UiT The Arctic University of Norway

Faculty of Science and Technology

Thermal properties of neoprene and natural rubber in wetsuits

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Preface & acknowledgements

"As I roll in on the parking lot at Unstad, a solid set of waves approach, the first wave hit close to the rocks and continue to peel down the line for some 150 meters before it explodes on the inside. No time to lose, I pull my wetsuit on and run down to the beach. When I go into the water, I feel it immediately; ice-cold water entering the suit, a burning sensation, like needles on my skin. By the time I start paddling, the water lays like a freezing belt around my stomach. As I make my way out into the lineup, the water slowly warms up, but at the expense of my own body heat. I silently curse the wetsuit manufacturers who after over 50 years of making wetsuits, still haven't figured out how to make one that keep me warm"

The text above sums up some of my motivation for writing about wetsuits in the TEK-3901 course. As a surfer for fifteen years, I have owned many wetsuits and unfortunately, the experience is not unique. I began working on a similar project in TEK-3004 last semester with the guidance of associate professor Hassan Abbas Khawaja, which laid the foundation for this project. It has been interesting diving deeper into- and learning more about a topic that I care about.

I would like to say thank you to those who have helped me along the way:

- First and foremost, I would like to thank my supervisor associate Professor Hassan Abbas Khawaja for his guidance and positive spirits, and for always taking the time to explain in a way that I can understand.
- I would also like to extend my gratitude to my co-supervisor Professor Jinmei Lu for guidance and feedback on the Life-cycle assessment part of the thesis.
- Lastly, I would like to thank Professor Javad Barabady for his help with solving some administrative struggles in the beginning of the semester.

With regards

Mads H. Busvold

Abstract

Surfers have concurred some of the harshest regions of the world with their surfboard, like the arctic waves of Norway. This is only made possible due to the wetsuit, a critical piece of equipment that enables surfers to stay in frigid waters and temperatures for hours. To understand the thermal behavior of wetsuits, knowledge on the phenomenon of heat transfer, and especially the conductive and convective heat transfer modes are important. By capturing the thermal signature of frozen samples of neoprene and natural rubber in dry and wet phase with FLIR T1030sc infrared camera, and comparing the results with simulations, the conductivity and the overall heat transfer coefficient of the materials was estimated. The simulations were carried out in MATLAB® and Ansys and the solution is based on the Heat equation. The approximated solution to the Heat equation is discretized using the finite difference method and solved using the FTCS (Forward-Time-Central-Space) method in MATLAB® software. The results reveal acceptable agreement between the experimental data and the simulations, except for the wet samples. It was found that the presence of water inside the material, compromises the thermal properties of the wetsuit.

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1 Introduction

1.1 Background

The first attempt of riding waves on surfboards in Norway was in 1963 (Fredriksen, 2018). Throughout the 80s and 90s it was still a relatively small but dedicated group that surfed regularly in Norway. By the mid-2000s, there was an explosion in number of surfers. Today, surfing has become mainstream with a number of surfshops, surfschools and rentals, and established surf communities scattered along the Norwegian coastline, from Lista in the south to Varanger in the high north. Saltstein, Jæren, Stadt and Lofoten are the main surf destinations in Norway, and it is not unusual to see hundreds of surfers at these locations when the conditions are right (Hans Kristian Waarum, 2008).

Lofoten has a growing surf population and some of the best surf spots in Norway, some would argue in all of Northern Europe. Unstad, a small fishing village in Lofoten, has gained worldwide recognition due to its quality of waves and scenic backdrop; snow covered mountains and icy, green ocean. There has been an increased interest in cold water surfing world-wide for the last two decades. Places like Iceland, Alaska, Canada, Ireland, and Norway to name a few, attracts surfers from all over the world. Advances in wetsuit technology has made these cold-water locations that ones were inaccessible, accessible to an increasingly larger crowd.

As surfers, we are literally immersed in the elements. Surfing in the arctic often means dealing with sub-zero temperatures and gale force wind. This environment presents unique challenges when it comes to thermoregulation of the human body. Staying in the ocean for hours will lead to a reduction in body temperature. Normally the human body is steady at 37 °C. Heat is generated via metabolic reactions, but if heat is withdrawn at a higher rate than it is generated, hypothermia can occur. Other reactions to the cold environment include skin problems, trench foot and frostbite as well as psychological reactions like decreasing motivation and concentration (Leyli et al., 2021). Surfing is one of the most technical demanding sports, thus, the ability to maintain a healthy body temperature and muscle functioning is crucial to enhance surfing performance (Smith et al., 2020).

To be able to withstand the cold environment, surfers wear wetsuits that come in a range of thicknesses made for different water temperatures. Traditionally wetsuits have been produced from neoprene, a synthetic rubber made from petrochemicals. Neoprene production is known for having adverse effects on the environment and human health and as a result of this, more wetsuit manufacturers are turning to natural rubber as a substitute for neoprene (Holmström and Mattsson, 2019).

To fully understand how wetsuits work, knowledge on heat transfer and the different heat transfer modes are necessary. In addition, the phenomenon of evaporation also plays an important role in thermoregulation for surfers (Çengel et al., 2012). Wetsuits work mainly through insulation and the thickness of the material usually determines the suitability for thermal protection. Thermal conductivity of water is 25 times that of still air. Water absorbs heat more efficiently than air and water movement increases convective heat transfer (Naebe et al., 2013). This makes the conductive and convective heat transfer modes important for evaluating the performance of wetsuits (Holmström and Mattsson, 2019).

Although wetsuit technology has come a long way since legendary wetsuit pioneer Jack O’neill made his first wetsuits in the early 1950s, there is still room for improvement (O'neill, 2023). More than 70 years later, wetsuits still lack durability and tend to lose much of its thermal properties when it is used (Holmström and Mattsson, 2019).

Figure 1: "It's always summer on the inside". Early days of making wetsuits (O'neill, 2023).

1.2 Objective

The main objective of this project is to investigate the thermal properties of neoprene and natural rubber used in surfing wetsuits by determining the constant of thermal conductivity and the heat transfer coefficient. This is achieved by capturing the infrared signature of dry and wet samples of neoprene and natural rubber and compare the experimental temperature data with simulated results.

In addition, this project involves a simplified Life cycle assessment (LCA). The objective with the LCA is to compare two alternative disposal options for wetsuits that have reached their “end-of -life” (EOL).

1.3 Structure of the thesis

In addition to the Introduction chapter where background and objectives are stated, this thesis contains the following chapters:

- **Chapter 2- Literature review:** In this chapter, the phenomenon of heat transfer and the different heat transfer modes are explained. In addition, wetsuits design and purpose are described. Chapter 2 also include a brief description of the methodology for conducting an LCA.
- **Chapter 3- Methodology:** In this chapter, the methods used to perform the thermal test and the thermal simulations are explained. In addition, theory on infrared radiation and imaging, and a description of the equipment and the different software used are also included. In addition, Chapter 2 also explains how the LCA of two different EOL options for wetsuits was performed.
- **Chapter 4- Results and discussion:** This chapter presents and discuss the results obtained from the thermal analysis and the results from the life cycle assessment.
- **Chapter 5- Conclusion and future work:** This chapter presents the conclusion from the results of the experiment and the LCA and propose future work.

Figure 2: The author himself, patiently waiting for the next wave, on a quiet, beautiful winter day in Unstad bay. Photo by: Hallvard Kolltveit.

2 Literature review

This chapter explains the phenomenon of heat transfer and the different heat transfer modes. In addition, wetsuit design and purpose are described. The chapter also include a brief description of the methodology for conducting an LCA.

2.1 Heat transfer

2.1.1 Heat transfer modes

Heat is a form of energy that can be transferred from one system to another as a result of a temperature difference. Transfer of heat is always from the higher temperature system to the lower temperature one. When two systems reach the same temperature, heat transfer stops. The rate of heat transfer is higher if there is a greater temperature difference between two systems. Heat can be transferred in three different modes: *conduction, convection,* and *radiation* (Çengel et al., 2012).

Conduction is transfer of heat due to collisions between more energetic particles of a substance with the adjacent less energetic particles. Conduction can take place in solids, liquids, and gases. In solids, conduction happens due to a combination of vibrations of the molecules in a lattice structure, and energy transport by free electrons. In liquids and gases, conduction is a result of collisions and diffusion of the molecules during their random motion. An example of conduction is the process of heating a pan on a stove (Çengel et al., 2012).

Convection is transfer of heat between a solid surface and the adjacent fluid in motion and involves the combined effects of conduction and fluid motion. If there is no fluid motion present between a solid surface and the adjacent fluid, then heat transfer is pure conduction. The faster the fluid motion, the greater the heat transfer. Convection heat transfer can be classified as either *forced* convection or *free* convection. Forced convection is when the flow is caused by external factors, for instance a pump, a fan or atmospheric wind. Free (or natural) convection is a result of buoyancy forces due density differences caused by temperature variations in the fluid. An example of convection is a heater warming up a room (Moran, 2003).

Radiation is transfer of heat in form of electromagnetic waves. Radiation, unlike conduction and convection, does not require any physical medium. An example of radiation is how energy from the sun warms the earth (Çengel et al., 2012).

2.1.2 Thermal conductivity

Rate equations can be used to quantify heat transfer processes and calculate the amount of energy being transferred per unit time (Moran, 2003). The rate of heat conduction through a medium depends on the medium's geometry, thickness, material of the medium and the temperature difference across the medium. Heat transfer through conduction is proportional to the area normal to the heat flow path and the temperature gradient along the heat flow path. This relationship is described by *Fourier's law* and can be written as shown in Equation 1. (Kraus et al., 2011).

$$q = -k\frac{dT}{dx} \tag{1}$$

In Eqn.1, q represents the heat flux (W/m^2), k the thermal conductivity of the material (W/m ·K) and dT/dx the temperature gradient, or the rate of change of T with x. Heat flux is the rate of heat transfer per unit area while heat rate (W) is the product of heat flux and the area. Heat is always transferred in direction of decreasing temperature, making the temperature gradient negative as temperature decreases with increasing x. In Eqn.1 the negative sign ensure that heat transfer is a positive quantity in the positive x direction. Thermal conductivity describes the rate the transferred heat dissipates within the body (Rashid et al., 2016).

2.1.3 Heat transfer coefficient

Equation 2 is known as *Newton's law of cooling*. Newton's law of cooling is a rate equation that can be used to describe convective heat transfer processes. In Eqn.2, q is the convective heat flux (W/m^2), which is proportional to the difference between the surface temperature (T_s) and the fluid temperature (T_∞), and the proportionality constant h (W/m^2·K). The proportionality constant h is also known as the *convection heat transfer coefficient.* Heat transfer is positive if heat transfer is from the surface such that $T_s > T_\infty$. If $T_\infty > T_s$, it implies that heat is transferred to the surface from the fluid, and heat transfer is negative.

$$q'' = h(T_s - T_\infty) \tag{2}$$

The convection heat transfer coefficient depends on boundary layer conditions, and are influenced by surface geometry, fluid motion and different fluid thermodynamic and transport properties (Moran, 2003). The heat transfer coefficient describes the heat transfer rate to the body (Rashid et al., 2016) and (Eidesen et al., 2022).

2.1.4 Heat equation

Equation 3 show the one-dimensional heat equation. The heat equation can be used to solve conductive heat transfer problems in solids, mathematically (Rashid et al., 2016).

$$\frac{\partial T}{\partial t} \rho c = Q + \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial t} \right) \tag{3}$$

In Eqn. 3, ρ is density (kg/m^3), c is heat capacity at constant pressure ($J/kg \cdot K$), Q is the volumetric energy generation term (W/m^3), k is the coefficient of thermal conductivity ($W/m \cdot K$), T is temperature (K), x is spatial position (m) and t is the time (s). If Eqn. 3 is expanded into three spatial dimensions (x, y, *and* z) and the volumetric energy generation term is neglected, we get equation. 4.

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \tag{4}$$

The thermal diffusivity constant, α, in eqn. 4, describes the rate at which a material reaches equilibrium and adapt to ambient temperature. It has units of $m^3 s^{-1}$ and can be stated as shown in equation 5. The product of ρc in units $Jm^{-3}K^{-1}$, are called the *volumetric heat capacity* and can be described as a materials ability to store heat (Eidesen et al., 2022). Materials with a large α absorb heat at a faster rate compared to materials with a small α (Moran, 2003).

$$\alpha = \frac{k}{\rho c} \tag{5}$$

2.2 Wetsuits

2.2.1 Purpose and design

Wetsuits come in a range of thicknesses made for different water temperatures and weather conditions, ranging from 1mm to 7mm as shown in fig. 3. Generally, the thicker the wetsuit is, the more insulation it will provide. Surfing in arctic waters requires a full wetsuit including hood, gloves, and boots. Usually, a 6mm wetsuit with 5mm to 8mm boots and gloves provides sufficient insulation and warmth for surfing in Norway during fall, winter, and spring, which is the prime months for surfing in Norway.

