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Thermal and Mechanical Analysis of a Sustainable Alternative to Neoprene Wetsuits

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Contents

Abbreviations

NR Natural Rubber

MTPS Modified Transient Plane Source

FSC Forest Stewardship Council

PAH Polycyclic aromatic hydrocarbon

Mat$_A$ new wetsuit material investigated in this report

Wet$_{ref}$ a high end wetsuit material on the market

Abstract

A novel material composition has been investigated in terms of thermal, mechanical, economical and sustainable aspects to be compared to neoprene wetsuits. It is believed that a sandwich structure produced by a dipping method with rubber layers containing an insulating textile can insulate better than foamed neoprene. The hypothesis is also that this sandwich structure can increase durability and have similar elastic behaviour as neoprene. The effect of using Forest Stewardship Council (FSC)®-certified rubber and recycled fabric has also been investigated from a sustainable point of view. To further test if this material can compete with neoprene, an economical analysis have been carried out. It was found using simulations and thermal conductivity measurements that the new material insulates approximately 35% better than a high end wetsuit material on the market (Wet_{ref}) which was expected due to the absence of rubber in the middle layer. In terms of elasticity, the new material has slightly higher elastic modulus than the neoprene suit, which is probably due to the use of solid instead of foamed rubber. Using a low modulus latex might change these results. Regarding sustainability many aspects are similar for both the new material investigated and neoprene such as transportation and disposition of the product. There is one large environmental gain for the novel material in using natural rubber with a FSC®-certification and recycled cotton. The relatively limited cost analysis shows that the neoprene suit is slightly cheaper to produce. The dipping method used to produce the samples in this report is believed to be easier to automate, but there are certain complex problems when scaling up production to full wetsuits that need to be addressed.

1 Introduction

Since the 1950s wetsuits have been produced using neoprene sheets offering insulating clothing for the water sport athlete. Trapped water between the neoprene and skin quickly reach body temperature and as long as the clothing is properly insulated, the trapped water will show relatively low variation in temperature, resulting in lower convective heat loss. The neoprene has the elastic characteristics of rubber and thanks to a closed cell foam of air or nitrogen it is also a great insulator [1]. One problem water sport users see today is that neoprene wetsuits are too bulky and have limited stretch. In a market research performed on different surfing forums in Sweden, 50% of 621 participants put the highest priority (1 to 10) on the wetsuit's flexibility, and 97% put 7 or higher, see figure 21 in Appendix A. Another factor that the users start to question is that neoprene is petroleum based and the search for more sustainable alternatives is also illustrated by the same market research where 66% put 5 or higher on the priority scale to use a wetsuit from sustainable materials. A third factor to consider is the durability of the wetsuit, which is an economical factor but also has a big impact on the sustainability of the wetsuit. Almost all of the survey's participants prioritise durability of the wetsuit as 7 or higher. Currently, foamed rubber such as neoprene is the only material with sufficient insulation and flexibility to use for water sports. Furthermore, to overcome the use of neoprene as the primary material for wetsuits all of these properties have to be either maintained or improved. In this report a new structural design is investigated, which could drastically improve the thermal insulation performance making it possible to reduce the thickness of the wetsuit. This could in turn increase the mobility for the user. Over half of the participants of the survey would pay an additional 1000SEK or more for a thinner wetsuit (meaning more flexibility), as long as the insulation is equivalent that of a neoprene wetsuit (see figure 21 in Appendix A for the market research). The aims of this report will be described more in detail below in section 1.2.

1.1 New structural design and production method

This report aims to assess whether neoprene can be replaced by alternative materials by engineering a sandwich structure with the hypothesis that the material composite will restrict heat loss better and increase flexibility. To enhance durability a new production method has been analysed for the possibility of producing a seamless wetsuit. Wetsuits tend to wear out in their weakest links and the seams are also parts that lowers the insulation and stretching capabilities. Stitching a wetsuit includes making holes in the neoprene which let water and wind enter [2]. Both neoprene and the conceptional sandwich structure are illustrated in figure 1.

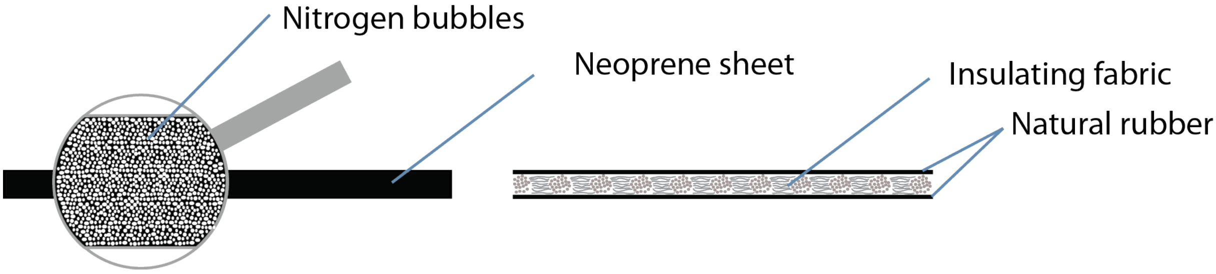


Figure 1: Illustrated structures of neoprene (left) and the sandwich structure (right).

In this report all materials, certainly the rubber, can not be classified as fully sustainable due to the availability of the materials. However it is considered to be relatively straight forward to use the same production process on more sustainable materials such as new FSC®-certified rubber alternatives. Two different yarns will be investigated as insulating materials being recycled cotton and fine merino wool.

To achieve a seamless wetsuit, a dipping method will be used to mold the rubber in non regular shapes. This is a well established method that has been used in almost a century. Combining this process with the materials mentioned above, it is hoped to achieve a wetsuit that insulates better, hence it could possibly be made thinner than today's wetsuits. Using solid rubber in a sandwich structure and totally eliminating seams is believed to increase durability considerably.

1.2 Tasks

Below, the different tasks of this thesis are presented with a label of either high or low priority.

