used for LSAM. However, print parameters and design guidelines need to be adjusted according to which material is being used. For example, adhesion modifiers may need to be used to increase layer adhesion. (Redwood et al., 2017)

4 Summary of interviews

To get a context for using recycled ocean plastic, interviews where performed to gain knowledge from industry, brand owners and academia. In this section, a summary from the interviews held is presented. Information about all interviewees are displayed in table 1.

Name	Company	Position at company	Date of interview
Johan Landberg	RISE	Laboratory engineer	8/3-2022
Torkel Bjarneman	Graphmatech	Business development manager	9/3-2022
Mikeal Skrifvars	University of Borås	Professor	15/3-2022
Isac Andersson	EcoRub	CEO	7/4-2022
Karl Tibratt	Nordiska plast	CEO	11/4-2020
Thomas Eriksson	Sotenäs Symbioscentrum	Site manager	12/4-2022
Nils Åsheim	Add:North	CEO & Co-founder	12/4-2022

Table 1: Information about representatives interviewed

4.1 Interviews - Recycled materials

Nordiska plast is a plastic manufacturer based in Gislaved, Sweden which have developed, manufactured and marketed various plastic products for 60 years. 25% of raw materials used last year by Nordiska plast was either recycled or came from fossil-free sources, according to Tibratt. About 85% of plastic used by Nordiska plast is polypropylene, which is bought from Europe. 10% is polyethylene and the rest is other plastic types. They buy post-industrial waste and get their own waste from production after color changes. They also use ocean waste plastics, mostly different ropes and fishing nets, which they get from a supplier in Norway. Nordiska plast was also the first plastic supplier in Scandinavia to be certified in accordance with the International Sustainability and Carbon Certification PLUS System (ISCC PLUS), and the polypropylene used is produced from fossil-free oil.

Andersson at EcoRub AB explains that the company compounds plastic materials which uses materials that the customers desire. Recycled plastic used in production can come from medical waste, industrial waste or from ocean plastics. They recycle some material internally but they also buy recycled materials from external sources, such as industrial spillage which otherwise would have been incinerated for energy recovery.

Skrifvars at Borås University has researched the possibility to extract glass fibers from a polymer composite through pyrolysis, but according to him it was not a profitable way to obtain glass fibers. To reutilize the composite, mechanical recycling of a composite with thermoplastic and glass fiber is possible since the properties of a thermoplastic material enables recycling. If necessary, virgin material can be added to achieve desired properties.

Add:north uses different recycled materials in their filaments, for example 100% recycled ABS which they buy from a supplier. Add:north also has a recycling program where customers can send in PLA spillage. They have collaborated with Sotenäs where contaminated plastics were passed through a melt filter at RISE to decrease the contamination. According to Åsheim, it is very important that the material is clean for a good filament.

According to Eriksson, Sotenäs received 207 tons of marine waste last year. It is first sorted rough in for example, ghost nets, large and small nets, trawl nets. After the first sorting, the nets are brought into the facilities and divided manually into different materials by cutting with knives. Metal is removed and divided, which Stena metall later collects for recycling. Plastics was 2021 divided according to customer needs, which could be plastic types of certain colors such as green PE nets. This year, they instead try to divide plastics into even more fractions, due to directives from the European Union about how waste should be sorted in the future. Examples of this are PA nets thinner than 1 mm, PA nets larger than 1 mm, PP, PE and PET. The largest fraction of nets is PE and smaller nets are often made out of PA.

Sotenäs receive marine waste through several different channels. Through Fiskereturen, which is an initiative founded by the Swedish Agency for Marine and Water Management, Sotenäs collaborates with Håll Sverige Rent, Båtskroten and Fiskareföreningen Norden to collect fishing gear which is no longer used. They have created advertising campaigns which have led to private individuals bringing in waste they have found in the environment. Projects with bottom trawling for ghost nets have also been initiated.

Eriksson says that between 60-80% ,of all material they received last year, was recycled, 10-20% was reused and 10-20% was sent to the thermal power plant in Uddevalla for energy recovery. No material went to landfill. Materials which went to energy recovery were mainly nets with high contamination of metals, clay and tar, nets which were extremely entangled or color contaminated.

4.2 Interviews - Compounding

According to Landberg, it is very important that the material is properly dried before compounding, to prevent degradation. If the moisture content is not lower than 0,02% there is a high risk of water evaporating during the compounding process, creating air bubbles in the material and the degree of filling.

If there is a large difference in size of the shredded fishing nets, it could lead to problems with the feeding mechanism. This is especially true if the shredded parts are too long, because they risk jamming between the screws and the barrel, which actually happened during the compounding of the test materials. Irregular feeding can lead to a difference in material composition of the finished compound, especially if individual pellets are studied. Landberg says that this have less impact when the whole batch is studied, since individual differences in pellets evens out over a entire batch.

EcoRub manufactures a material named TPRR (Thermo Plastic Recycled Rubber), which is a compound consisting of recycled plastic and rubber. More than 90% of TPRR consists of recycled materials and to improve the bond between the plastic and the rubber a certain copolymer is used. According to Andersson, the addition of rubber can in general lead to a material with enhanced properties, such as higher impact strength. However, it can in some cases yield a lower fracture toughness. It depends on the materials used and what properties are sought after, which requires testing to verify.

Skrifvars describes that the fishing nets consist of fibers in the form of filament. If all material is melted, this should not affect the flow properties and should in theory work to run in injection molding. Which parameters that have to be used for a good injection molding has to be tested. Skrifvars mentions that it could be interesting to further research if the fibers could be added to material with a lower melting point, so the fibers do not melt and stay intact. In that case, the fibers could add mechanical properties to the material.

4.2.1 Interviews - Graphene as an additive

Bjarneman describes that Graphmatech is a compounder who manufactures metal and polymer based compounds with graphene. In addition to compounding they also work with energy storing solutions. In their polymer division they mix graphene powder with thermoplastics such as PA, HDPE and TPU for example. They use graphene powder in varying chemical constellations, of which some is produced internally. They can functionalize the graphene for a better compatibility with the matrix material, and have a patented process to functionalize or modify the graphene so the flakes do not revert back to graphite. Graphene flakes tend to revert back to graphite, and to deal with the issue they try to disperse it in the matrix material to get the desired properties.