Wetsuits are made of sheets or panels of neoprene derived from either petroleum or limestone resources or natural rubber that are glued and stitched together. Panels are either single or doubled lined with nylon or polyester to increase durability and warmth and to reduce friction against the skin making it easier to pull the suit on and off. The inside lining also reduces the time it takes for the suit to dry up after it has been soaked in water. The outer lining reduces flexibility and stretch and adds weight. It can also result in increased heat transfer from the surfer to the environment as the outer layer will hold on to more water compared to a smooth skin neoprene (Smith et al., 2020). More water on the surface will increase windchill and heat loss as the water vaporizes (Staal, 2019).

Wetsuits are designed to allow a small amount of water to enter the suit. Water finds its way through seems and seals in the arms, legs, and neck area (Holmström and Mattsson, 2019). The trapped water inside the suit is heated up by the body to near body temperature, creating a barrier between the skin and the cold environment surrounding the surfer (Naebe et al., 2013).

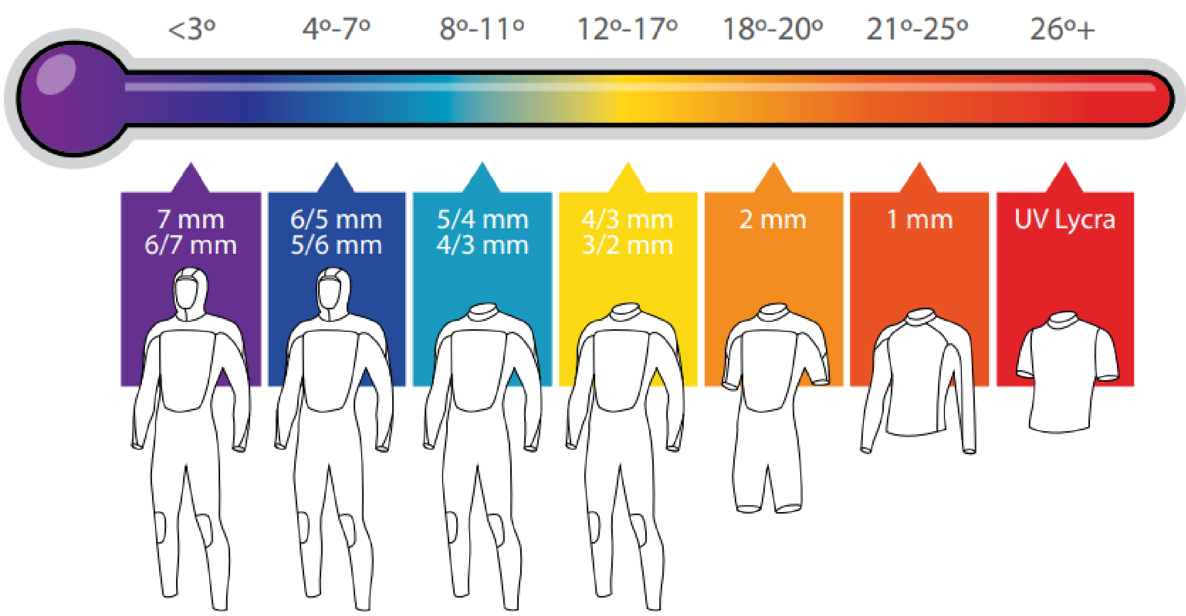

Figure 3: Surfing temperatures of different wetsuit thicknesses (Staal, 2019).

The most important properties in wetsuits are *warmth*, *flexibility*, and *durability*. Also comfort and fit is crucial. A suit that lacks the right fit will feel uncomfortable and bulky to wear and can restrict body movement. It can also lead to “flushing”. Flushing is exchange of inner water and is one of the most uncomfortable feelings surfer’s experiences. When cold water enters the suit through seams and openings, it increases convective heat loss (Holmström and Mattsson, 2019). It is a good balance between the properties above that makes an excellent wetsuit.

2.2.2 Different wetsuit materials

Wetsuits are made from either natural- or synthetic rubber. There are three different types of materials most common in surfing wetsuits: neoprene, limestone, and natural rubber.

2.2.2.1 Wetsuits made from Neoprene

Neoprene, or polychloroprene, is a form of synthetic rubber made from polymerizing chloroprene monomers. Neoprene was first invented by DuPont in 1930 and have been used in wetsuits since the 1950s. Neoprene is still to date the most common material in wetsuits. Neoprene contains small bubbles of gas, either air or nitrogen, which makes it a good insulator. (Naebe et al., 2013). Neoprene is known to have high tensile strength and elasticity, and depending on the thickness of the neoprene sheets, it can stretch up to 650% (Staal, 2019).

Neoprene is produced from petrochemicals which is a non-renewable resource. It is energy intensive to make and non-biodegradable (BioSourced, 2023). Neoprene production process is directly linked to different forms of cancer. Japanese chemical company, *Denka Performance Elastomers*, is the only producer of chloroprene and neoprene in the United States. The residents that live near Denka’s chemical plant face the highest risk of developing cancer, according to *United States Environmental Protection Agency (EPA)*. The increased risk of developing cancer from breathing the air around Denka’s production facility is almost 50 times the national average due to air pollution from chloroprene, and the area have been given the name “Cancer Alley” (University Network for Human Rights, 2019).

2.2.2.2 Wetsuits made from limestone

Several wetsuit manufacturers use calcium carbonate from limestone rock to produce neoprene instead of petrochemicals extracted from oil and gas. Like traditional neoprene, limestone wetsuits are produced by polymerizing chloroprene monomers into polychloroprene rubber chips. The rubber chips are melted and mixed with a foaming- agent and pigment, usually carbon-black, and baked in an oven to make it expand. For limestone neoprene, the *acetylene* used to make the chloroprene monomers is derived from limestone rock, while traditional neoprene uses *butadiene* from petroleum (Design Life-Cycle, 2014). According to producers of limestone wetsuits, this type of neoprene have as good or better elongation, flexibility, and insulation characteristics as traditional neoprene. (Srface, 2022). Limestone neoprene is 95% water impermeable compared to 65 % for petroleum-based neoprene. This makes for a lighter and warmer wetsuit (Staal, 2019).

Limestone, just like oil and gas, comes from a nonrenewable resource. Limestone mining is energy intensive and can have several negative effects on the environment, for instance water pollution, land disruption and loss of biodiversity. Chloroprene derived from either petroleum or limestone is chemically equivalent, and it is only the process of producing the chloroprene monomers that differ (Yulex, 2022).

2.2.2.3 Wetsuits made from natural rubber

Natural rubber is extracted from rubber producing trees and plants e.g., *Hevea brasiliensis* or *Guayule.* The latex is harvested from the inner bark of the trees and used to produce natural rubber, a long chain polymer that consists mainly of isoprene monomers. Through a vulcanization process the rubber increases its elasticity and tensile strength (Holmström and Mattsson, 2019). Natural rubber compounds are known for having good strength, durability and flexibility and forms an excellent barrier to water. Natural rubber is also biodegradable. Therefore, wetsuits made from natural rubber is more environmentally friendly compared to wetsuits from neoprene and limestone (Navodya.U. et al., 2020).

Due to the adverse effects of neoprene production on the environment and human health, more wetsuit manufacturers are turning to natural rubber as a substitute for petroleum and limestone-based neoprene.

Figure 4: The author in action at Unstad wearing a 6mm Xcel wetsuit made from limestone. Photo by: Fredrikke Sofie Jerring.

2.3 Life cycle assessment

LCA is a technique that analyze environmental impacts associated with all stages of a product’s life, from raw material extraction, through material processing, manufacturing, distribution, use and end of life as shown in fig. 5. LCA can help provide answers to decision makers and stakeholders on important questions such as which product or process causes the least environmental impact, overall or in each stage of production, or how a process can be changed to reduce a specific environmental impact of concern e.g., global warming or acidification. This information can in turn be used to prioritize and make improvements on products or processes (Tukker, 2000).

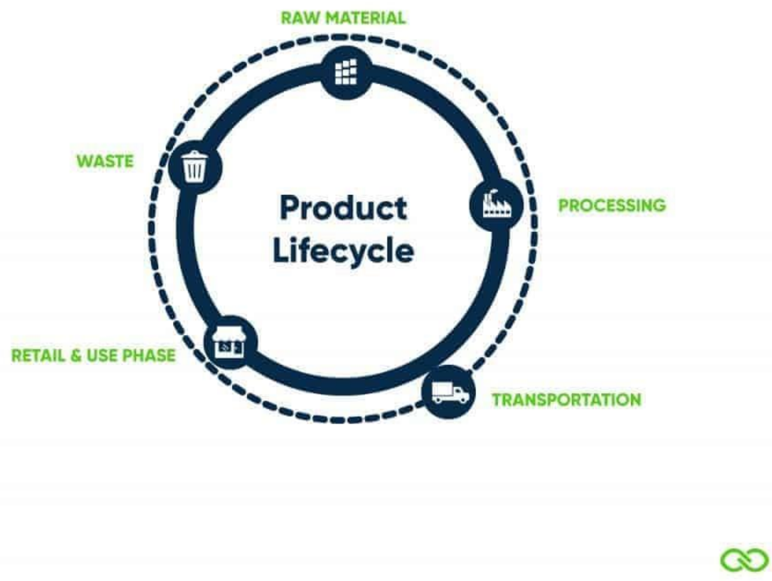

Figure 5: Product lifecycle (Ecochain, 2023).

The LCA method has a fixed structure and is conducted according to framework of the International Organization of Standardization (ISO) *14040 and 14044* (Krishna et al., 2017). According to the *EN ISO 14040* standard, an LCA consist of four stages: *goal and scope*, *life cycle inventory*, *impact assessment* and *interpretation.*

Goal and scope definition: The purpose of the goal and scope definition is to define the objective of the study, and why and for whom the LCA is performed. The depth and accuracy of the assessment need to be clearly stated, and it is equally important to specify what the study will *not* be assessing as it can easily get too comprehensive. In this stage the *functional unit* is established which tells how much of a particular product that are going to be assessed and the *impact categories* the study will focus on. The product system is usually described by a flow chart.

Life cycle inventory: This stage involves assessing the environmental inputs and outputs of a product or service and collecting the necessary data for conducting the assessment. The goal is to quantify the environmental inputs and outputs of the system, for instance raw materials, energy- or water consumption or emissions to land or sea. This information is usually illustrated in a flow model.

Life cycle impact assessment: Based on the inventory flow model, the goal of impact assessment is to assign the environmental inputs and outputs to the impact categories and evaluate how significant their impacts are. For instance, a common impact category is *Global warming potential* (GWP) measured in CO_2- equivalents. Since it is not only CO_2 that contribute to global warming, but also Methane or Nitrous oxide among other gases, these gases are all measured in CO_2 equivalents so that it is possible to compare their respective contribution to global warning. Finally, the data is summed up in an overall impact category total.

Interpretation: The final phase is where the result of the assessment is interpreted, and the most reliable conclusions and recommendations are made. Potential limitations of the study are also mentioned as well as an evaluation of the study itself, how complete it is and if it is done sensitively and consistently (Ecochain, 2023).

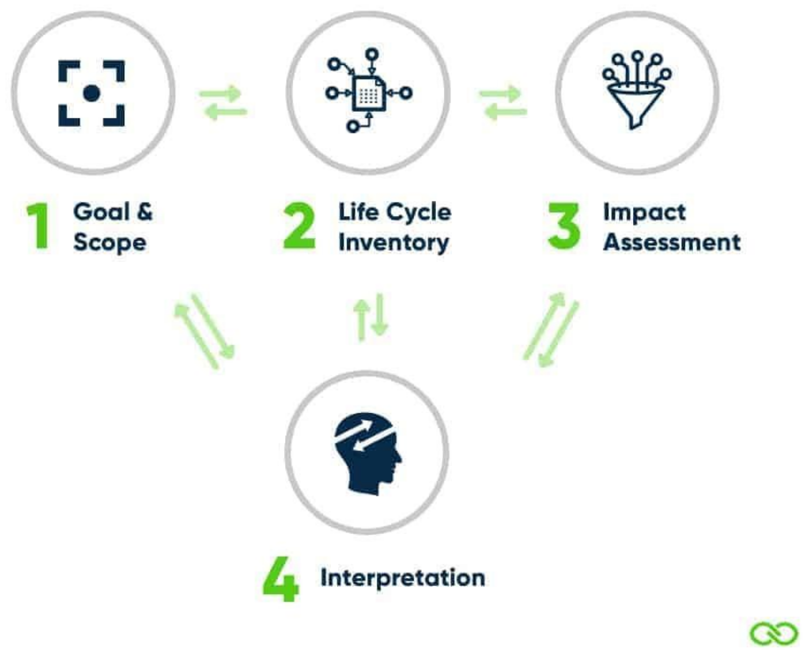

Figure 6: The four phases of LCA according to ISO 14040 and 14044 (Ecochain, 2023).