High priority

Task 1 - *Create small samples using a dipping method* - A new structural design and material will be created using a dipping method in natural rubber latex.
Task 2 - *Simulate thermal conductivity* - Simulations of thermal conductivity will be carried out in COMSOL® for neoprene and the sandwich structure.
Task 3 - *Thermal conductivity testing (flash method)* - Thermal conductivity measurements will be carried out on the small samples using a flash-method.
Task 4 - *Thermal conductivity (MTPS-method)* - Thermal conductivity measurements will be carried out on the small samples using a Modified Transient Plane Source (MTPS)-method.
Task 5 - *Tensile testing* - The elastic behaviour of the materials will be analysed with tensile testing.

Low priority

Task 6 - *Create a wetsuit shoe using a dipping method* - Depending on the time a wetsuit shoe will be prepared using the same method as in Task 1.
Task 7 - *Thermal insulation test of wetsuit shoes* - The shoe from Task 7 and its insulation properties will be tested and compared with a wetsuit shoe on the market.
Task 8 - *Assessment of sustainability* - A study will be carried out on the sandwich structure and on neoprene to assess if there are any differences in terms of sustainability.
Task 9 - *Cost analysis* - Approximations on the cost of producing a wetsuit with both methods will be done to establish the possibility of creating a product that can compete on the market.

2 Theory

2.1 Heat flow

Engineering a wetsuit requires extensive knowledge about material properties, especially about heat flow. It is paramount for the functionality and performance of a wetsuit. As the functionality of a wetsuit is to reduce heat loss from the body while in water, the main mechanisms for heat transfer is convection and conduction. At $0.6\,\mathrm{W\,m^{-1}\,K^{-1}}$ water is 25 times more conductive than air: $0.024\,\mathrm{W\,m^{-1}\,K^{-1}}$ [3], which makes conductive heat transfer an important mechanism for evaluating the performance. The thermal conductivity is used as an indicator of the conductive performance in this report. Convection of trapped water between skin and the wetsuit is assumed to be negligible.

Wetsuits are designed so that it allows a small amount of water leakage to enter through seams, insufficient seals by the legs, arms and neck. The body then warms this trapped water to body temperature which acts as a shielding layer between the environment and the body. This inner water layer has limited exchange with the environment. Consequently, the trapped inner water layer together with an insulating material like neoprene, drastically reduces the convective heat loss. The convective heat insulation performance is similar in most wetsuits, but is affected by the exchange of the inner water layer with the environment, so called 'flushing'. Flushing is more common in low-end wetsuits, where water can penetrate more readily through seams and other openings [2]. A consequence of using the dipping method is that no seams will be present and hence no water exchange will happen at these points.

One aim of this report is as mentioned earlier to assess whether a new material combination can increase the insulation properties, primarily the conductive heat insulation performance. Heat flow mechanisms will therefore be presented more in detail below.

2.1.1 Fourier law of heat conduction

To model heat transfer for real problems, the first law of thermodynamics needs to be supplemented by heat transfer functions such as Fourier's law and Newton's cooling law. The one dimensional model shown in figure 2 will be used as model for the equations below, where the cuboid in the figure has the thermal conductivity λ.

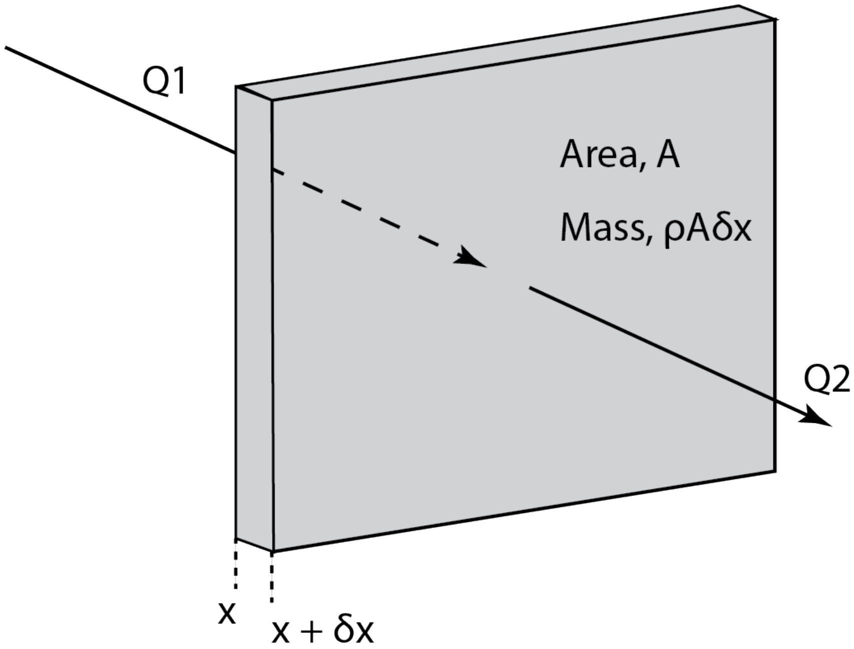


Figure 2: A one dimensional heat conduction model.

Fourier's law state the heat transfer by conduction

$$\vec{q} = \frac{Q_{net}}{A} = \frac{Q_2 - Q_1}{A} = -\lambda \nabla T \tag{1}$$

where $\vec{q}$ is the heat flux, λ is the thermal conductivity, Q is the heat transfer rate and ∇T is the temperature gradient. Combined with the first law of thermodynamics the heat diffusion equation in three dimensions can be written as

$$\nabla \cdot \lambda \Delta T + \dot{q} = \rho c_p \frac{\delta T}{\delta t} \tag{2}$$

where $\dot{q}$ is a volumetric heat release, ρ the density and c_p the specific heat capacity. The limitations of this equation is that the medium is considered incompressible and no convection is accounted for [4].

2.1.2 Newton's law of cooling

Newton's law of cooling states that a typical convective cooling situation can be explained such that the energy from the warmer body is proportional to the temperature difference between the body and convective medium.

$$Q \propto T_{body} - T_\infty \tag{3}$$

This can be written in terms of the heat flow q where $\bar{h}$ is called the heat transfer coefficient.

$$q = \bar{h}(T_{body} - T_\infty) \tag{4}$$

$\bar{h}$ is an average of h over the surface of the body and varies significantly for different situations [4].