According to Bjarneman, the main strengths of using graphene are electric and thermal conductivity, enhanced mechanical properties and as a barrier for gases. Graphene as a material exhibits permeability towards gases which makes it a good barrier material. However, since graphene is a nanomaterial, and it can be difficult to extract from the matrix material during recycling.

Graphmatech began as a startup which did a lot of projects adapted to customers. Their main focus has been on compounding graphene with thermoplastics which can be used primarily in injection molding and extrusion. Bjarneman explains that they have worked with many different matrix materials earlier but moves towards a more standardized material range to simplify application for the industry. Masterbatches are the main focus, simply because incorporating graphene into plastics is one of the major difficulties in the industry. Graphmatech uses traditional compounding methods to make masterbatches which can be added in later compounding to get a finished compound which is graphene enhanced. At present, they have a standardized masterbatch based on HDPE but the next standardized masterbatch will probably be based on PA. In addition to masterbatches Graphmatech also works with graphene-coated polymer powders and graphene-enhanched filaments to target additive manufacturing methods such as selective laser sintering (SLS) and FDM.

Application of graphene is still in a development stage and the mass industry has not found major uses yet so a large demand for graphene does not exist today. Graphene producers say that they will not scale up production until that demand is met. According to Bjarneman, there is enough to meet the demand in the coming years. However, upscaling of graphene production, especially in Europe, needs to take place relatively soon in order to be competitive.

4.3 Interviews - Quality requirements

Tibratt mentions several limitations when using recycled plastics. Contact with food, scent, coloring difficulties and mechanical properties are a few examples. These limitations can restrict which applications the recycled plastics can be applicable for, for example if there are requirements for food grade or color. Tibratt says that ocean plastics are viscous, which makes it difficult to use in injection molding. To overcome this, they mix it with polypropylene at a ratio of 70/30 to increase the flow rate.

Andersson says that quality requirements for plastic depend largely on the requirements for the end product. Different manufacturing methods require materials with different properties. An example of this is polypropylene which is a commonly used plastic but not really suited for 3D-printing, compared to PLA which is a frequently used filament. PP has to be adapted more compared to PLA when used in 3D-printing. However, it can be costly to upcycle a material to achieve desired properties. He means that it is better to instead locate material flows where the properties of the material already match the product demands to get a more cost effective material. Basically to find the right material match for each product.

Eriksson describes that the nets they receive at Sotenäs can be of varying quality. Ghost nets are often of poor quality, some nets are almost brand new and some lay in between. They experiment with washing of dirty nets but it is not something they do at a larger scale today, but they are discussing about implementing it in the future. To try and decrease contamination of metals and organic materials, experiments with passing nets through a melt filter at RISE have been conducted. Cleaning with melt filters is a relatively expensive process which can lead to difficulties in implementing at an industrial level.

According to Eriksson, metal contamination has been a problematic issue for their customers. In general, the material has to be clean for a successful recycling. Although, some companies do not require as clean materials for the manufacturing process. Eriksson gives an example of a company which makes pallets out of plastic, which does not have as strict demands for material properties.

4.3.1 Interviews - Quality assurance

Quality assurance is an important part of a compounding process, to ensure that the material fulfills the desired properties. Andersson at EcoRub strives to have an equal process for quality assurance of recycled materials as for virgin materials. This includes standardized tests such as tensile and impact tests to verify that their materials have the desired standard. They have seen a continuity in their materials but if the quality would differ much between batches the production would stop until the fault is corrected.

Tibratt states that quality assurance for virgin materials is easier since data sheets are often available. Material testing has in that case already been conducted and the expected properties are known. Since the quality of recycled materials can vary depending on prior usage, it is harder to know material properties beforehand. Therefore, quality assurance is important to verify material properties of recycled materials, and they test for example melt index and impact strength.

Quality assurance is an important step in the process at Graphmatech. According to Bjarneman, graphene in itself can be characterized in several different ways. This includes for example specific surface area and thickness. Their output is to measure the end material and a good indication if the dispersion of graphene is sufficient is to measure electric conductivity. They also perform tests to verify that the material achieve desired properties.

At Add:north, they perform several different tests to ensure that their materials live up to required standards. Dogbones are created for tensile testing, impact strength is measured and test prints are performed. Åsheim emphasizes that the melt flow index is one of the most important parameters when a material should be used in additive manufacturing. When the material is extruded into filament, it is advantageous to have a low melt index. For a material to work well in 3D-printing, it is instead preferable to have a high melt index. Therefore, it is important to try and find a material which lies somewhere in between. It is also important to have a continuity in the diameter of the filament to achieve a quality print.

4.4 Interviews - Circularity of sustainable plastics

A circular flow plays a key role in the philosophy at Nordiska plast, explains Tibratt. Spillage from production is shredded and reused in new products, such as bins. They reuse in average an average year more than 500 tonnes of spillage. To take responsibility externally, products are designed to be easily recycled and they are marked with material symbols.

Customer circularity is an important part of the vision at EcoRub. Andersson says that designing for recyclability is an important step towards getting circular flows. Since EcoRub is a compounding company, they do not manufacture products where designing for recyclability is applicable. Instead they try to raise that point of view with their costumers, so they hopefully include it in their design process.

Sotenäs is running a project, called Spiral, which aims to improve circularity. It consists of two parts and the first part is a standardization of fishing gear to design fishing nets in the future with the intention to ease recyclability. They discuss identification markings in the form of microchips to be able to identify manufacturer, material composition and how to divide the nets during recycling. They also discuss establishing a database where this information can be stored. Parts of this project takes place at an European level.

The second part is, in collaboration with the Swedish Agency for Marine and Water Management and the Swedish Environmental Protection Agency, about producer responsibility which shall be implemented by 2025. They study how to improve collection of marine waste and they have invited several producers into collection groups, since it is their responsibility to make it work in the future. Eriksson also mentions another project called Digital Twin, where they want to digitize the material flow at Sotenäs to be able to follow the recycling process and sorting flows. The vision is to be able to follow the entire journey from cradle to grave for a single net.