3 Methodology

Part 1 of the methodology chapter explains the methods used to perform the thermal test and the thermal simulations and include theory on infrared radiation and infrared imaging. A description of the equipment and the different software used in both the experiment and the simulations are also described.

Part 2 of the chapter explains how the LCA of two different EOL options for wetsuits was performed.

3.1 Part 1: Thermal analysis

3.1.1 Infrared radiation

The electromagnetic spectrum is divided into subcategories based on wavelengths and include *gamma rays*, *X-rays*, *ultraviolet radiation*, *visible light*, *infrared radiation*, and *radio waves* as shown in fig. 7. Each of the different types of rays (bands) in the spectrum transmit different amounts of energy (Çengel et al., 2012). All objects give of some kind of electromagnetic radiation, but humans are only able to see a small portion of this, namely visible light. Infrared radiation refers to electromagnetic waves between 1mm to 0.7 µm wavelengths. Everything with a temperature above absolute zero (zero degrees Kelvin) emits thermal radiation, and more IR is emitted with increasing temperature (Teledyne Flir, 2022b).

Emissivity is a measure of how efficiently an object radiates heat. Values range from 0 to 1, where 0 is a perfect reflector that reflect all energy, and 1 is called a *black body* and is defined as a perfect emitter and absorber of radiation (Teledyne Flir, 2021). Values 0 and 1 are theoretical values and cannot be achieved in reality. In the real world, objects are described with values between 0.01 and 0.99 on the emissivity scale. For instance, human skin has emissivity of 0.98 while a highly polished metal surface will have emissivity below 0.10.

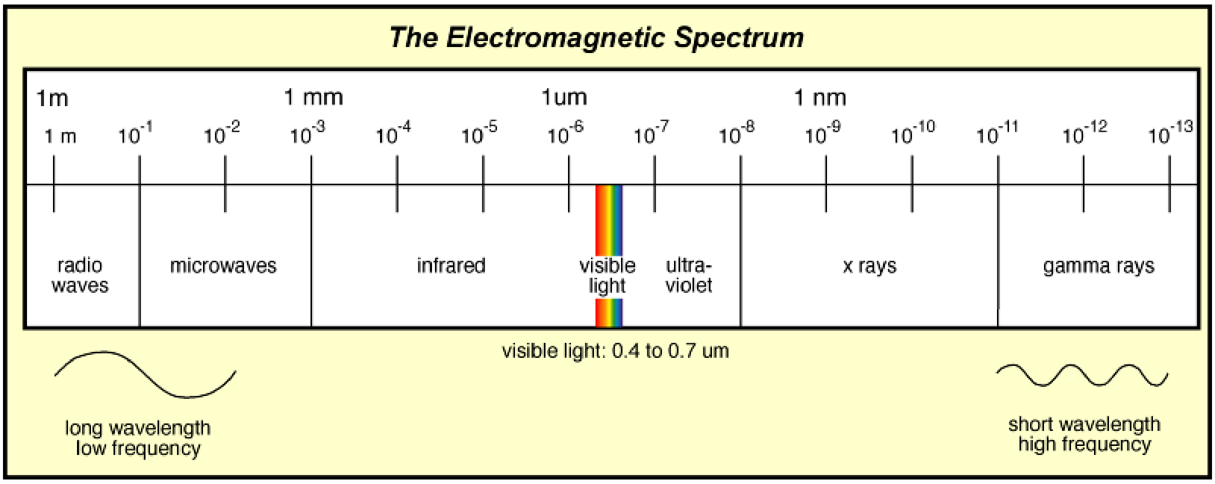

Figure 7: The electromagnetic spectrum (Columbia University).

3.1.2 Infrared imaging

Infrared cameras detect thermal energy and convert it into an electrical signal. These signals are used to produce an image that visualizes not only the thermal radiation of an object, but also quantify and measure it. IR cameras does not depend on light conditions and will detect thermal energy whether it is bright day or pitch dark (Teledyne Flir, 2022b).

Objects with low emissivity can give inaccurate results when using an IR camera to measure its thermal signature. The surface of these objects acts like mirrors, and instead of measuring the temperature of the object itself, the IR camera will detect the *reflected temperature* or *background temperature* instead. Background temperature is any thermal radiation from other objects that reflect off the target you are measuring (Teledyne Flir, 2021).

3.1.2.1 FLIR T1030SC

The FLIR T1030sc is a handheld, high definition, longwave infrared (LW-IR), spectral range (7.5-14µm) camera with IR sensors and 1024 x 768 pixels that are able to produce both images and videos. It has 8x digital zoom and offers full color digital image as well as full color IR images. The camera works over a wide temperature range with calibrations up to 2000°C (Teledyne Flir, 2022a).

Figure 8: FLIR T1030sc infrared camera (Teledyne Flir, 2022a).

3.1.2.2 FLIR Research IR

FLIR Research IR is a thermal analysis software package for FLIR Research and Science cameras. It provides camera control, high-speed data recording, image analysis, and data sharing. The software enables different analysis options and measurement tools, including line profiles, histogram charts and temporal plots. Image and plot data can be exported to other software programs such as Microsoft Excel and MATLAB.

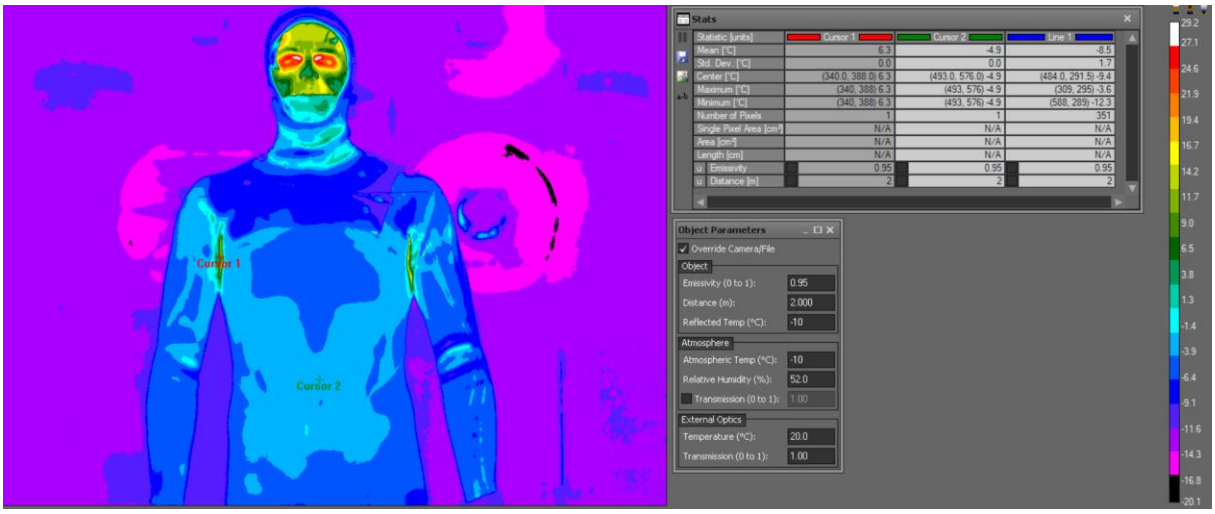

Figure 9: FLIR Research IR software used to extract temperature data.

3.1.3 Experiment

3.1.3.1 Sample preparation

Two wetsuits that had reached their end-of-life were used to prepare the samples for the thermal test. Details on the suits are found in table 1. A patch on the back thigh of each suit were cut to ensure a uniform sample. Two samples of approximately *100mm x100mm* were cut from each patch. A total of four samples were prepared for the test.

Table 1: Information on the old wetsuits used to prepare the samples.

Wetsuits	Brand and model	Thickness	Details of suit
Suit # 1	Patagonia R5 Yulex	6/5mm	Wetsuit made of natural rubber.
Suit # 2	Xcel 6/5 Infinity RR	6/5mm	Wetsuit made of foamed neoprene.

One sample from each suit were put in a small container filled with water for ten days and dried for one day prior to the experiment. The purpose of this procedure was to investigate how absorbed water inside the material effected the thermal properties and the thermal signature of the samples.

Figure 10: Sample preparation from old wetsuits of both neoprene and natural rubber.

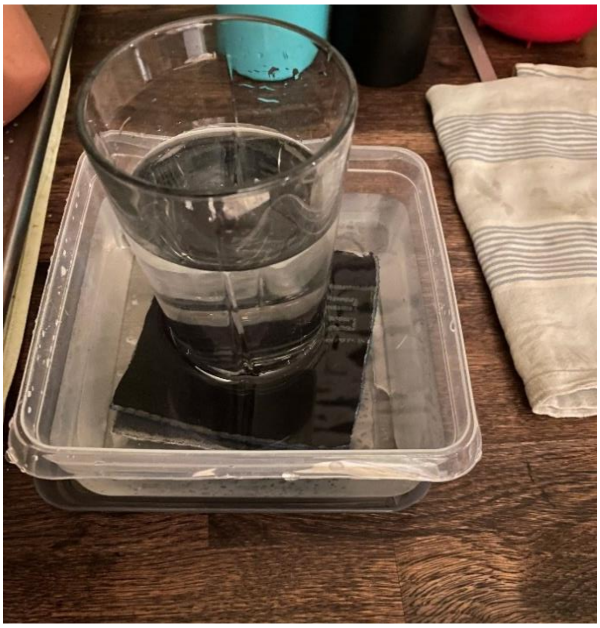

Figure 11: Samples soaked in freshwater for ten days prior to experiment.

A setup made of wooden strips was made to facilitate the IR imaging of the samples. Due to the low thermal conductivity of the wetsuit samples, it was important that the samples didn’t come in contact with other materials during the IR imaging as this would affect their thermal signature and give inaccurate results. The samples were placed inside the wooden frame where it would hang freely, connected in each corner only by a thin nylon thread as seen in fig. 12.

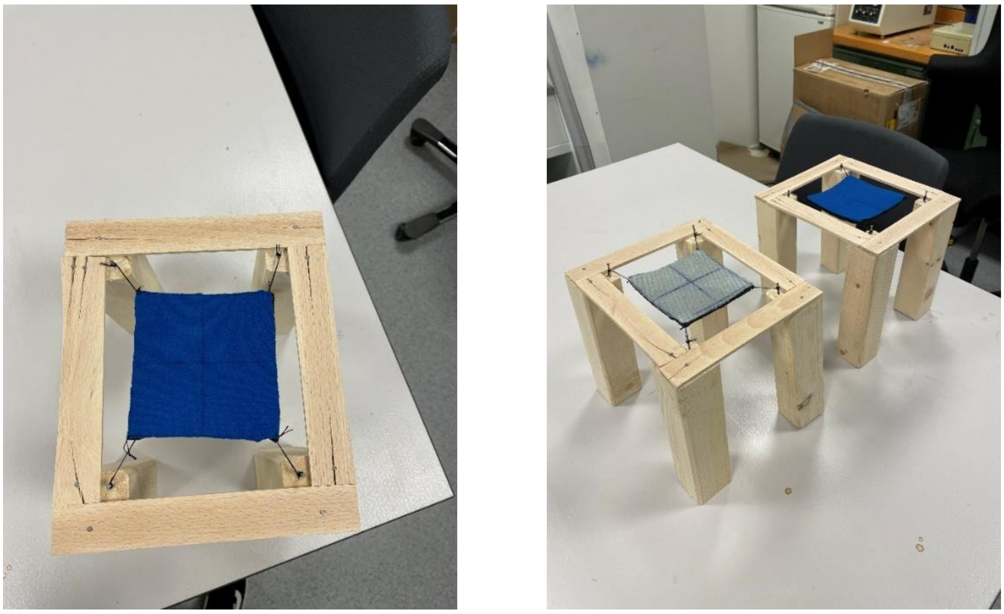

Figure 12: Setup of wooden strips with samples, prepared for IR imaging.