2.1.3 The energy equation

Extending the heat conduction equation with the convection term is necessary when studying a realistic situation in simulation programs such as COMSOL®. The equation is usually written with four different parts: energy storage, enthalpy convection, heat conduction and heat generation.

$$\rho c_p(\underbrace{\frac{\delta T}{\delta t}}_{\text{energy storage}} + \underbrace{\vec{u} \cdot \nabla T}_{\text{enthalpy convection}}) = \underbrace{\lambda \nabla^2 T}_{\text{heat conduction}} + \underbrace{\dot{q}}_{\text{heat generation}} \tag{5}$$

$\vec{u}$ is the velocity flow field of the fluid or gas [4].

2.2 Measuring thermal conductivity

Thermal conductivity measurements were carried out using a MTPS-technique and a flash method. Both techniques will be described in the sections below.

2.2.1 Modified Transient Plane Source-technique

This technique uses a sensor spiral heating element together with a guarded ring to apply a one-dimensional heat transfer to the sample. When a known current is applied to the spiral heating element, it heats up and supplies heat to the sample, see figure 3. The temperature increase in the interface between the sensor and sample, induces a change in the voltage drop in the sensor element. This drop depends on the thermal properties of the sample. The thermal conductivity is inversely proportional to the rate of increase in the temperature at the interface. A steeper rise in temperature will be observed for materials with low thermal conductivity since they have poor heat transfer [5].

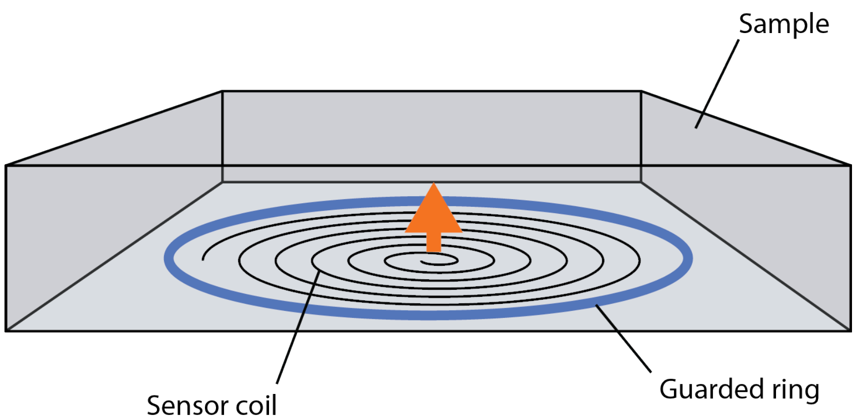


Figure 3: MTPS-setup. The orange arrow indicates the thermal gradient direction.

2.2.2 Flash method

The Flash-method uses a powerful flash to apply a momentary temperature increase at the surface of the sample, while the temperature change over time is recorded by a thermal imaging camera placed on the opposite side, see figure 4. The result is a temperature transient which can be compared to a simulation in COMSOL® where the thermal conductivity parameter is varied to match the recorded transient. Specific heat, density and sample dimensions must be known beforehand.

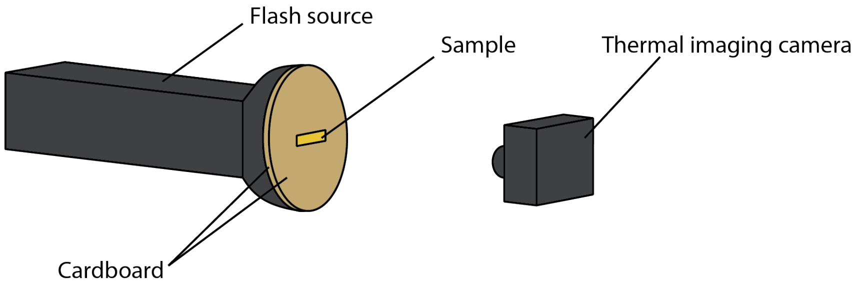


Figure 4: Setup for the flash experiments.

2.3 Tensile testing

One of the most important parameters for engineering wetsuits is their flexibility. To determine wetsuits' flexibility, more precisely their elasticity, a tensile test is performed. The sample is clamped together on two ends. The machine exerts a force stretching the sample. The elongation length as well as the applied force is continuously measured. The resulting force is divided by the original cross-section area to obtain the engineering stress, see equation 6.

$$\sigma = \frac{F}{A_0} \tag{6}$$

The strain is measured by the difference in elongation divided by the original elongation.

$$\epsilon = \frac{\Delta L}{L_0} \tag{7}$$

The stress as a function of strain is then shown in a plot, which is called 'Young's modulus'. Elongation at break is important, but for a wetsuit it also needs high flexibility at low strains to be comfortable to wear. Thus, low elastic modulus is required for high performance wetsuits [3]. The elastic modulus can be calculated through the slope of the linear part of Young's modulus, which corresponds to the elastic behaviour of the material. The 'yield strength' can be obtained by using this slope with a 0.2% offset on the strain.

2.4 Producing latex

There are many ways of producing latex products. In this report a method called dipping will be used. Dipping is a well-established method for producing rubber products with good control of the thickness on the final product. Using latex dipping, non regular shapes can be produced and this enables the possibility to produce a wetsuit without having to sew pieces together.

When creating a seamless wetsuit by latex dipping it is important to understand how the process works to obtain high quality samples and to be able to engineer a sandwich structure that can insulate as good as neoprene, at a fraction of the thickness.

2.4.1 Coagulant dipping

The dipping process that will be used in this report is called coagulant dipping, which uses a coagulant to more easily regulate the rubber thickness.

When Natural Rubber (NR) is collected from the inner bark of Hevea brasiliensis (or other trees containing rubber latex), the dried product is not the rubber as we know it. This rubber is a thermoplastic polymer with low tensile strength and low elasticity much due to the absence of crosslinks. When adding sulphur to the latex, that contains chains of isoprene, the sulphur will create bridges between these chains (see figure 5) [6]. This reaction occurs faster with added heat and the vulcanisation process usually takes place in an oven.