4.5 Interviews - 3D-printing

According to Åsheim, PE, PP which are commonly used plastics works poorly in filament printing. In general, it is more difficult to use partly crystalline plastics in 3D-printing, than amorphous. When developing a filament, a high flow and low shrinkage is preferred. Processing temperature should also not be above 300 °C. Amorphous PET has a melting point above 300 °C but if modified with glycol into PET-G, lowers the melting point and makes it more suitable for filament printing. In general, filament printers can print with more precision while pellet based printers can make larger objects. Common issues when a new material is tested in 3D-printing is too much shrinkage and poor adhesion between layers and to the print bed. Print bed adhesives can be used to try and mitigate poor adhesion.

5 Results from material testing

In this chapter the results from MFI and tensile tests will be presented.

5.1 Abbreviations for tested materials

Two different types of material testing was conducted, a tensile test and a test of melt flow rate. Abbreviations are used for each compound and can be seen in table 2.

Material	Abbreviation
Ravamid	Rav
Fishing net + 10% Graphene(MB)	FN + G10
Fishing net + 20% Graphene(MB)	FN + G20
Ravamid + 20% Graphene(MB)	Rav + G20
Fishing net + 20% Boat fibers	FN + BF20
Ravamid + 20% Boat fibers	Rav + BF20

Table 2: Abbreviations of the different compounds

5.2 Results for melt flow rate

The melt flow tests was carried out by Landberg at RISE, since equipment for those tests was not available at the university's facilities. The main intention of the melt flow tests are to study material degradation, since during every processing cycle, polymer chains breaks and gets shorter which results in an increase of MFI. Therefore, MFI is often a good indication on material quality of polymers. (Jmal et al. 2018) The results from tests of melt flow index can be seen in table 3.

Material	**g/10 min**
Ravamid	27,5
Fishing net + 10% Graphene(MB)	8,9
Fishing net + 20% Graphene(MB)	5,4
Ravamid + 20% Graphene(MB)	12,1
Fishing net + 20% Boat fibers	104,6
Ravamid + 20% Boat fibers	72,9

Table 3: Results from melt flow rate tests

5.3 Results from tensile testing

Tensile testing took place at LTH, supervised by Dmytro Orlov who is a professor at Materials Engineering at the university. Two choices of machines were available with the main difference being the maximum force available. The smaller machine could apply up to 2 kN of force, while the larger machine could apply up to 10 kN of force. To know which equipment that should be used, an estimate of the required force to break the specimen was calculated by measuring the cross-section area of the specimen and multiplying it with the yield stress of Ravamid from the data sheets (Resinex, n.d.).

$$F_{exp} = \sigma_{exp} * A_{cross} \tag{1}$$

The calculated force required for Ravamid was 2 kN and since the reinforced materials were expected to require more force, the larger machine was chosen. To see if the tensile tests would yield trustworthy results, Ravamid specimens were tested first and compared to its corresponding data sheet from Resinex. Results from tensile testing can be studied in table 4. Values shown are average values from the five tests of each material compound. The entire data from the tensile tests can be studied in Appendix C.

Material	Stress at yield MPa	Stress at break MPa	Strain at break $\delta L/L$	Tensile modulus GPa
Rav	49,64	60,52	17,32	2,44
FN + G10	45,35	51,82	21,17	2,13
FN + G20	42,66	57,68	15,75	2,09
Rav + G20	38,75	53,66	18,48	2,09
FN + BF20	48,56	58,82	2,31	3,38
Rav + BF20	38,37	56,54	2,74	3,08

Table 4: Results from tensile testing

6 Analysis of material tests

In this chapter an analysis will be presented and discussed about the results received from the material tests

6.1 Analysis of melt flow index

Melt flow index measures the flow rate of a material and is a good indication of material degradation. A high MFI means a material has lower resistance to flowing and often corresponds to a higher material degradation in where polymer chains have gotten shorter. Reinforcement additives also impacts the flow rate of a material. (Kumar et al. 2020)

The results provided from the MFI tests, which can be seen in table 3 show contradicting results. It makes it difficult to draw clear conclusions. However, some conclusions can still be made. Graphene increased the viscosity of the compounds which lowered the melt flow index. An increase in graphene content seemed to decrease the MFI. Boat fibers had the opposite impact of instead increasing the melt flow index.

It hard to say what the MFI of pure fishing nets is. If the graphene compounds are studied, MFI for pure fishing nets should be lower than for pure Ravamid. But if the boat fiber compounds are studied, fishing nets should have a higher MFI than Ravamid. Therefore it would have been advantageous to test melt flow index for uncompounded fishing nets to see material degradation in the material. In a study done by Kumar et al. (2020) it was observed that the melt flow index of recycled PA6 was 19.01 g/10 min compared to virgin PA6 which was 23.30 g/10 min. The decrease in MFI of recycled PA6 showed degradation in flow-ability of the material after recycling.

MFI is also an important parameter to consider in additive manufacturing. According to Åsheim, it is preferred to have a low melt flow index for filament extrusion and a high melt flow index for 3D-printing. It is therefore important to find a material which lays somewhere in between. Because of this, adding too much graphene may cause the material to be less suited for additive manufacturing.

6.2 Analysis of tensile tests

To validate if the performed tensile tests gave trustworthy results, Ravamid was used as a reference point since the material is quality assured and material properties are available from data sheets. If the test results corresponds to what is stated in the data sheets, it confirms that the test yields valid results. This comparison is visualized in figure 14. Green bars shows average values for Ravamid during the tests and red bars is expected values from the data sheet. As seen in the figure, data from the tests with Ravamid corresponds fairly well to expected values from the data sheet. The main difference is in stress at break, which showed higher values than expected. However, in three out of five specimen the values for stress at break were closer to the expected values but two specimen showed diverging results which altered the average value. Therefore, if more specimen would have been tested the results for stress at break would probably lay closer to the values from the data sheet. Due to this, the tests are considered to provide reliable results.