3.1.3.2 Experimental setup and execution

The experiment took place in a laboratory at The Arctic University of Norway, Tromsø (UiT). The purpose with the experiment was to measure the established temperature gradient as a function of time and space by capturing the infrared signature of the wetsuit samples. The results from the experiment would later be compared with thermal simulations with the aim of determining the thermal conductivity (k) and the heat transfer coefficient (h) of the wetsuit samples.

Before IR images were captured, length, width and masses of each sample were measured, as seen in table 2. FLIR T1030sc camera was used to capture the infrared radiation of the wetsuit samples, and FLIR Research IR software used to extract the temperature data. Figure 13 shows how the experiment was set up.

Table 2: Measurements of samples before IR imaging.

Sample No.	Description	Weight (g)	Length (mm)	Width (mm)	Thickness (mm)	Volume (mm^3)	Density (kg/m^3)
1	Neoprene dry	12,5	100,11	103,59	6,52	67614,97	184,87
2	Natural rubber dry	15,0	100,53	98,63	7,63	75628,75	198,34
3	Neoprene wet	16,0	104,28	103,64	6,19	66898,91	239,17
4	Natural rubber wet	23,0	104,31	101,07	7,10	74799,83	307,49

Each sample were put in a freezer for approximately 30 minutes before IR images were captured to obtain a temperature difference between the samples and the environment. The surrounding temperatures where the experiment took place were steady at about 19,5 °C.

The software was set to capture an image every 5 second. For the dry wetsuit samples, the camera recorded for 10 minutes, producing a total *120 frames*. For the wet samples, the recording time was 40 minutes, producing a total of *480 frames*.

Figure 13: Experimental setup with FLIR T1030sc and FLIR Research IR connected in laboratory at UiT.

To extract temperature data from the IR images, a ROI (short for "*Region of interest")* was created in the software. Both *temperature profile* and *box-plot function* were used for this purpose, as seen in fig. 14. The extracted data were further processed in Microsoft Excel.

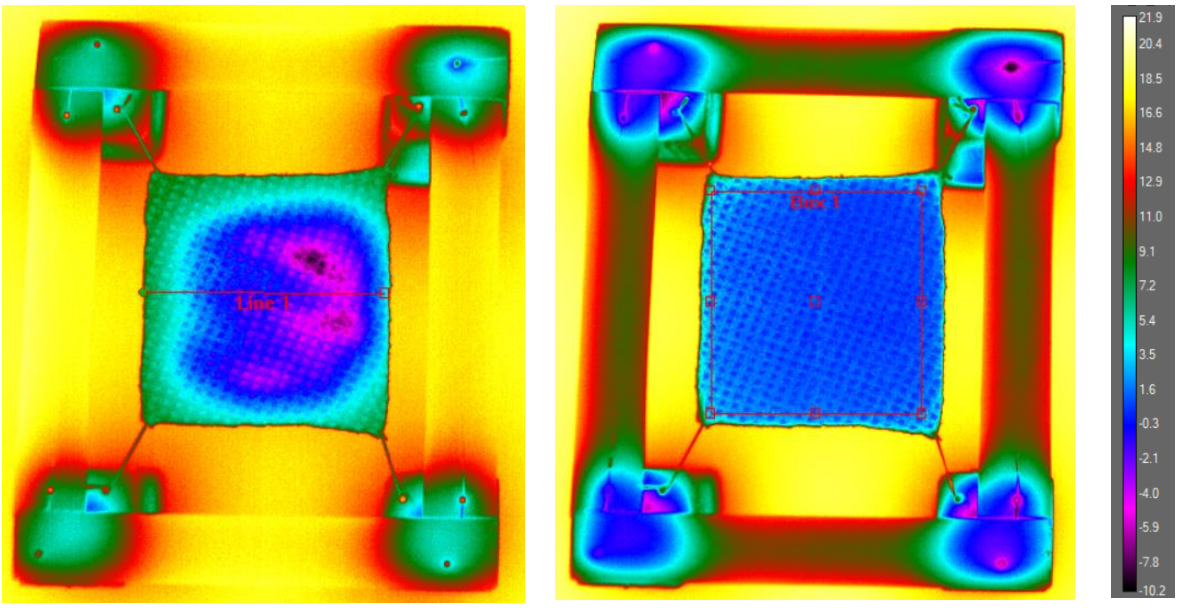

Figure 14: Temperature profile and box-plot ROI in FLIR Research IR.

3.1.4 Thermal simulation

To perform the thermal simulations, simulation software tools MATLAB® (R2021b version) and ANSYS Multiphysics (student 2023 R1 version) was used.

To be able to determine the thermal conductivity (*k*) and the heat transfer coefficient (*h*) of the different wetsuit samples, the heat equation (eqn. 4) was solved in MATLAB and ANSYS. To solve the heat equation and other partial differential equations (PDEs) for that matter, *The Finite Difference Method* (FDM) can be used. This method approximates the differentials by discretizing the dependent variable, in this case the temperature, in the independent variable domains, space and time. Each discretized value of the dependent variable is known as a nodal value (Rashid et al., 2016).

The heat equation was discretized using Forward-Time-Central-Space (FTCS) FDM. This technique makes it possible to estimate the temperature at each node, one timestep forward. The discretized heat equation in three dimensions is given in equation 6. In eqn. 6, superscript *t* refers to time and subscript *i,j* and *k* refer to position. Δt is the timestep size (s), and Δx, Δy and Δz the differences in the spatial positions of the temperature nodes (Eidesen et al., 2022).

$$\begin{aligned} T_{i,j,k}^{t+1} = T_{i,j,k}^{t} &+ \alpha\left(\frac{T_{i+1,j,k}^{t} - 2T_{i,j,k}^{t} + T_{i-1,j,k}^{t}}{(\Delta x)^2}\right)\Delta t \\ &+\alpha\left(\frac{T_{i,j+1,k}^{t} - 2T_{i,j,k}^{t} + T_{i,j-1,k}^{t}}{(\Delta y)^2}\right)\Delta t \\ &+\alpha\left(\frac{T_{i,j,k+1}^{t} - 2T_{i,j,k}^{t} + T_{i,j,k-1}^{t}}{(\Delta z)^2}\right)\Delta t \end{aligned} \tag{6}$$

Data from table 2 and table 4 was used as input data for the thermal simulations. For the wet samples, it was necessary to model these with both an ice-phase and a water-phase. This was due to formation of ice inside the material when the samples were put in the freezer. The specific heat capacity and the thermal conductivity for the ice-phase and the water-phase for both the wet neoprene and the wet natural rubber sample was calculated. Calculations can be found in Appendix-A.

Table 3: Thermal conductivity and specific heat capacity of water and ice (The enginnering toolbox, 2003).

Material	**Thermal conductivity (W/(m·K))**	**Specific heat capacity (J/(Kg · K))**
Water	0,6	4187
Ice	2,25	2108

Table 4: Calculated values of thermal conductivity and specific heat capacity of the wetsuit samples in dry, wet, and frozen state (MakeItFrom, 2020a) and (MakeItFrom, 2020b).

Material	**Thermal conductivity (W/(m·K))**	**Specific heat capacity (J/(Kg · K))**
Neoprene dry	0,19	1120
Natural rubber dry	0,14	1550
Neoprene wet	0,28	1791
Natural rubber wet	0,30	2467
Neoprene ice	0,64	1336
Natural rubber ice	0,87	1744

The discretized heat equation was first solved in MATLAB. The MATLAB code was developed by associate professor, Mr. Hassan Abbas Khawaja. The experimental data was implemented in MATLAB and compared with the simulated results. By adjusting the two constants *k and h,* the simulated results were tuned to match the experimental data. Once the two constants were determined, the same values for *k* and *h* were used to conduct the thermal simulation in Ansys. Finally, both the experimental- and simulated results were plotted together.

Due to low durability of wetsuits, surfers often need to buy a new wetsuit, depending on how much the suit is used and how it is maintained. This results in a lot of wetsuits ending up as waste. To investigate different waste management options for wetsuits that can no longer be used, an LCA was conducted.

3.2 Part 2: Life cycle assessment

3.2.1 Introduction

When wetsuits reach their EOL, there are usually no other option than traditional waste disposal, which depending upon the country, either means waste going to landfill or incineration. Wetsuits are a big source of pollution and landfill waste, and it is estimated that more than one million wetsuits, or 8 380 tons of neoprene wetsuits are ending up as waste every year globally (Circular flow, 2023). Due to an exponential growth of people who practice different water sports that requires a wetsuit, such as surfing, diving and triathlon and lack of a functioning collection- and recycling system, this number is set to grow (Navodya.U. et al., 2020).

Thermal decomposition of these rubber products can have several negative environmental impacts and release hazardous air pollutants and emissions of greenhouse gases (Leong et al., 2023). Combustion of polychloroprene can lead to formation of toxic chlorinated aromatic hydrocarbons due to the high chlorine content of the polymer. Studies of combustion of polychloroprene showed that more than two hundred compounds were generated, mainly aromatic hydrocarbons (Aracil et al., 2010).

Recycling wetsuits into new products is a sustainable option in the future. However, here are certain difficulties with recycling neoprene wetsuits, and other rubber products for that matter. During the vulcanization process, sulfur crosslinks are formed between the polymer chains. This increases the materials mechanical strength, as well as physical and chemical properties (Leong et al., 2023). The intermolecular bonds that are formed during vulcanization are difficult and energy intensive to break up. Through de-vulcanization methods, cross-links can be removed, but the process usually result in rubber with less quality (Holmström and Mattsson, 2019). Other factors that complicate recycling, is due to how wetsuits are designed. Wetsuits are often made of several different types of neoprene for stretch, and different thicknesses and fabrics for warmth, durability, and comfort. These are glued and stitched together, making it difficult to dismantle the suits for further recycling (Finisterre, 2021).

Figure 15: Different panels in wetsuits. Showing inside (right) and outside (left) (Finisterre, 2021).

Despite these challenges in recycling neoprene wetsuits, a few companies are currently working on recycling EOL wetsuits. One of these are outdoor company and wetsuit manufacturer “Finisterre”. Finisterre and their campaign “Wetsuits from wetsuits” have partnered with “Circular flow” to create an effective and sustainable solution to the waste problem from EOL wetsuits. Through their recycling process they are able to turn old wetsuits and neoprene products into a range of new high-quality products, such as gloves, running socks and yoga mats (Circular flow, 2023). The recycled neoprene is not of the same quality as virgin neoprene; thus, so far, they have not managed to create new wetsuits from the recycled material. Recycling where the recycled product is used for an application of lower value than the original purpose is labeled “down-cycling, as compared to “up-cycling” where the material is used for products of greater quality (Di Maria et al., 2018).

3.2.2 Goal and scope

LCA can be used to determine the environmentally most favorable alternative of different waste management options (Hunkeler, 2016). There is currently no recycling system available for wetsuits in Norway, and it is assumed that wetsuits are sent to incineration when they are no longer functioning. Thus, the purpose of this study is to compare two alternative disposal options for EOL-wetsuits: material recovery (alternative A), and waste incineration with energy recovery (alternative B). The goal is to compare both alternatives in terms of recovered material and energy recovery and the monetary values each alternative generates. Therefore, the final aim is to determine which option is economically feasible in the long term.

3.2.3 Functional unit

The functional unit is one medium-large, 6mm wetsuit with weight of 5kg made from neoprene. Material composition of the wetsuit in percentage of weight can be seen in table 5. The values are assumed values as it was not possible to find actual data on the composition of the wetsuit.

Table 5: Material composition of neoprene wetsuit.

Material composition	Percentage of weight
Neoprene	80%
Carbon black	8%
Nylon	7%
Polyester	4%
Glue	0.95%
Steel (zipper)	0.05%

3.2.4 System boundaries

The system boundaries are limited to two options for managing EOL wetsuits: recovery of neoprene material and incineration with energy recovery, as seen in fig. 16. The analysis focuses only on the neoprene material, and do not consider other compositions in the wetsuit.

The analysis also limits to the benefit from the management method, and don't consider the relevant cost during the management process.