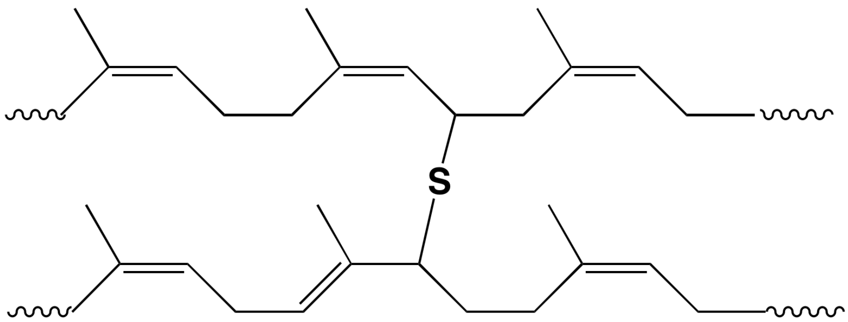


Figure 5: Sulphur bridge between to polymer chains of isoprene building up the crosslinked network.

Two advantages of using coagulant dipping are the possibility to make thin coats and to more accurately adjust the thickness. The principle is that the negatively charged latex particles in solution will need to coagulate at the surface of the used mold. Dipping the mold in a salt solution, usually calcium nitrate in alcohol, the relatively diluted latex dispersion will start to form a three dimensional network at the surface of the mold. This happens because the positively charged calcium ions interact and break up the electrostatic stabilisation between the latex particles resulting in them approaching each other. Here Van der Waal forces dominate which cause the particles to coagulate (see figure 6). Hence, the thickness of the film depends on diffusion of Ca^{2+} through the formed latex network. Since diffusion length of the calcium ions depend on the square root of the time, the thickness that is built up stagnates accordingly. From an industrial point of view coagulant dipping is said to create rubber products with a maximum thickness of 1.5 mm. In the case where one wants higher thickness, it is possible to dip multiple times and the layers then fuse together during the final vulcanisation [7].

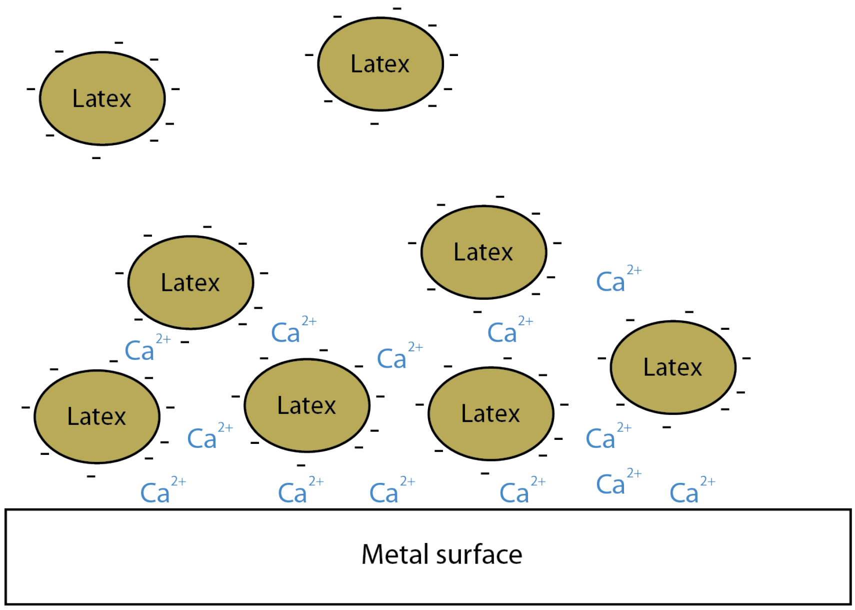


Figure 6: Colloidal explanation of the coagulation reaction happening on the mold.

3 Methods

3.1 Simulation

COMSOL® Multiphysics (Classkit License) version 5.3a has been used for simulation of heat flow in the different structures. Geometries were drawn in the program itself (see figure 7) and the physics used was 'heat flow in solids'. Table 1 shows the parameters on specific heat (C_p), thermal conductivity (λ) and density (ρ).

When carrying out the simulations, all boundaries were set to be insulating except the contact boundary to the body and to the ocean. Doing so, it was assumed that heat transfer in the lateral direction parallel to the body could be neglected. The heat flow from the body was set to 50 W/m^2 and the boundary to the ocean was set to 10 °C. Initial value in all geometries was 20 °C [8]. The boundary between skin and the inner water layer water was measured over time.

Table 1: Input parameters for simulation in COMSOL®.

	C_p (J/kgK)	λ (W/mK)	ρ (kg/m^3)
Polyisoprene	1880 [9]	0.14 [10]	910 [11]
Water	from program	from program	from program
Air	from program	from program	from program
Nitrogen	from program	from program	from program
Titanium dioxide [12]	690	5	4000
Neoprene	2100 [13]	0.19 [14]	1240 [15]
Nylon	from program	from program	from program

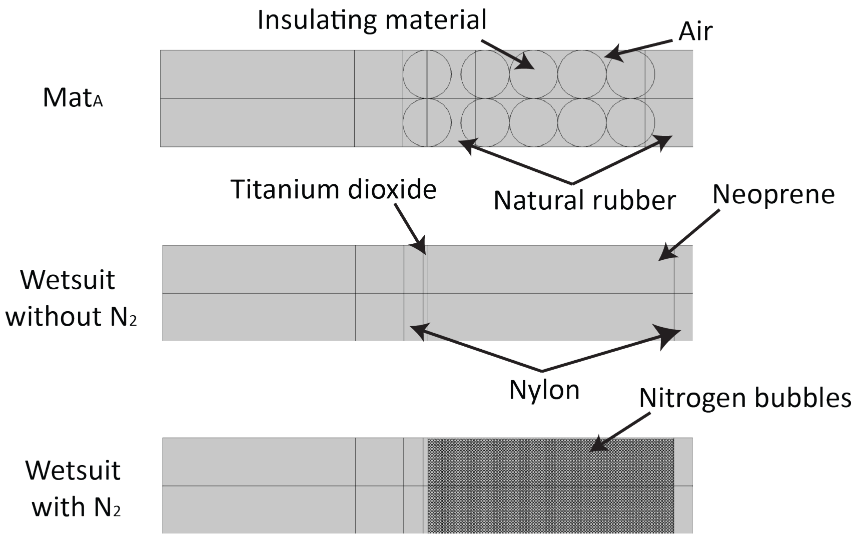


Figure 7: Geometries used in simulation.