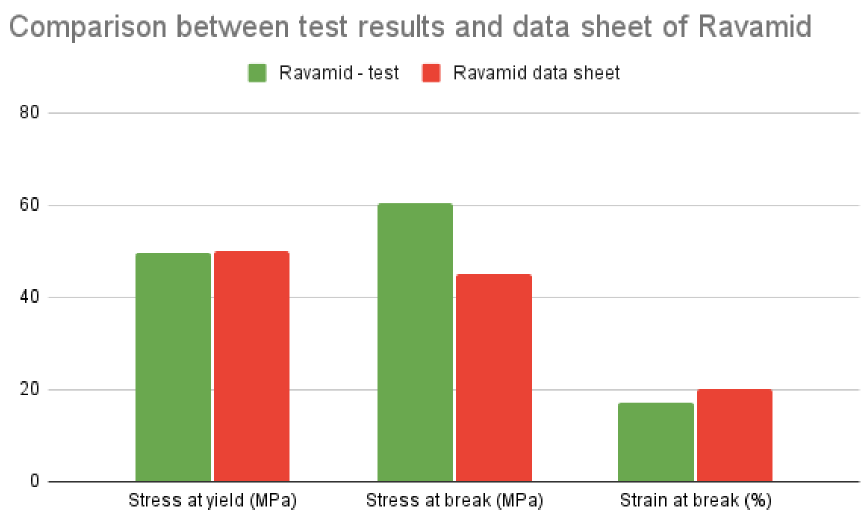

Figure 14: Comparison between test results and data sheet of Ravamid

When comparing the recycled fishing nets to the reference material Ravamid, the fishing nets showed a slightly stiffer behavior compared to Ravamid. That is true for all cases tested, which can be seen in figures 15-18. When the same type and amount of additive was used, the compounds which were based on recycled fishing nets could withstand more stress and showed a lower elongation at break. One reason for this could be that the fibers in the fishing nets contributes in making the compound more stiff. However, all compounds showed a reduction in stress at yield and break compared to pure Ravamid.

When studying the results of compounds with graphene, which can be seen in tables 15 and 16, an increase of graphene content lead to a decrease in yield strength but an increase in stress at break. According to Takai et al. (2020) if graphene is poorly dispersed in the compound, an increase in graphene content actually decreased the mechanical strength of the material. This could be a reason why the tests show a decrease in yield stress when there was an increase in graphene content.

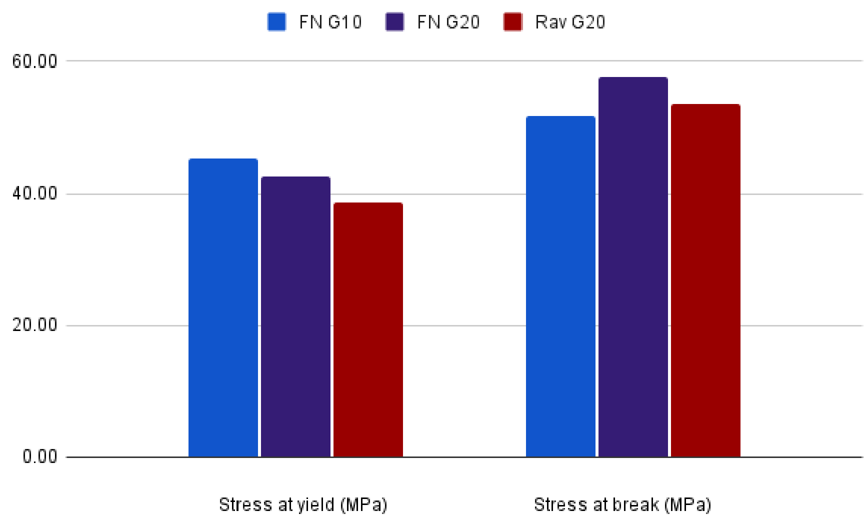

Figure 15: Stress at yield and break for the different compounds with graphene

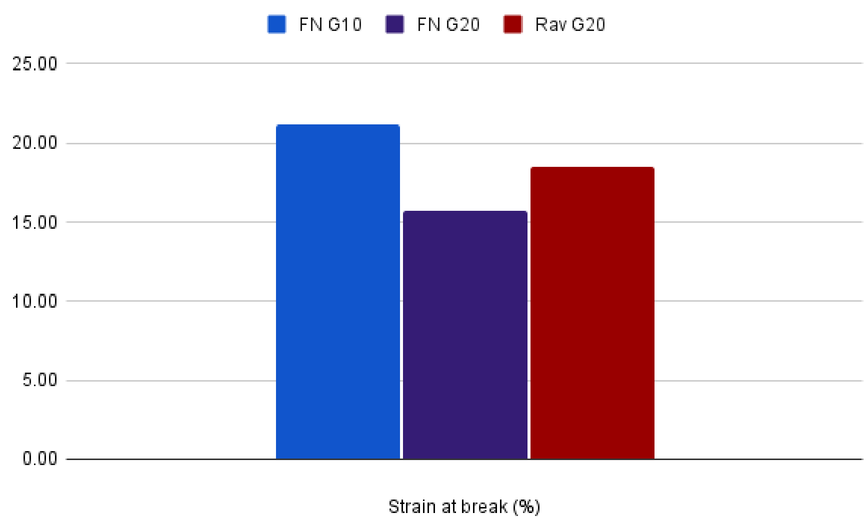

Figure 16: Strain at break for the different compounds with graphene

In the compounds with boat fibers, seen in tables 17 and 18, they showed similar behaviors compared to glass fiber reinforced PA6 by experiencing strain at break around a few percent. Information available from data sheets on Resinex's website shows that Ravamid with 15% glass fiber experience a strain at break of 4,5% and decreases with higher amounts of glass fiber reinforcement. The glass fiber content in the recycled boat fibers was 33%, with the rest being epoxy. This corresponds to a glass fiber content of around 7,5% in the boat fiber reinforced compounds. This should imply that strain at break should be slightly higher than 4,5% for the tested boat fiber reinforced compounds. It is clear from the tests that it was not the case, as seen in table 18 where for both matrix materials the strain was below 3%. However, it is hard to make a exact comparison between boat fiber and glass fiber since it is difficult to anticipate the impact of epoxy.