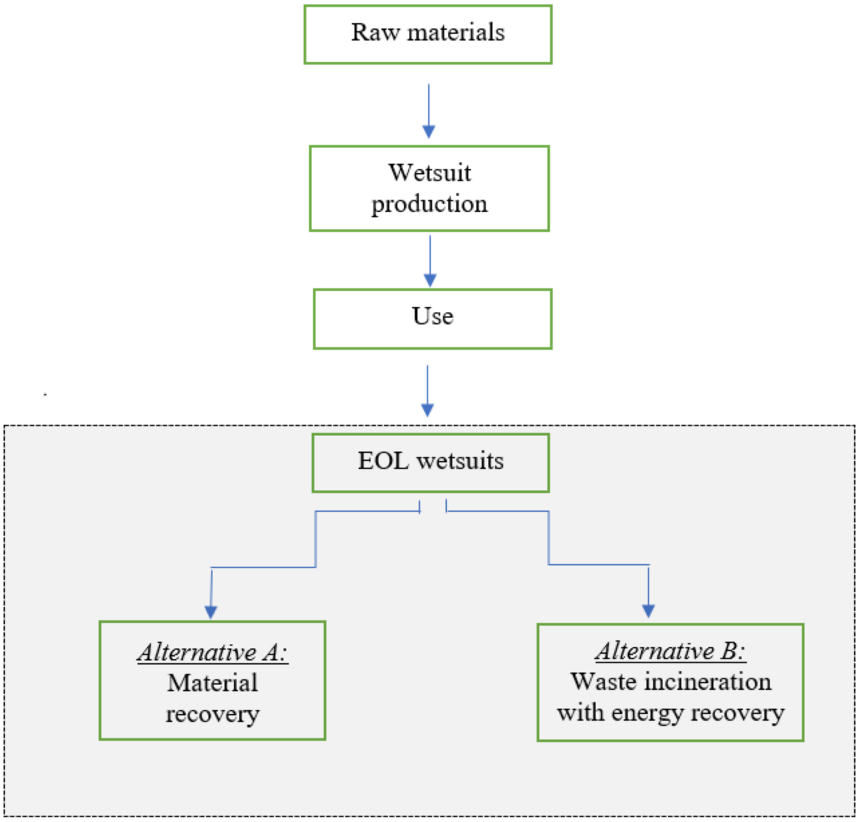

Figure 16: System boundaries of LCA.

It was not possible to find a value for the recoverable energy from incineration of neoprene wetsuits. Thus, the recoverable energy value of Styrene-butadiene rubber (SBR) from motor-vehicle tires was chosen for this purpose (Amari et al., 1999). Using the value for SBR is considered a good approximation as SBR-foam are also used in wetsuits. SBR-foam are common in low-end wetsuits and lack the flexibility and elongation of traditional neoprene.

To calculate the energy and the monetary values generated in each alternative, the following values were used:

- The energy recovery value from SBR-tires = *32 MJ/kg* (Amari et al., 1999)

- Price of neoprene/kg = *128 NOK/kg* (© RS Components AS, 2023)
- 1 MJ of energy = *0,2777777778 kWh*
- Average price for 1 kWh of electricity = *1 NOK* (SSB, 2023)

4 Results and discussion

Part 1 of the results and discussion part show the results obtained from the thermal analysis of the two wetsuits materials, neoprene, and natural rubber.

Part 2 describes the results from the LCA of two alternative waste management options for EOL wetsuits.

4.1 Part 1: Thermal analysis

In order to determine the thermal properties of neoprene and natural rubber, thermal imaging was performed. The samples were first put in a freezer and then allowed to warm under room temperature conditions. IR capture software was used to measure the established temperature gradient of the samples. The results from the experiment were compared with thermal simulations. By adjusting the value for thermal conductivity (k) and the overall heat transfer coefficient (h) in the code in MATLAB®, the simulation results were tuned to match the experimental findings as closely as possible.

Variation in temperature on the surface of the samples can be described by the constant of thermal conductivity and determines the amount of heat that is transferred based on a temperature difference between two points. The overall heat transfer coefficient determines the amount of heat flux from one body to another. In this case, the h-value determines how rapidly heat is absorbed by the frozen wetsuit sample from the surroundings (Rashid et al., 2016) and (Eidesen et al., 2022).

The IR imaging of the wet samples reviled a particularly interesting result. Due to trapped water inside the material, ice was formed when the samples were put in the freezer. When the samples were left to warm in room temperature, the recorded temperature data clearly showed a phase change from solid ice to liquid water at around 0°C. This phenomenon is called *latent heat of fusion* and describes the amount of energy absorbed during melting. It generally takes a large amount of energy to melt a solid, and the latent heat of fusion of water (at 1 atm pressure) is 333,7 KJ/Kg (Çengel et al., 2012). Figure 17 show the latent heat of fusion taking place between approximately 100s and 300s. Due to water having higher heat capacity than ice, the ice will warm up faster compared to the liquid phase, as seen in the time-temperature curve in fig. 17.

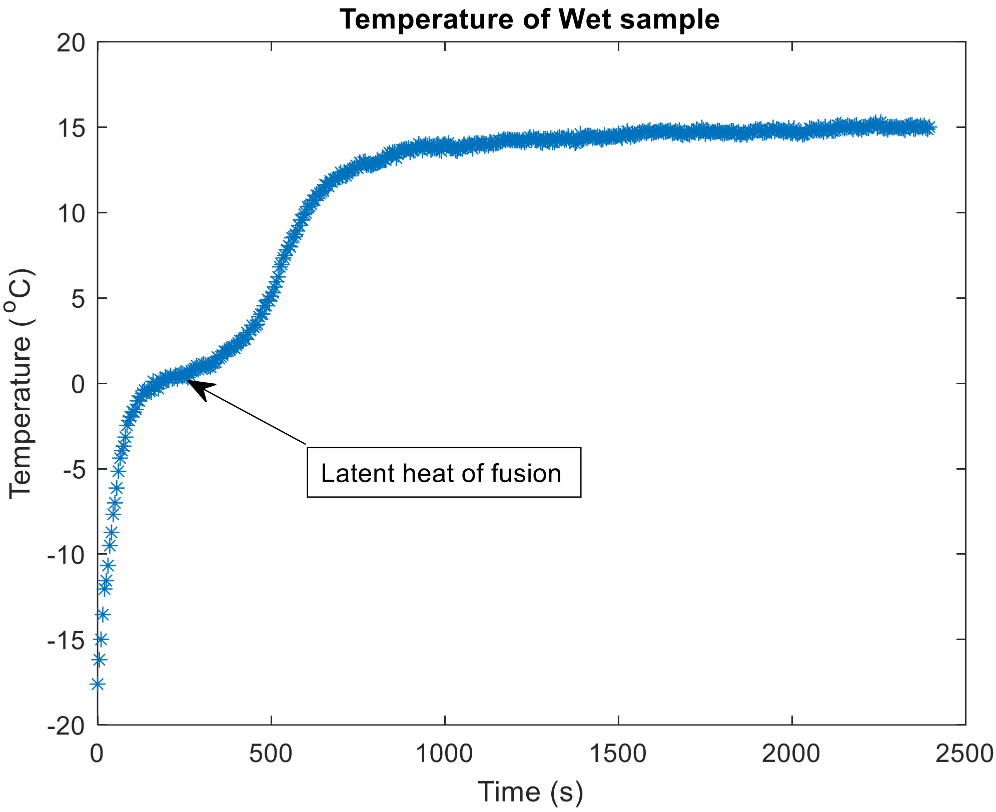

Figure 17: Latent heat of fusion in frozen wet sample.

The coefficient of thermal conductivity and the heat transfer coefficient for the dry, wet and ice phase of neoprene and natural rubber can be seen in table 6. The temperature plots as function of space and time can be found in fig. 18-29. Considering the method used, the numerical analysis provides approximate values for k and h. The analysis is highly dependent on several variables other than the k and h-value; thus, the values obtained are not to be considered as absolute values.

Table 6: Values for thermal conductivity and heat transfer coefficient from simulations.

Material	**Coefficient of thermal conductivity (W/(m ·K))**	**Heat transfer coefficient (W/(m^2 ·K))**
Neoprene dry	0,095	4,5
Natural rubber dry	0,085	7,25

Neoprene wet	0,05	6,3
Natural rubber wet	0,095	7,0
Neoprene ice	0,095	5,6
Natural rubber ice	0,06	5,85

4.1.1 Coefficient of thermal conductivity

The dry samples of neoprene and natural rubber (fig. 18 and fig. 19) showed an acceptable match between the experimental temperature data and the simulated results. For the wet samples it was not possible to achieve the same match as can be seen in fig. 22 and fig. 23. The MATLAB code does not consider the trapped water inside the material, and thus, it was not possible to simulate the phase change that took place for the wet samples.

Comparing the results for the k-values (table 6) with values obtained from literature (table 4), the thermal conductivity of both neoprene and natural rubber are less than values stated in literature. One explanation for this could be that the literary values are for solid neoprene and natural rubber, and not foamed rubber that contains air/gas bubbles inside the material. The presence of air/gas bubbles reduces the thermal conductivity of the material. It will lead to a nonuniform sample and thickness which is difficult to simulate.

4.1.2 Coefficient of overall heat transfer

From table 6, the values for the overall heat transfer coefficient are well within the range of typical h-values for natural convection for gases, usually ranging from 2-25 (W/m2 ·K) (Moran, 2003). The h-value is a property of the surrounding air and describes how much heat the air transfer to the frozen wetsuit samples. In the laboratory, the h-value was considered under natural convection conditions. In a real environment, the h-value will be higher due to the fluid motion of both water and air.

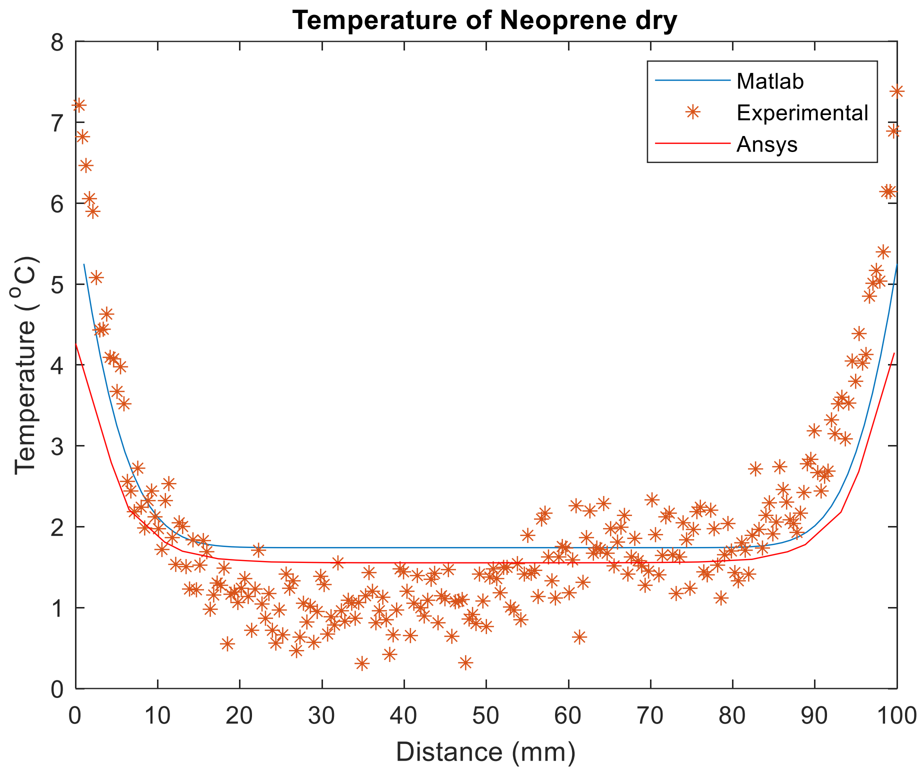

Figure 18: Temperature in dry neoprene sample as a function of position.