Different parameters were varied for the new wetsuit material investigated in this report (Mat_A) to establish if these have influence on the heat flow or not. A factorial design was implemented to make this work as logical and effective as possible (see table 2).

Table 2: Codes and values for the factorial design for simulation of Mat_A.

Name	+	-	**Code**
Penetration	0.5 mm	0.2 mm	P
Thickness rubber	1 mm	0.5 mm	T
Diameter fibre	1 mm	0.5 mm	W
Skin temp (15 min)			Y

3.2 Sample preparation

A dipping process was used to prepare the samples, see figure 8. Four samples were constructed where the vulcanisation temperature and the type of yarn used was varied (see table 3). The Mat_A has consistently been prepared using this dipping process that will be described more in detail below.

An aluminium mold was used to dip in the latex after being treated with coagulant. Keeping the mold warm in an oven assured good heat transfer to the latex and for the vulcanisation process. There was no need for glue to seal the edges since the second rubber layer was applied within the same process before final vulcanisation. This allowed the rubber layers to fuse together providing a water-tight seal. The rubber layers were of similar thicknesses for all the samples: minimum thickness of 0.8 mm and thickest at 1.5 mm. However, the thickness of the insulating layer differed between the structures. Wool showed the highest thickness at 1.9 mm due to it having the largest fibre thickness. Cotton had a smaller thickness at roughly 1.1 mm.

Figure 8: Images from the latex dipping process performed to produce the samples.

Table 3: Summary of the prepared samples.

	Temperature (°C)	Fibre type
Sample 1	96	Merino wool
Sample 2	116	Merino wool
Sample 3	96	Recycled cotton
Sample 4	116	Recycled cotton

A shoe was moulded for further testing (see section 3.5). This was created using a vulcanisation temperature of 96°C and a sock containing merino wool and various synthetic fibres.

3.3 Thermal Analysis

To determine the insulation performance of the samples, the thermal conductivity was used as a benchmark. The measurements of the thermal conductivity was performed using a MTPS-technique from *C-Therm*, see section 2.2.1, and a Flash method, see 3.3.1. *Elastocon AB* performed the MTPS-measurements on five different samples and two neoprene samples as references.

3.3.1 Flash method

The sample was placed on the lamp shield about 10-15 cm from the flash-source, see experimental setup in figure 4. The sample was painted with black spray paint to ensure the heat absorption at the surface would be sufficient, as well as a well defined emissivity to match the setting of the camera. Attaching the sample between two pieces of circular cardboard with rectangular openings made it easier for simulation in COMSOL® and heat flow was directed through the sample. The camera was placed 20-30 cm from the sample. Figure 9 shows an image from the heat camera illustrating the small opening in the cardboard where the temperature data was collected.

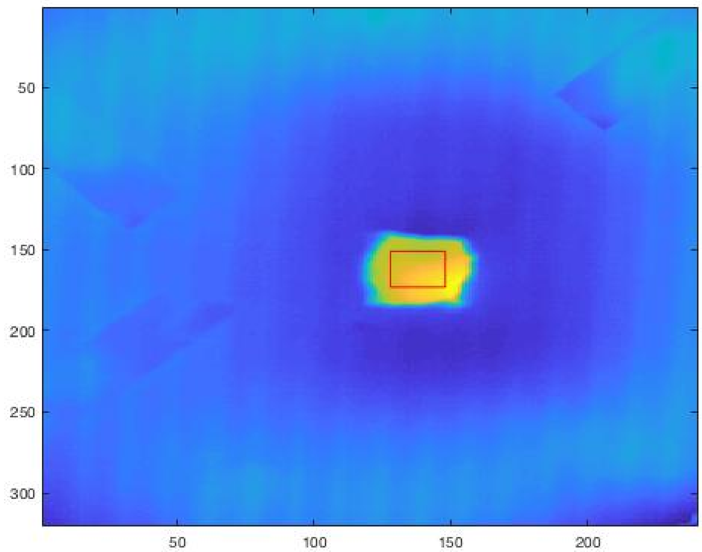


Figure 9: Picture from heat imaging camera showing the sample (yellow) with surrounding cardboard (blue).

The flash was fired six times at intervals of 10 seconds, which caused a temperature increase recorded by the thermal imaging camera. Thermal conductivities were matched by fitting a simulated curve in COMSOL® with the obtained time vs temperature graph. Geometry dimensions and densities were measured and values of C_p were chosen as weight averages from table 1.

3.4 Tensile testing

The sample was clamped together on two ends with a spacing of 3.8-10 mm. This spacing was measured closely and recorded as L_0, see equation 7. The clamps were 5 cm wide. The machine was set to a pulling speed of 15 mm/min with an extensiometer with a maximum range of 20 mm. With the data-collecting program started, the machine was set to begin pulling. When the extensiometer had reached its limit the measurement was ended. By using this raw data together with the recorded dimensions the stress strain– and force strain curves could be produced.

3.5 Thermal insulation testing of wetsuit-shoe in water

To investigate the thermal properties of Mat_A in a situation more close to where it will be used by the user, a test in cold water was performed. A wetsuit-shoe prepared according to section 3.2 was compared with a shoe from Wet_{ref}. Both shoes were filled with 300 mL of warm water and placed in a plastic box containing cold water with an initial temperature of 3 °C. The opening in both shoes were sealed with styrofoam and the thermometer was attached to the styrofoam measuring the warmer shoe reservoir. To keep the shoes from floating up to the surface weights were placed on top of them. Temperatures were collected every 60 seconds. Figure 10 illustrates the experimental setup.