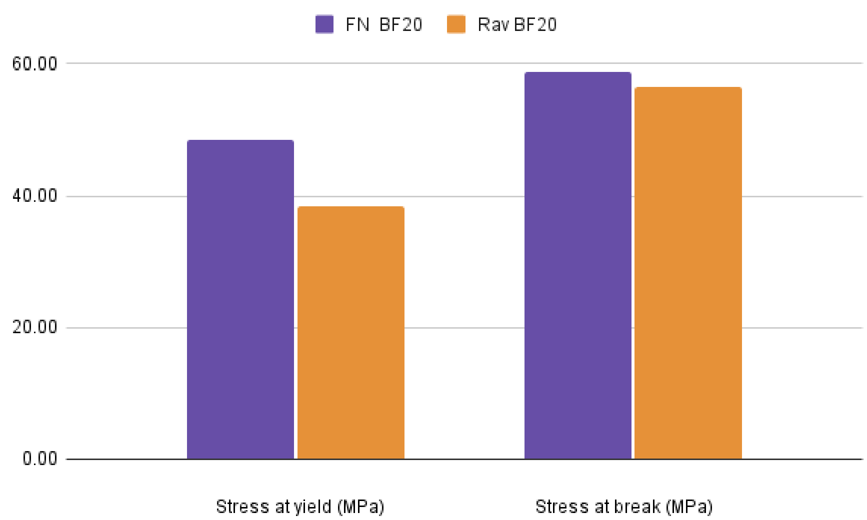

Figure 17: Stress at yield and break for the different compounds with boat fibers

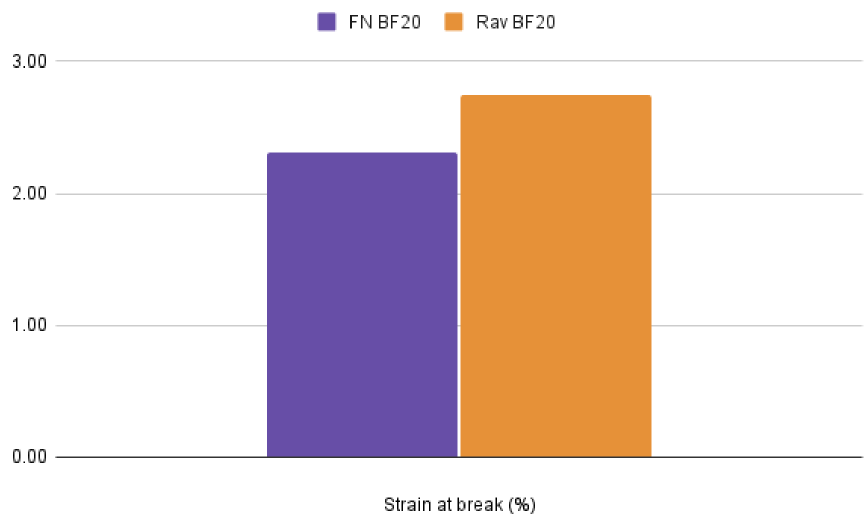

Figure 18: Strain at break for the different compounds with boat fibers

A reduction in material strength occurred for all compounds when a reinforcement additive was used. It gave the opposite effect of what was sought after. The reasons behind this has probably to do with issues during compounding. For a reinforced material to have an increased strength, it is essential to have a good dispersion of the reinforcement additive in the matrix material. Irregularities in dispersion can lead to weak spots in the compound, which can affect the material properties negatively. Moisture content in materials before compounding and temperature control during compounding are also important parameters to achieve a compound with desired properties.

To better validate the results, more specimen should have been tested to get a better statistical basis. Since only five specimen were tested of each material, any irregularity will have a greater impact on an average result. In half of the materials tested there was at least one specimen which showed irregular behavior.

7 Discussion

The methodology applied can be divided into three categories; a literature study to lay a foundation of prior knowledge, interviews with company representatives and researchers to understand how this knowledge is applied in the industry today and performing material tests on own compounded material to see how well it corresponds to expected results. In general, this arrangement felt like a structural approach to tackle this task but some improvements could be made.

First of all, there was not a possibility to perform material tests on pure recycled fishing nets due to limited quantity available from OCT. A recycled PA6 material from Resinex, which should have similar properties, was used instead as a substitute. To increase credibility, it would have been advantageous to perform tests on pure recycled fishing nets and compare it to virgin material to collect data about the quality of recycled nets. This could further on be complemented with tests of recycled fishing nets with varying quality and degradation to build up a database similar to what exist for virgin materials.

The interviews held covered the research questions but could be complemented with more interviews, especially with international representatives to get a deeper global insight and a wider perspective. Waste management of ocean plastics is after all not only a local issue and it would have been interesting to discuss how the cooperation between different global actors works today and how it could be improved in the future. It would also have been preferred to have had all the interviews recorded since it was difficult to keep notes while simultaneously leading the interview.

Many of the interviewees underlined the importance of using recycled material without much upcycling and find product flows where material properties match the requirements of the product. It can be expensive to improve the quality of a material, by trying to purify the material or compensate for lost mechanical properties. To be able to stay competitive cost wise against virgin materials, which are relatively cheap depending on plastic type, upcycling should be minimized. However, the type of plastic recycled can play a key role. For example, Eriksson at Sotenäs said that the most common plastic found in the nets received was PE, where smaller nets were often made by PA. PA is a higher quality plastic compared to PE, with better mechanical properties and also more expensive. This gives a higher economical incentive for recycling PA nets.

Another important aspect to consider is the ability to market products as recycled, which could make consumers willing to pay more even if the recycled material is more expensive to produce compared to virgin material. Directives from the European Union also puts demand on all plastic requiring to be either reused, recycled or compostable, which increases the incentive to use recycled plastics.

To be able to replace existing materials, it is crucial to know the material properties of the recycled materials. Establishing a database of recycled materials is key in creating opportunities for producers to start considering recycled options. Quality assurance should be of the same importance as for virgin materials. It would also be interesting if information about materials life-span and place of origin could be available. Eriksson mentioned projects concerning tracking the fishing nets journey by the use of for example microchips or QR-codes.

Graphene is a material with excellent properties such as; electrical conductivity, thermal conductivity, permeability, light weight and high mechanical properties. However, it is an expensive material which can narrow the application areas. If these properties are utilized, it can be a great choice of material. Since the today's availability of graphene is limited and still in a developing stage, the target products should match the supply.

To utilize the material properties of graphene, it is very important to disperse it well in the matrix material and ensure that it does not revert back to graphite. It can be difficult to achieve for a producer which is not experienced in working with graphene. It is therefore advised to let an external party with experience in graphene applications to prepare it in the form of masterbatches, which are applicable more easily.

Graphene is absolutely not a poor option as an additive, but should it be used to upcycle recycled materials? Another option would be to try and straight out replace products which are produced by virgin materials with recycled materials and instead use virgin materials for products with higher demands. If only mechanical strength is sought after, a cheaper option such as glass fibers might be a more suitable option.