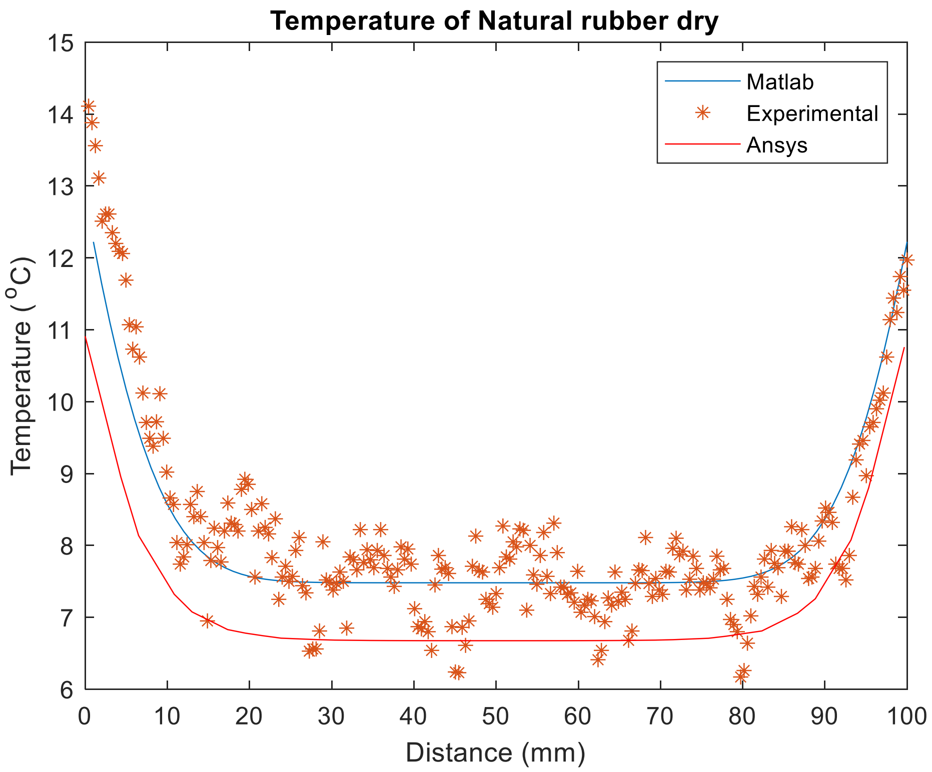

Figure 19: Temperature in dry natural rubber sample as a function of position.

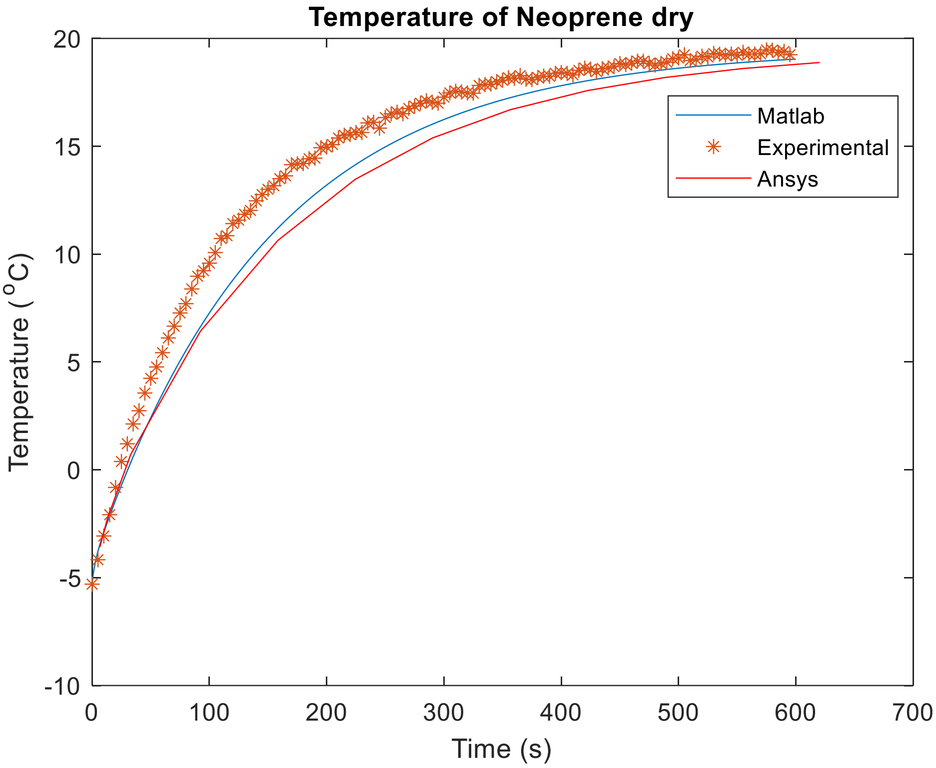

Figure 20: Temperature in dry neoprene sample as a function of time.

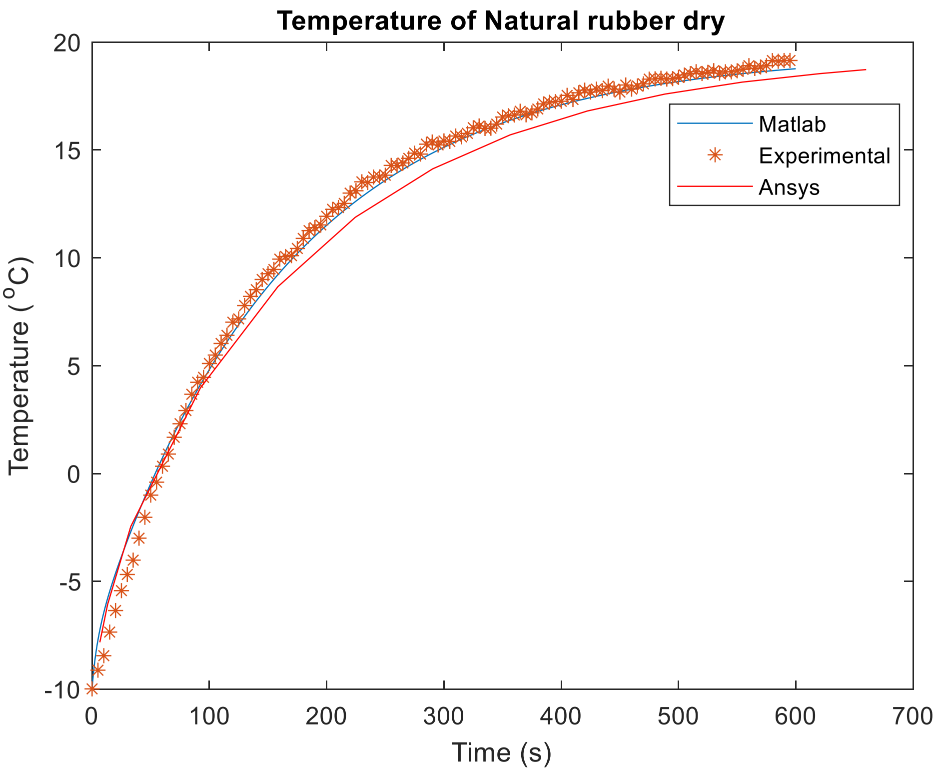

Figure 21: Temperature in dry natural rubber sample as a function of time.

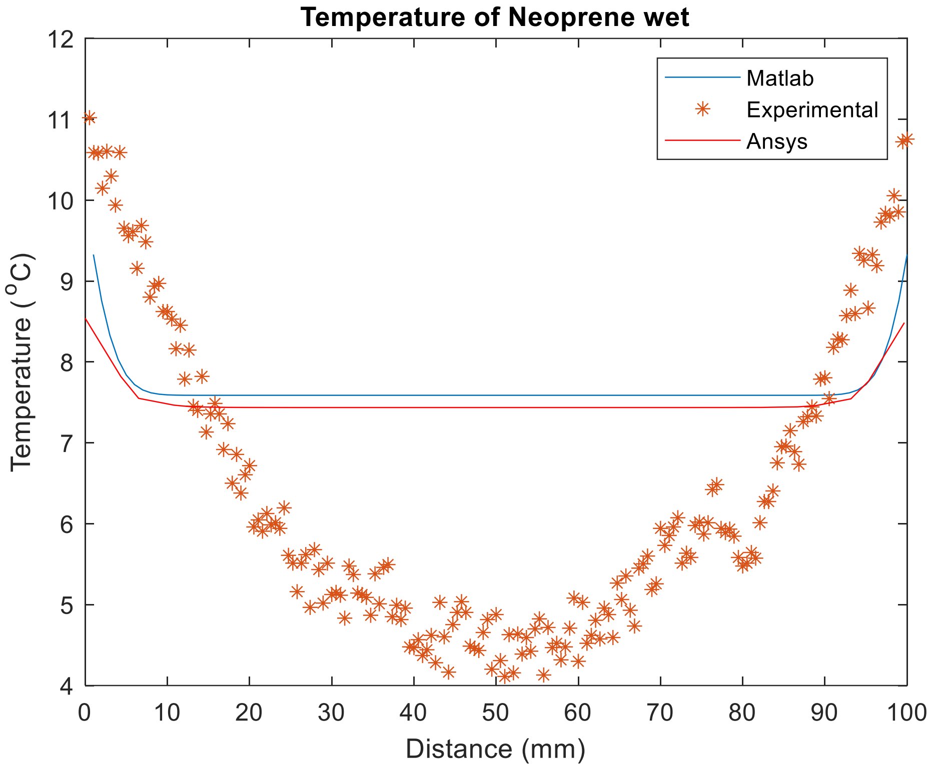

Figure 22: Temperature in wet neoprene sample as a function of position.

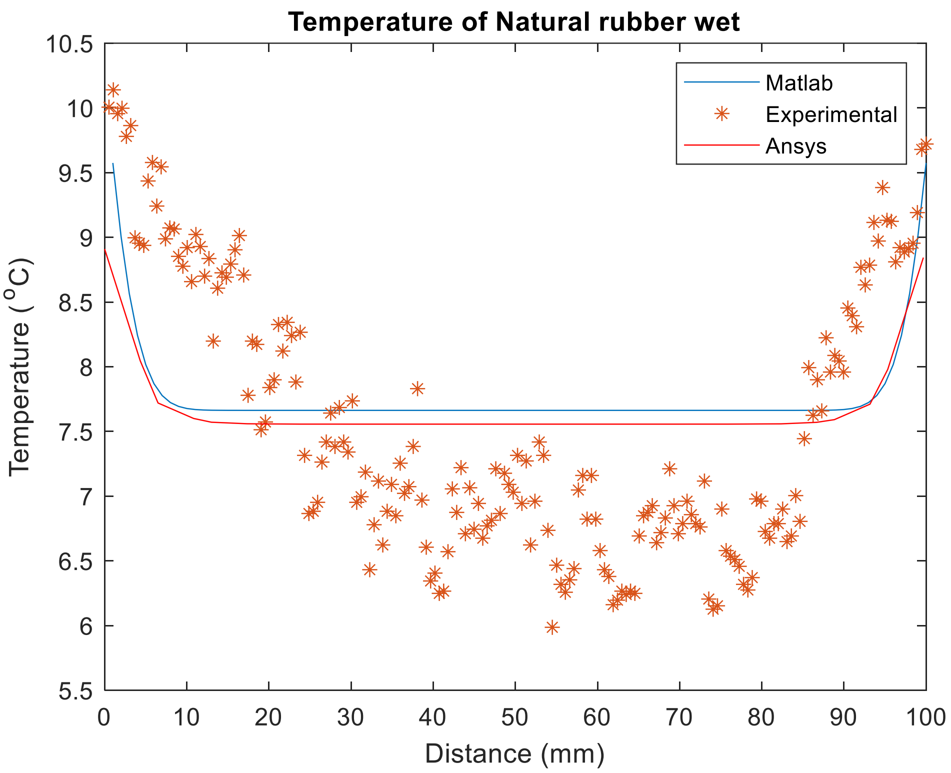

Figure 23: Temperature in wet natural rubber sample as a function of position.

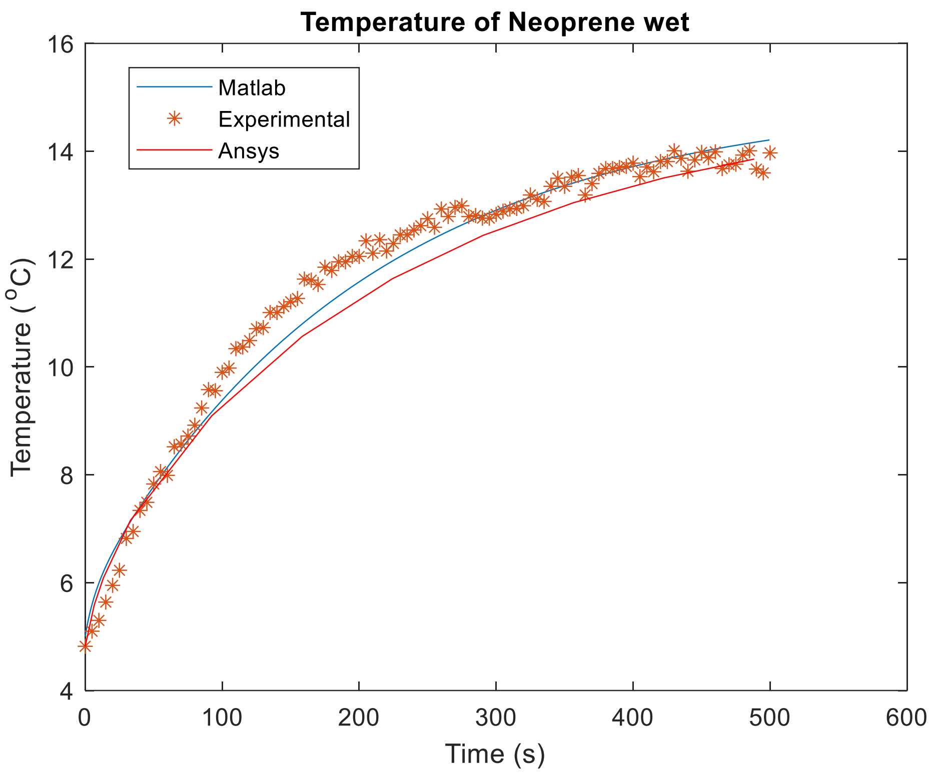

Figure 24: Temperature in wet neoprene sample as a function of time.