Figure 10: Experimental setup for thermal testing of the wetsuit-shoes.

3.6 Assessment of sustainability

An assessment of sustainability was performed. It followed Fiksel et al. [16] by using three sections: *Resource and value*, *Three aspects* and *Life cycle*. Sustainable products should minimize resource consumption while maximizing value creation, which is covered by *Resource and value*. Both resource and value creation should then be examined using the *Three aspects*; economic, environmental, and societal aspects. Lastly, an evaluation of the life cycle of the resources as production or re-use was performed.

3.7 Cost analysis

Production costs for Mat_A have been analysed in a rather limited manner to compare this new possible production route with the already established production of neoprene wetsuits. For simplification, one wetsuit shoe produced in the classic way of sewing/gluing neoprene sheets together was compared with the dipping method of one wetsuit shoe described in this report. Due to limited information about the production facilities, the material costs, production times etc., they had to be estimated using several different references. Furthermore, this analysis is limited to the actual time of producing one shoe and the costs that is included in that process. Costs that are not considered are for instance: rents, warehouse costs and transportation. Production times are estimated from lab work and the limited insight in the production of neoprene wetsuits.

4 Results

4.1 Simulation

Different structures were built in COMSOL® (see figure 7) in two dimensions and the geometries were then used in simulation using the physics heat flow in solids, see section 3.3.1. Figure 11 shows skin temperature as a function of time for Mat_A, Wet_{ref} with nitrogen bubbles and Wet_{ref} without nitrogen bubbles. It can be seen that Mat_A shows a significant difference in insulation by conduction compared to the other two. As expected, the nitrogen bubbles have big influence over the insulation properties in the Wet_{ref}. The nitrogen bubbles have significantly lower thermal conductivity than the surrounding rubber and additional nitrogen is believed to increase the insulation. To demonstrate what thickness of Mat_A that corresponds to Wet_{ref} in terms of insulation, figure 12 was constructed by increasing the neoprene (containing nitrogen) geometry to 5 mm. It is clear that according to these simulations, 3 mm of Mat_A has insulation properties matching 5 mm of Wet_{ref}.

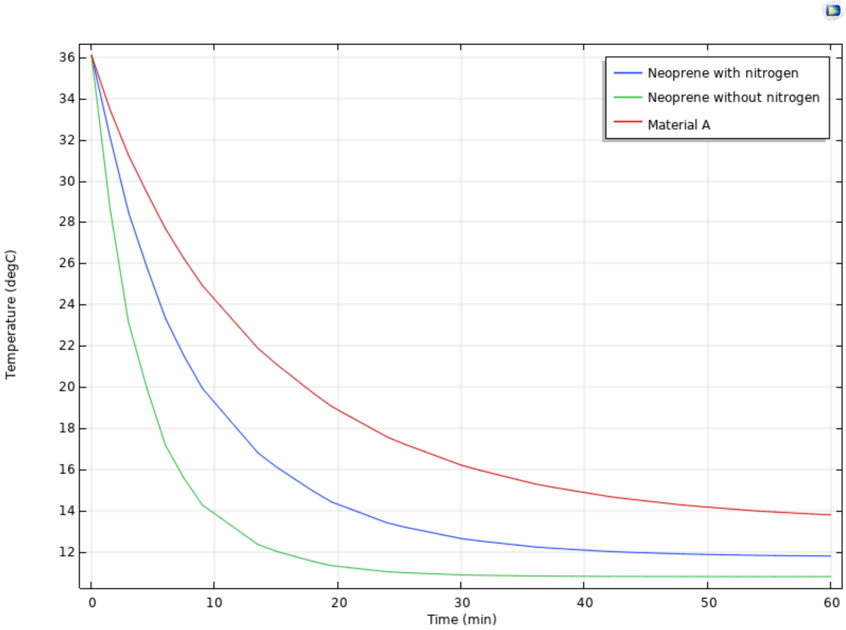


Figure 11: Skin temperature vs. time for a wetsuit with: a) neoprene (Wet_{ref}) with nitrogen bubbles, b) neoprene (Wet_{ref}) without nitrogen bubbles and c) Mat_A.

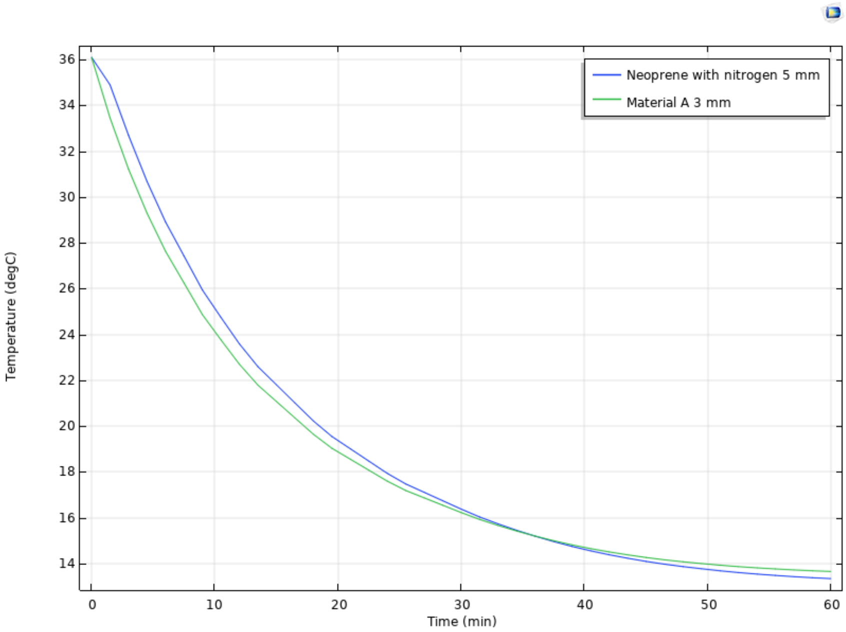


Figure 12: Skin temperature vs. time for a wetsuit with: a) neoprene (Wet_{ref}) with nitrogen bubbles (5 mm) and b) Mat_A (3 mm).