As a manufacturing option, 3D-printing has a strong upside by being flexible in what products can be produced with short lead times. Recycled fishing nets can not be ensured to always sustain a steady supply, as with virgin materials. Therefore, being able to adapt the production method to create products which reflects the quality of the current batch is optimal. Since the fibers of the fishing nets leads to a material with low flow rate, it can be difficult to use in injection molding which is a conventional manufacturing option. Extrusion is not as affected by this, and since additive manufacturing methods such as FFD and LSAM are basically extruders, it further motivates 3D-printing as a manufacturing option.

The two material test methods which were chosen gives a good indication of material properties and degradation of the recycled fishing nets but they do not display the whole picture. In order to get an even better understanding of the material properties, these tests could have been complemented by more tests of for example impact strength, aging and tests to determine material composition.

The analysis of the tensile testing were done by calculating the average value from each material tested. This gave a rough estimate of the material properties but to get more accurate results, a more in-depth method of analyzing could have been applied. An example would be to standard deviation and to discard values which exceeds 90% of the population. Since the material quality varies more in recycled materials compared to virgin materials, using a material analysis which is not as affected by extreme cases is preferred.

For future studies it would be interesting to delve deeper into implementation of quality assurance for recycled materials. How to actually implement a database based on results from quality assurance, both nationally and at a global level. How products made out of recycled materials should be designed to enable repeatable reuse and recycling is a very important part for a circular material, and should be looked into further in future studies.

It would also be interesting to perform a design of experiments on the tests and reinforcement content in the compounds to get a better understanding of how the reinforcement content affect the material properties. This could then be used to optimize the material compounds to achieve desired properties.

The real question is why should recycled material be used. Is it to tackle the increasing waste problem or to try and create a new unique material with excellent properties? These two approaches do not have to contradict each other but researching a new material and implementing it takes time. Therefore, to make use of recycled material today, low effort solutions must take place where material upgrading is minimized and properties sufficiently fulfills the requirements for the end product. To meet the required properties, quality assurance of recycled material has to take place and be documented. This could be by measuring melt flow index to examine degradation and by performing mechanical tests to study mechanical properties. By knowing the material properties for every recycled batch, it will be easier to match it to product flows and also help in seeing patterns in quality of fishing nets from different conditions and suppliers.

8 Conclusions

A good division of materials is the key for a functional recycling, which means that information about material content of the fishing gear is very important and that materials can be easily separated. To simplify data collection of quality for the nets, identification of origin, manufacturer, material composition and time of use would have to be implemented. The quality of nets can be very different, often poor in the case of ghost nets and high for nets which have barely been used. It is important that the material is not too contaminated to retain good enough material properties.

Recycling should be prioritized in the following order today; reuse, mechanical recycling, chemical recycling and energy recovery. Reusing is the most cost effective way to recirculate materials, since no granulation or further recycling is needed. If the fishing gear still retains working quality for fishing, they can be sold on the second hand market. If further recycling is needed, mechanical recycling by granulation is preferred. To be successful, the material requires to be clean from contamination, such as metals, organic materials and tar, and be divided into material types. If the materials are too contaminated, they can either try to be washed or chemically recycled. However, chemical recycling is still in a developing stage and not really utilized in the industry today. It could be a more viable option to energy recovery in the future, which is the final recycling step today.

Plastic materials can in general be heated to melt around seven times until material properties are reduced too much due to thermal degradation. Therefore it is important when compounding to handle the material as gently as possible. Moisture content of PA needs to be reduced below 0,02% by drying before compounding and during compounding the heat dispersed should be controlled carefully. If possible, double screw extruders should be used to mix the materials faster and gentler which can reduce the required barrel length and therefore the time being treated with heat.

The use of additives should try to be limited and reflect what is needed for the end product, both to reduce cost and to simplify recycling. A material which overachieves in required properties can have difficulties in staying market competitive, which is really important if recycled materials should be implemented. This means, for graphene to be a viable additive option, the end product needs to have high demanding material properties.

Additive manufacturing is a viable manufacturing option for recycled ocean plastics due to it being less affected by the high viscosity of the recycled fishing nets compared to injection molding. It is also an adaptive production method which can create products which match the quality of the current batch, which can vary for recycled materials.

To conclude this report and answer the research questions presented in the beginning the following things can be said. It is important that the fishing nets are clean and separated by materials and that the recycling process follows the priority of re-use, mechanical recycling, chemical recycling and energy recovery. Quality assurance is a very important step in order the know the material properties of the recycled material. This is key both when it comes to upgrading and to compare it to other available materials on the market. 3D-printing is a viable manufacturing option for recycled fishing nets due to the flexibility to produce products which matches the quality of the current batch. It is also less affected by a decrease in viscosity from the recycling process.

Potential activities which could follow up on this report can be to research how to better implement a standard for quality assurance for recycled materials. Another possibility is to delve deeper into the compounding process to optimize material compositions and processing conditions to achieve better quality materials.

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A Appendix A Time plan and outcome

Time plans for the project can be seen in figure 19. The left image is the time plan which was made at the beginning of the project and the right image is how the actual outcome of the project. The main differences between planning and actual result are colored yellow in the right image.

The project ran according to plan until I started to write the report. It took a lot more effort than I did expect, which for example led to a decision to not try and find more people to interview and focus solely on completing the report in time. The writing continued to go slow, and a decision was made to postpone the hand-in and presentation of the thesis to August instead of June. This allowed me to finish the writing at a slower pace and led to a finished report at the end of August.