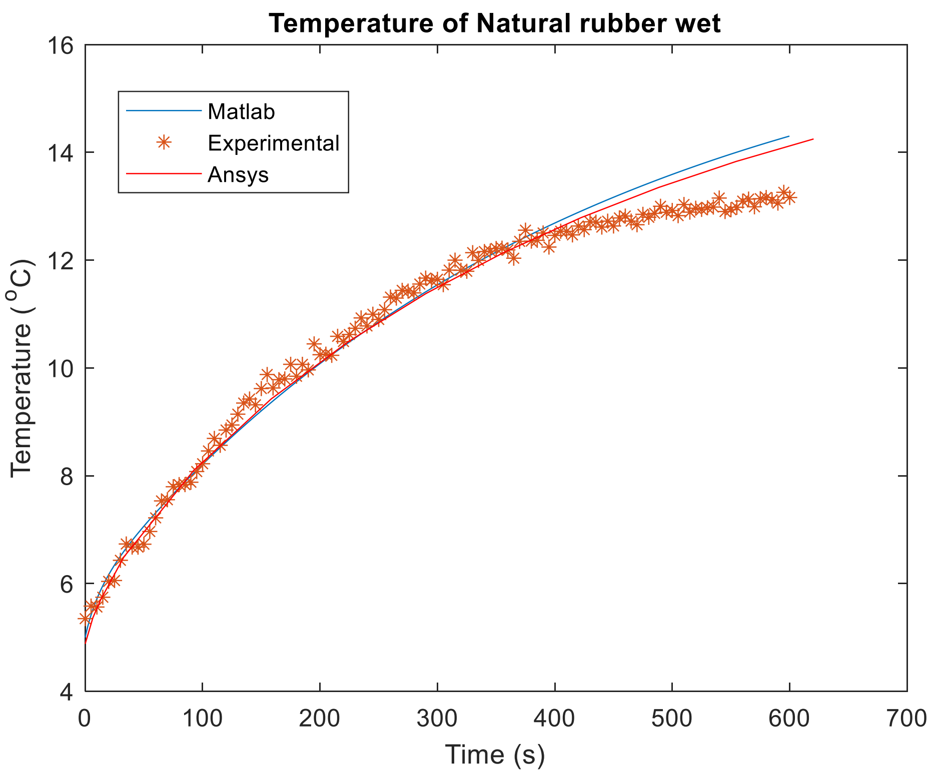

Figure 25: Temperature in wet natural rubber sample as a function of time.

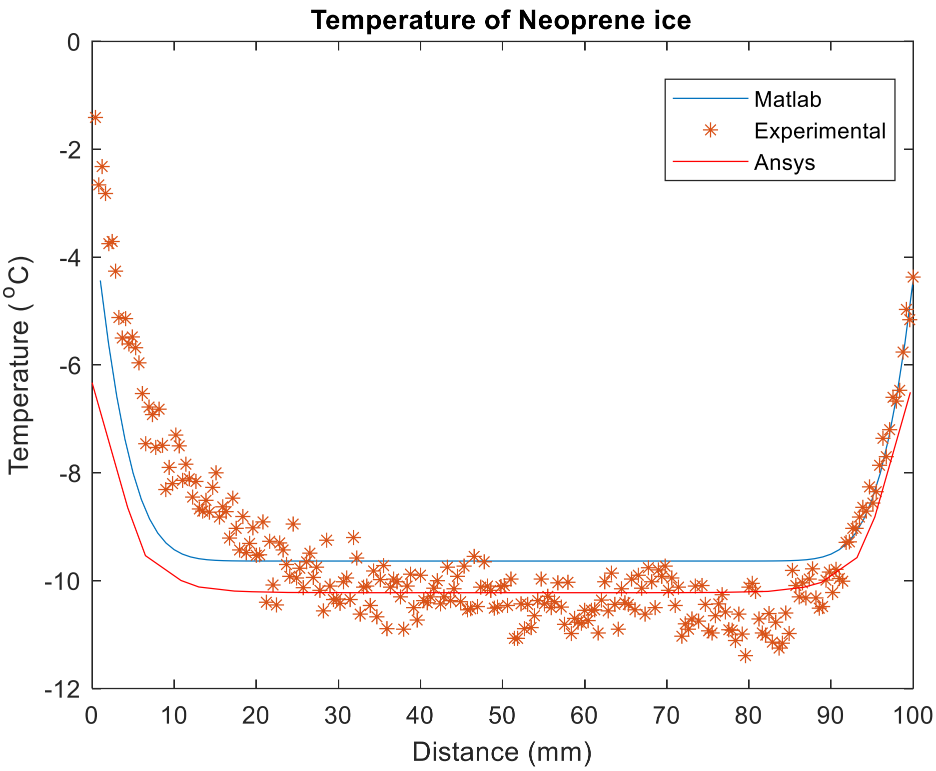

Figure 26: Temperature in ice neoprene sample as a function of position.

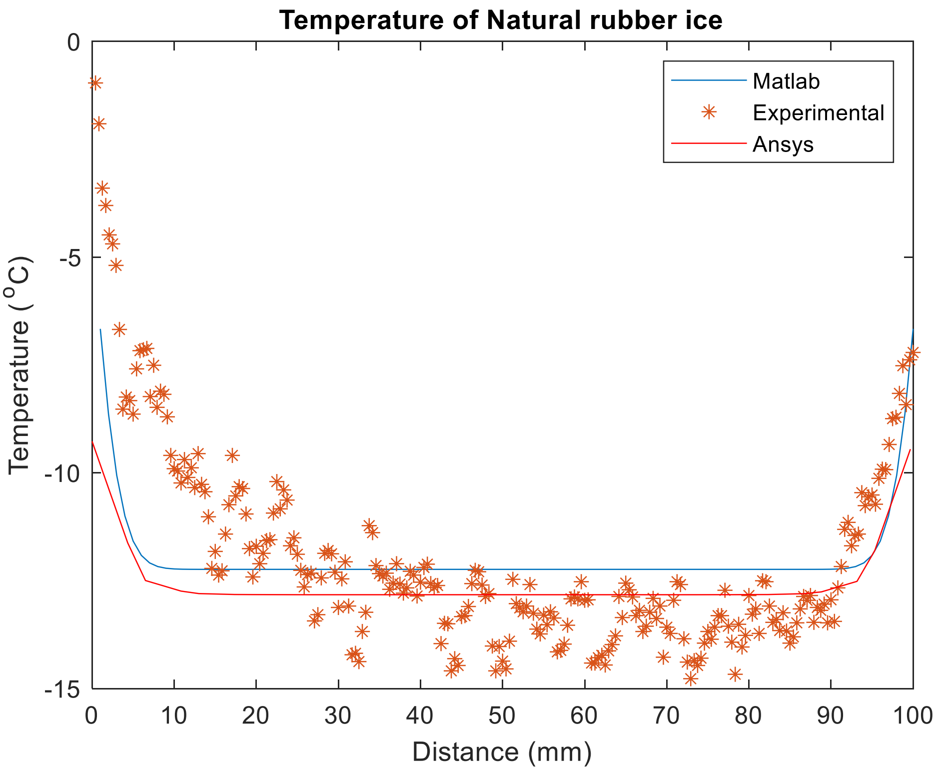

Figure 27: Temperature in ice natural rubber sample as a function of position.

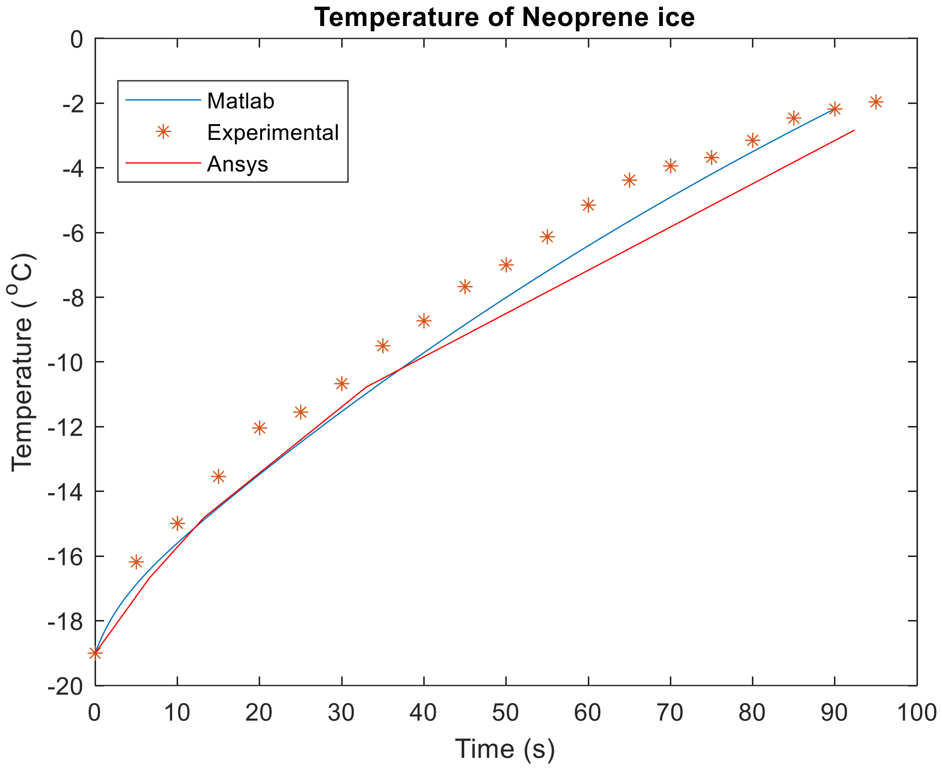

Figure 28: Temperature in ice neoprene sample as a function of time.

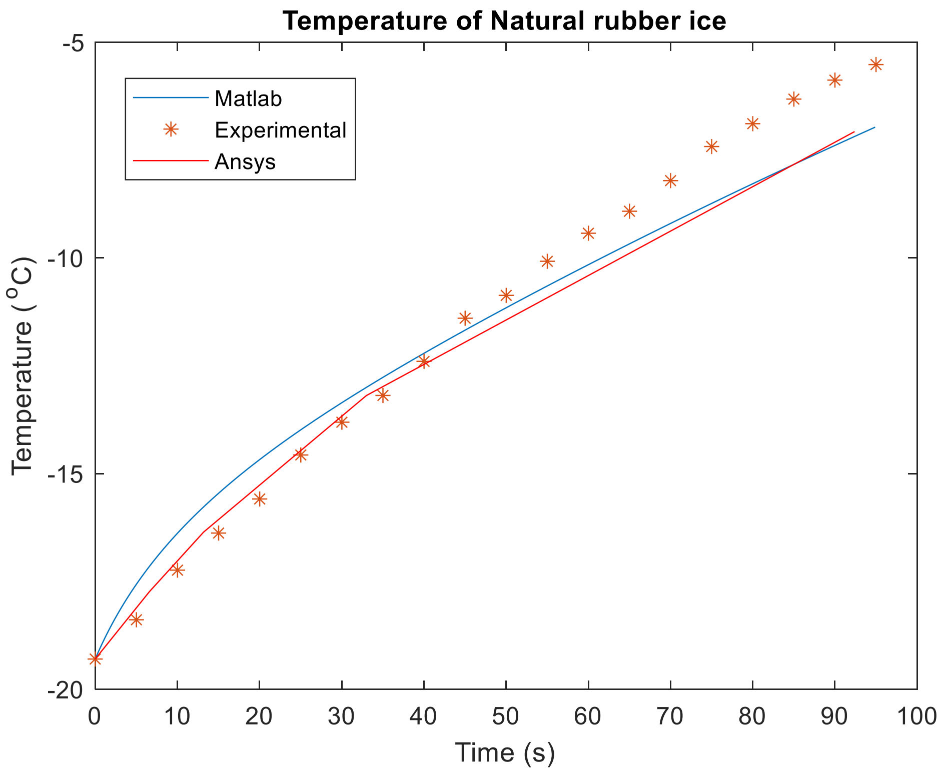

Figure 29: Temperature in ice natural rubber sample as a function of time.