A 1D simulation was performed with the same dimensions used as in figure 7 but as a homogeneous material. Values of C_p were chosen from table 1 as weighted averages. ρ for Wet$_{ref}$ without nitrogen bubbles was also chosen from table 1 while measured densities were chosen for Mat$_A$ and Wet$_{ref}$ containing nitrogen bubbles. The thermal conductivity was then varied to match the curves in figure 11. The result is shown in table 4. Wet$_{ref}$ without nitrogen shows the same thermal properties as in the 2D simulation which was expected since the material throughout the 2D structure was principally homogeneous. The results can be interpreted such that the Wet$_{ref}$ with nitrogen conducts heat 33% better than Mat$_A$. Literature values on foamed neoprene is about 0.054 W/(m K) which is rather low compared to the obtained value in table 4 [3]. Hence, the drawn geometry in figure 7 can be questioned of its accuracy. The ratio between nitrogen and neoprene is crucial for insulation and this could have a big effect on the results.

Table 4: Results from the 1D simulation.

Sample	λ (W/(m K))	ρ (kg/m^3)	c_p (J/(kg K))
Mat$_A$	0.048	680	1790
Wet$_{ref}$ with nitrogen	0.072	210	2100
Wet$_{ref}$ without nitrogen	0.19	1240	2100

Skin temperatures were calculated for 8 different structures from the factorial design (see table 5 and compared with Wet$_{ref}$. A high skin temperature means that the material is insulating better. All structures had a thickness of 3 mm when doing the calculation. Looking at tables 5 and 6 it seems that thickness of the rubber has a significant effect on a significance level less than 0.1 % represented by the P-value in the statistical model of the factorial design. This was an expected result since the higher ratio polyisoprene present in the structure should theoretically make Mat$_A$ conduct heat closer to polyisoprene itself. Interestingly enough nothing can be said about the fibre diameter. The fibre contains lots of air itself and this could possibly explain why it does not seem to significantly affect the result. Figure 13 and 14 both illustrate the result where figure 14 shows the heat flow through the different geometries. It is clear that for all 8 variations of Mat$_A$ it still insulates better than Wet$_{ref}$.

Table 5: The structure of the factorial design for the simulation work.

P	**T**	**W**	**Y (°C)**
-	-	-	21.41
+	-	-	21.97
-	+	-	18.37
-	-	+	20.92
+	+	-	19.72
+	-	+	21.77
-	+	+	17.96
+	+	+	18.86

Table 6: Results from the simulation work based on the factorial design from table 2 and 5.

	P	T	W
P-value	0.778	**0.000742**	0.430

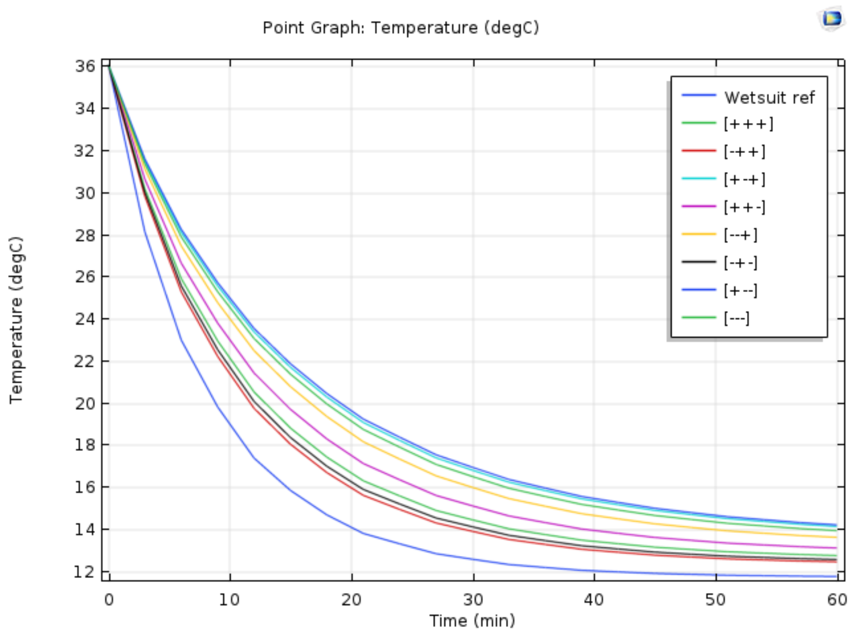


Figure 13: Skin temperature vs. time for all geometries in the factorial design.

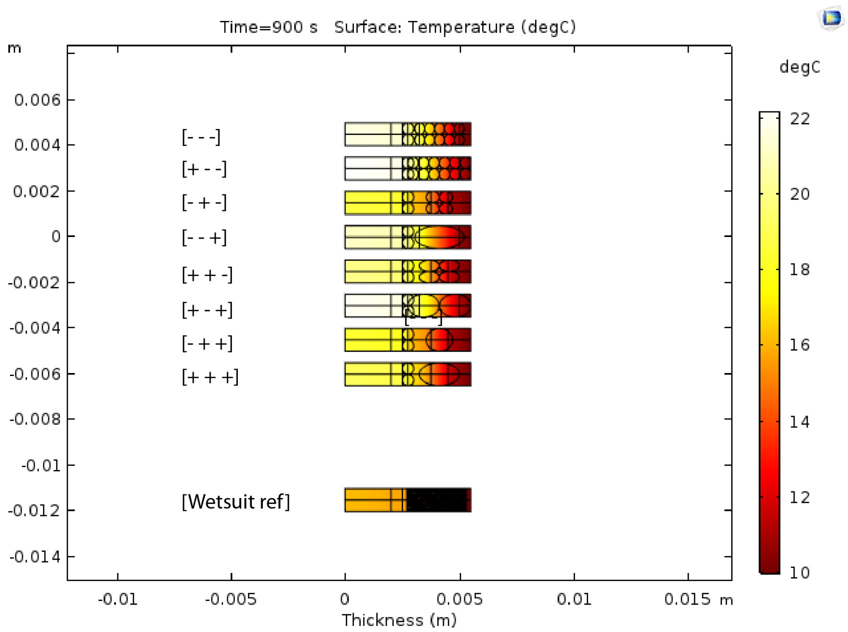


Figure 14: Showing all simulated geometries including Wet_{ref} at 900 s. Skin is on the left boundary and the ocean is on the right boundary.