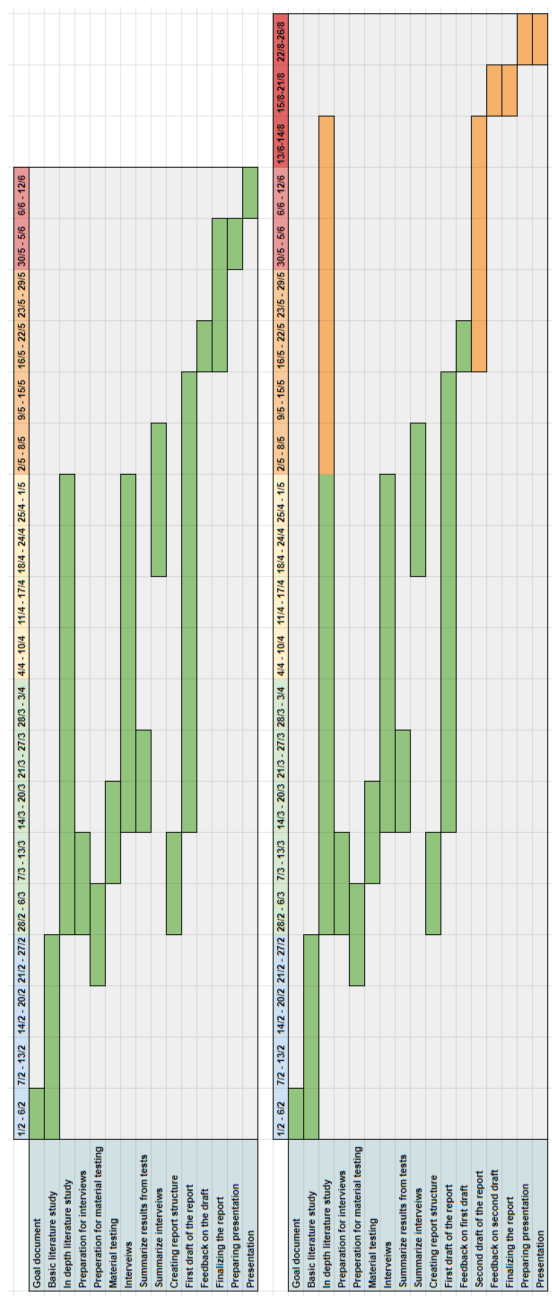

Figure 19: Expected time plan and actual outcome for the project

B Appendix B Interview questions

B.1 Johan Landberg - RISE

- How long is the material dried before compounding and at what temperature?
- What type of extruder is used? What feed rate, screw speed and temperature is used? Does it differ between the different compounds?
- Which materials are used and what is the ratio of the different materials in each compound?
- How and when is graphene added into the extruder?
- What is the size of the pellets after extrusion?
- Which source of errors in compounding can lead to a material with poorer properties? What is critical that it is done correctly?
- Are there any difficulties in injection molding of dogbones, regarding the fiber quality of the fishing nets?
- What do you see as mandatory properties for an additive to improve the properties of recycled polyamide?
- What possibilities/difficulties are there in recycling the compounded material?
- What is the difference in using epoxy reinforced glass fibers compared to regular glass fibers and how does it affect the material properties?

B.2 Torkel Bjarneman - Graphmatech

- How do get your graphene? Do you buy it from a supplier or do you extract it yourself?
- How is the supply of graphene today globally?
- What is the environmental impact of graphene production?
- Can you elaborate on your tailor made masterbatches?
- How do you work with quality assurance of your materials?
- What shape, size and dispersion is the graphene in your masterbatches?
- What is important to take into account if you want to use graphene?
- Which polymers are suitable for compounding with graphene?
- What material properties does graphene mainly contribute with?
- What opportunities/difficulties do you see in recycling a product containing graphene?

B.3 Mikael Skrifvars - Borås textilhögskola

- How are the fibers for fishing nets produced?
- What are the difficulties in recycling fishing nets?
- How is the fiber quality affected of fishing nets which have been in the oceans? Degradation, infiltration of microorganisms etc.
- How does the extrusion/injection molding quality of the fibers affect recycled fishing nets? How does the rheology change?
- Fiber orientation in recycled composite material, can it be controlled and is it desirable to do so?
- What happens to the fibers when the material is melted?
- Regarding your report about chemical recycling of glass fibers, What are the possibilities of recycling glass fiber reinforced composite material?
- What would you say is the difference in material properties between glass fibers with epoxy and glass fibers without epoxy?

B.4 Isac Andersson - EcoRub

- What kind of recycled plastics do you use in your products?
- Where do you get the recycled plastic from?
- What are the requirements for plastic to be used in your materials? Homogeneous, quality, clean, etc.
- Do you recycle rubber yourself or do you buy it already recycled? What does the recycling process look like in such cases?
- How do you ensure the quality of your materials?
- How do you adapt your material for different production techniques such as injection molding or 3D printing?
- How do you manufacture TPRR? Is it through compounding or do you use some other manufacturing method?
- When you develop a new material, what are usually the greatest difficulties in developing a material with desired material properties?
- What are the strengths/disadvantages of using rubber as an additive?
- What are the requirement for plastics to be compounded with rubber? In your experience, which plastics works best together with rubber?
- On your website you state that you work with customer circularity, what kind of approach do you have regarding the materials you sell? What are possibilities to recycle/reuse your material?

B.5 Karl Tibratt - Nordiska plast

- What kind of plastics do you use today in your products and where do they come from?
- The marine plastic you use, what type is it and where do you get it from?
- What are the limitations of using recycled plastics and how do you try to overcome them?
- What are the opportunities/difficulties in recycling your products?
- How do you ensure the quality of your materials?
- What additives do you use in your products?
- How do you work with reuse, both internally and externally?
- Do you only sell finished products or do you also sell materials?
- Do you need to adapt your materials for different production techniques and what do you do in such cases?
- Plastic is a very good material that is both cheap, adaptable and durable. In recent years, however, it has gained a worse reputation, especially with regard to disposable items. How has it affected you and how are you working to reverse that trend?

B.6 Thomas Eriksson - Sotenäs Symbioscentrum

- What is the breakdown of the marine waste you receive?
- How is the marine waste collected?
- What is the quality of the fishing gear you receive? Does it differ much from case to case?
- Which materials does the nets consist of?
- How is the degree of contamination by unwanted particles and organisms in the fishing nets?
- Do the nets often contain lead from for example weights?
- How is marine waste divided and sorted?
- Do you treat the waste in any way?
- What percentage of the material you receive would you say can be recycled and used in new products? What new applications do you see for the material?
- Can some waste be reused without recycling?

- What is the demand for recycled marine plastics today?
- Is there any way to find out the origin of marine plastics today?

B.7 Nils Åsheim - Add:North

- Do you use recycled materials in your products?
- What would you say is required for a material to work well in 3D-printing? Material properties, clean, print bed, etc.
- How do you ensure the quality of your materials?
- How does it work to use several different materials in the same print?
- Do material properties need to be adapted depending on which printing technology that is used? Is it something you do/ take into account?
- What are usually the main problems in the print when a new material is being tested?
- Advantages/disadvantages of using filament versus pellets?