The results clearly show the effect of water and the complex thermal behavior due to the latent heat of fusion taking place. From the calculations of thermal conductivity in table 4, it is evident that the conductivity of the material increases as the water content increases. In addition, wearing a wetsuit that contains water will cause evaporative cooling. This cooling effect happens due to of a phase change of liquid to gas, a process that demands a great amount of energy. The phenomenon of evaporative cooling was experienced firsthand in the TEK-3004 course last semester. In the course, different wetsuits were tested in a cold room at UiT and photographed with infrared camera with the goal of determining the insulating properties of the wetsuits. One of the wetsuits had been soaked in water prior to the experiment. Due to the high-water content in the material and the high heat capacity of water, this particular suit showed excellent thermal properties from the IR images. In reality this suited felt the coldest and most uncomfortable to wear. The reason for this was due to evaporative cooling, absorbing heat energy from the body.

From this project and the TEK- 3004 course, it is evident that the presence of water in the material has a negative effect on the thermal properties of the wetsuits, and ideally water should not enter the material. One explanation to why wetsuits seem to lose their insulating properties as they get older, could be because they absorb more water compared to a new wetsuit. The experiment clearly show that the material has the ability to absorb a substantial amount of water as seen in table 2. For instance, the natural rubber sample had a water content of close to 35%, even after it had dried for one day prior to the experiment. If water would not be absorbed by the material, this could potentially increase the lifespan of the wetsuit.

4.2 Part 2: Life cycle assessment

Table 7 show the amount of recycled material (in kg) at different recycling rates for one medium-large sized wetsuit of 5 kg, ranging from 0% to 100% recovered material. The remaining material that can’t be recycled is sent to incineration and will generate energy when the waste material is burned. This energy can be used to produce electricity and/or heat for district heating.

In alternative A, the recycling process contributes to recovery of material and is added to the system. The energy produced from incineration should also be added to alternative A. In alternative B, 100% of the material is sent to incineration and will generate a total of 128 MJ of energy per functional unit. This alternative does not include any recycled material that can be used for making new products. Figure 30 show the added values for both alternatives at a recycling rate of 80% which will generate 3,2 kg of recycled material and 25,6 MJ of energy per functional unit. (Hunkeler, 2016).

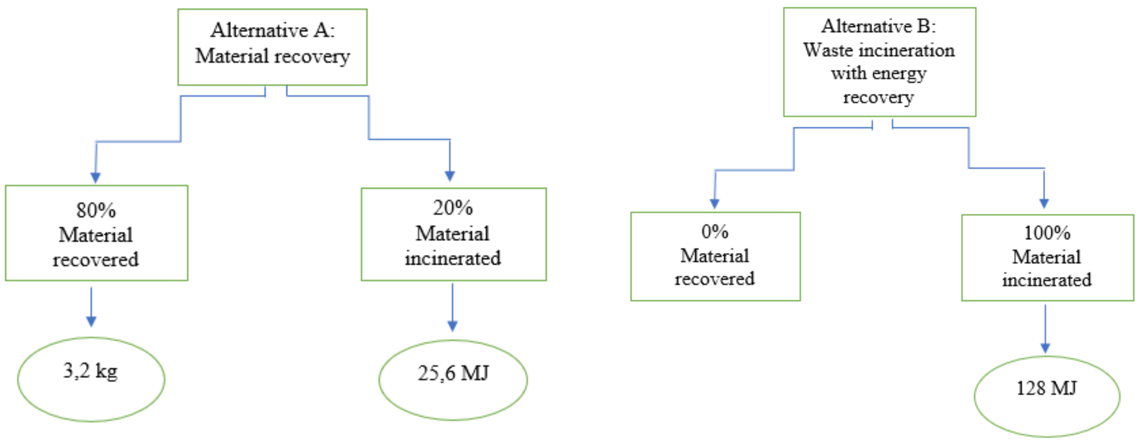

Figure 30: Added values in terms of recovered material and energy for alt. A and B.

Table 7: Output values in terms of recycled material and generated energy- and monetary values in alt. A and B.

Recycling rate (%)	Amount of recycled material (kg)	Remaining material incinerated (kg)	Energy generation from incineration (MJ)	Monetary values generated (NOK)
0%	0	4,0	128	35
20%	0,8	3,2	102,4	131
40%	1,6	2,4	76,8	226
60%	2,4	1,6	51,2	321
80%	3,2	0,8	25,6	417
100%	4	0	0	512

Table 7 show that as recycling rate increases, the monetary value generated increases. Therefore, recycling can be a feasible alternative to incineration from an economical point of view. It should be noted that the assessment only considered the monetary values generated in alternative A and B, and doesn't include the economic costs of the two waste management options.

As more material is recovered, less will be sent to incineration or landfills, which will have a positive impact on the environment. By using more recovered material, the need for virgin neoprene will be less. The harmful way of extracting the raw materials and the toxic process of producing the chloroprene will also be reduced, which will benefit especially the people living in proximity of the production plants (University Network for Human Rights, 2019).

As described in the introduction (section 3.2.1), wetsuit recycling is not always straight forward, mostly due to the chemistry of rubber but also because of how the wetsuits are designed. To increase recycling, research on more effective technologies and ways to recover material with the right quality is important. Wetsuit manufacturers also have responsibility to design wetsuits that are easier to recycle. One of the biggest issues with wetsuits is lack of durability (Holmström and Mattsson, 2019). By making wetsuits that can be used longer, it will drastically reduce the material consumption and at the same time reduce the waste stream from EOL wetsuits. Government and policy makers should strive to incentivize industries, projects and initiatives that contributes to reducing the waste stream from rubber (Leong et al., 2023).

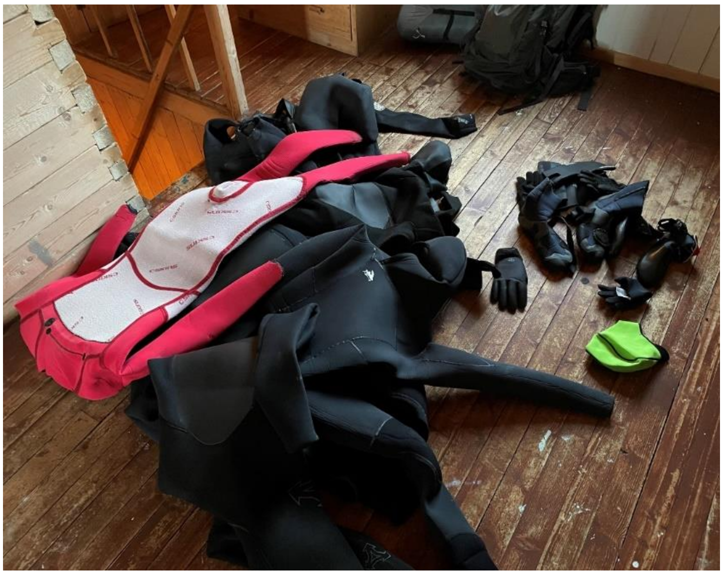

Figure 31: The author's own collection of EOL wetsuits. Waste or resource?

5 Conclusion and future work

This chapter presents the conclusions from the project and recommendations for future work.

5.1 Conclusion

To determine the thermal properties of neoprene and natural rubber used in surfing wetsuits, a finite difference methodology has been employed. By using IR thermography and comparing results with simulations, the two thermal constants, thermal conductivity and the heat transfer coefficient were estimated for dry, wet, and frozen samples of neoprene and natural rubber. The results reveal lower values in conductivity of samples compared to values obtained from literature. The values for the heat transfer coefficient showed values well within the range of those typical for natural convection for gases. The variability in the simulated results can be due to air/gas bubbles in the samples, creating a non-uniform material. In addition, the effect of water became evident in this experiment. For the wet samples, a phase change (latent heat of fusion) was observed as the frozen, wet samples were melting. A theory is that as wetsuits get older, they start to absorb more water which eventually lead to wetsuits losing their thermal properties and insulating abilities. Both neoprene and natural rubber showed the ability to absorb substantial amounts of water. Less absorbed water could potentially increase the lifespan of wetsuits.

The LCA showed that recycling of EOL wetsuits can be a feasible alternative to incineration from an economical point of view. In addition, increased recycling will have a positive environmental effect as less raw material is required, as well as the negative impacts from incineration of neoprene is reduced. Further research on new methods and technologies to enhance rubber recycling is needed to ensure recycled material with the right quality that can be used for making new wetsuits and rubber products.

5.2 Future work

Based on the results and the methods that have been described, the following further work can be initiated:

- Further research into the absorption properties of wetsuits and means to reduce absorption in wetsuits
- Develop a simulation code in MATLAB® that are able to simulate phase change/latent heat of fusion

- An extended, combined LCA and Life cycle costing that compares the potential environmental and economic impacts of different waste management options of EOL wetsuits

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Appendix - A

$$\boldsymbol{c_{p\ ice\_sample}} = \frac{\left(\boldsymbol{m_{ice}} * \boldsymbol{c_{p\ ice}}\right)_{ice} + \left(\boldsymbol{m_{rubber}} * \boldsymbol{c_{p\ rubber}}\right)_{rubber}}{\boldsymbol{m_{ice}} + \boldsymbol{m_{rubber}}}$$

$$c_{p\ ice\_neoprene} = \frac{(0{,}0035kg * 2108)_{ice} + (0{,}0125kg * 1120)_{rubber}}{0{,}0035kg + 0{,}0125kg}$$

$$c_{p\ ice\_naturalrubber} = \frac{(0{,}0080kg * 2108)_{ice} + (0{,}0150kg * 1550)_{rubber}}{0{,}0080kg + 0{,}0150kg}$$

$$\boldsymbol{k_{ice\_sample}} = \frac{(\boldsymbol{m_{ice}} * \boldsymbol{k_{ice}})_{ice} + (\boldsymbol{m_{rubber}} * \boldsymbol{k_{rubber}})_{rubber}}{\boldsymbol{m_{ice}} + \boldsymbol{m_{rubber}}}$$

$$k_{ice\_neoprene} = \frac{(0{,}0035kg * 2{,}25)_{ice} + (0{,}0125kg * 0{,}19)_{rubber}}{0{,}0035kg + 0{,}0125kg}$$

$$k_{ice\_naturalrubber} = \frac{(0{,}0080kg * 2{,}25)_{ice} + (0{,}0150kg * 0{,}14)_{rubber}}{0{,}0080kg + 0{,}0150kg}$$

$$\boldsymbol{c_{p\ wet\_sample}} = \frac{\left(\boldsymbol{m_{water}} * \boldsymbol{c_{p\ water}}\right)_{water} + \left(\boldsymbol{m_{rubber}} * \boldsymbol{c_{p\ rubber}}\right)_{rubber}}{\boldsymbol{m_{water}} + \boldsymbol{m_{rubber}}}$$

$$c_{p\ wet\_neoprene} = \frac{(0{,}0035kg * 4187)_{water} + (0{,}0125kg * 1120)_{rubber}}{0{,}0035kg + 0{,}0125kg}$$

$$c_{p\ wet\_naturalrubber} = \frac{(0{,}0080kg * 4187)_{water} + (0{,}0150kg * 1550)_{rubber}}{0{,}0080kg + 0{,}0150kg}$$

$$\boldsymbol{k}_{\ wet\_sample} = \frac{(\boldsymbol{m}_{water} * \boldsymbol{k}_{\ water})_{water} + (\boldsymbol{m}_{rubber} * \boldsymbol{k}_{rubber})_{rubber}}{\boldsymbol{m}_{water} + \boldsymbol{m}_{rubber}}$$

$$k_{\ wet\_neoprene} = \frac{(0{,}0035kg * 0{,}6)_{water} + (0{,}0125kg * 0{,}19)_{rubber}}{0{,}0035kg + 0{,}0125kg}$$

$$k_{\ wet\_naturalrubber} = \frac{(0{,}0080kg * 0{,}6)_{water} + (0{,}0150kg * 0{,}14)_{rubber}}{0{,}0080kg + 0{,}0150kg}$$