C Appendix C Data from tensile tests

Data from tensile tests, where green corresponds to highest value and red is lowest value for each material tested.

Materials:	Gauge length L0 (mm)	Width b (mm)	Thickness h (mm)	Cross-sectional area Ac (mm^2)
FN PA6 G10 (1)	85	10.005	4.010	40.120
FN PA6 G10 (2)	85	10.005	4.010	40.120
FN PA6 G10 (3)	85	10.005	4.010	40.120
FN PA6 G10 (4)	85	10.005	4.010	40.120
FN PA6 G10 (5)	85	10.005	4.010	40.120
FN PA6 G20 (1)	85	10.000	4.010	40.100
FN PA6 G20 (2)	85	10.010	4.010	40.140
FN PA6 G20 (3)	85	10.010	4.010	40.140
FN PA6 G20 (4)	85	10.005	4.010	40.120
FN PA6 G20 (5)	85	10.010	4.010	40.140
FN PA6 GF20 (1)	85	10.000	4.005	40.050
FN PA6 GF20 (2)	85	10.000	4.010	40.100
FN PA6 GF20 (3)	85	10.000	4.005	40.050
FN PA6 GF20 (4)	85	10.000	4.005	40.050
FN PA6 GF20 (5)	85	10.005	4.005	40.070
RC PA6 G20 (1)	85	10.000	4.010	40.100
RC PA6 G20 (2)	85	10.000	4.005	40.050
RC PA6 G20 (3)	85	10.000	4.005	40.050
RC PA6 G20 (4)	85	10.000	4.000	40.000
RC PA6 G20 (5)	85	10.000	4.005	40.050
RC PA6 (1)	85	10.005	4.010	40.120
RC PA6 (2)	85	10.010	4.005	40.090
RC PA6 (3)	85	10.010	4.010	40.140
RC PA6 (4)	85	10.010	4.010	40.140
RC PA6 (5)	85	10.005	4.010	40.120
RC PA6 (T1)	85	10.010	4.010	40.140
RC PA6 (T2)	85	10.010	4.010	40.140
RC PA6 GF20 (1)	85	10.005	4.005	40.070
RC PA6 GF20 (2)	85	10.005	4.005	40.070
RC PA6 GF20 (3)	85	10.005	4.005	40.070
RC PA6 GF20 (4)	85	10.005	4.005	40.070
RC PA6 GF20 (5)	85	10.005	4.005	40.070

Figure 20: Measurements from tested specimen during tensile testing

Materials:	Stress at yield (MPa)	Load at yield (N)	Maximum load (N)	Young's modulus (GPa)	Stress at max load (MPa)	Stress at break (MPa)	Extension at break (mm)	Strain at break (dmm/mm)
FN PA6 G10 (1)	45.292	1817.114	2851.338	2.130	71.07	55.079	18.446	0.178
FN PA6 G10 (2)	44.853	1799.502	2819.473	2.117	70.28	51.563	20.628	0.195
FN PA6 G10 (3)	45.836	1838.934	2866.050	2.164	71.44	50.871	19.889	0.190
FN PA6 G10 (4)	45.154	1811.580	2835.688	2.144	70.68	51.972	20.912	0.197
FN PA6 G10 (5)	45.614	1830.034	2855.992	2.074	71.19	49.625	10.118	0.106
FN PA6 G20 (1)	42.247	1694.118	2685.877	2.036	66.98	54.420	15.920	0.158
FN PA6 G20 (2)	43.079	1729.183	2721.593	2.064	67.80	64.560	6.856	0.075
FN PA6 G20 (3)	42.458	1700.460	2685.277	2.108	67.05	60.102	10.510	0.110
FN PA6 G20 (4)	42.896	1717.977	2700.639	2.124	67.43	56.572	16.720	0.164
FN PA6 G20 (5)	42.599	1709.941	2693.503	2.127	67.10	52.761	16.947	0.166
FN PA6 GF20 (1)	48.768	1953.161	2342.527	3.416	58.49	58.490	1.915	0.0220
FN PA6 GF20 (2)	48.347	1938.707	2366.126	3.319	59.01	59.006	2.016	0.0232
FN PA6 GF20 (3)	48.754	1952.581	2368.331	3.401	59.13	59.134	1.970	0.0227
FN PA6 GF20 (4)	48.300	1934.418	2340.969	3.383	58.45	58.451	1.953	0.0225
FN PA6 GF20 (5)	48.616	1948.035	2365.507	3.377	59.03	59.034	1.973	0.0227
RC PA6 G20 (1)	38.813	1556.413	2482.969	2.106	61.92	52.576	16.567	0.163
RC PA6 G20 (2)	38.709	1550.308	2466.755	2.098	61.59	51.003	16.782	0.165
RC PA6 G20 (3)	38.817	1554.624	2488.934	2.095	62.15	52.456	17.076	0.167
RC PA6 G20 (4)	38.817	1552.696	2483.553	2.085	62.09	54.453	16.767	0.165
RC PA6 G20 (5)	38.618	1546.643	2485.466	2.044	62.06	57.797	11.369	0.118
RC PA6 (1)	49.572	1988.832	2919.635	2.470	72.77	52.464	19.880	0.190
RC PA6 (2)	49.281	1975.688	2914.015	2.453	72.69	56.275	16.662	0.164
RC PA6 (3)	49.809	1999.353	2930.251	2.439	73.00	54.601	16.627	0.164
RC PA6 (4)	50.078	2010.154	2969.317	2.426	73.97	71.352	7.650	0.083
RC PA6 (5)	49.483	1985.260	2891.089	2.393	72.06	67.903	12.775	0.131
RC PA6 (T1)								
RC PA6 (T2)								
RC PA6 GF20 (1)	38.108	1526.998	2281.847	3.112	56.95	56.946	2.411	0.0276
RC PA6 GF20 (2)	38.151	1528.699	2212.461	3.081	55.21	55.215	2.149	0.0247
RC PA6 GF20 (3)	38.607	1546.988	2313.256	3.122	57.73	57.730	2.373	0.0272
RC PA6 GF20 (4)	38.413	1539.220	2285.652	3.100	57.04	57.041	2.309	0.0264
RC PA6 GF20 (5)	38.593	1546.414	2260.776	2.990	56.42	55.779	2.418	0.0277

Figure 21: Data from tensile tests