4.2 Production

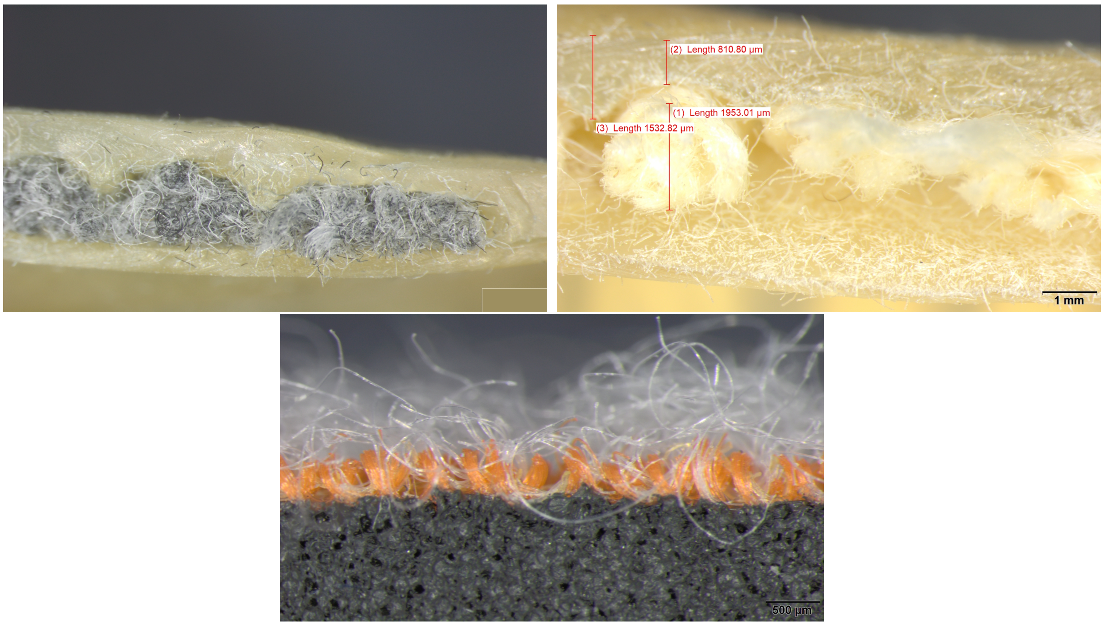


Figure 15: Microscope images. From top to bottom: NR with cotton, NR with wool and Wet_{ref} with lining.

4.3 Thermal Analysis

Thermal conductivity measurements were carried out using a MTPS-method and a flash method and the results are shown below.

4.3.1 Modified Transient Plane Source-technique

Samples were sent to *Elastocon AB* in Borås who performed measurements on seven different samples, see table 7. The values for neoprene is slightly high compared to the values in literature that is around 0.054 W/(m K) [3]. The values for the tested wetsuit is in the same range as the reference neoprene material. However, the result is rather different depending on what side of the material that is facing the heating element. The values for Mat_A are much higher than expected by simulations. According to the company, the method is not working accurately with layered heterogeneous materials and this might have big influence on the results. Depending on how far the heat flows in the material, not all layers might be affected by the heat pulse. For instance the wetsuit tested shows quite different values depending on which side that is heated and this suggests that the nylon lining in that case has big influence whether it is in close contact with the heat source or not. Further, the values obtained for Mat_A is closer to that of polyisoprene which is the outer material of the structure which again suggests that the heat did not penetrate the structure enough.

Table 7: Results from the MTPS-measurements using C-Therm by *Elastocon AB*. The values enclosed in parenthesis are measurements from the opposite side of the sample.

Sample	Thermal conductivity, λ (W/(m K))
Neoprene foam 5.02 mm	0.060
Neoprene foam 25.07 mm	0.070
Mat_A	0.170 (0.160)
Wet_{ref}	0.070 (0.044)
Wet_{ref} seam	0.072 (0.054)
Wet_{ref} without lining	0.080 (0.060)

4.3.2 Flash measurements

Thermal conductivity measurements were also carried out using a flash method. The results are summarised in table 8. Values on density and thickness were measured and specific heats were estimated using weight averaged values from literature (see table 1). Mat_A shows a lower thermal conductivity than Wet_{ref} by around 35% which can be compared to the factor obtained by simulation that was 33%. This low conductivity of Mat_A is probably due to the amount of air trapped in the structure that is considered to have negligible convection. It is an interesting result that this layered structure containing solid rubber trapped with a layer of air/fabric seems to insulate better than homogeneous neoprene foam according to the measurements carried out with this instrument. It is important to notice that the flash method lets the heat travel through the sample before the temperature is measured on the other side of the sample. In comparison to the MTPS-technique it means that the obtained λ-values is an average of the total layered structure and probably more suitable for these materials.

Looking at the obtained λ-values for Mat_A in table 8, it is clear that the values are getting very close to air itself, certainly when using cotton. Theoretically the λ-value should be an average between the fiber, rubber and air. For this reason it is unlikely for the value to approach that of air itself. Reasons for this could be slight offset in measurement and estimation of density, thickness and specific heat which plays a major role in the calculation of the thermal conductivity. Another factor could be lateral heat loss that would for all samples result in a lower thermal conductivity value than expected. Since this error source has similar effect on all samples, the comparative values should still be applicable. Since Wet_{ref} shows a lower λ-value than literature values, this might be a reasonable explanation. Cotton seems to lower the thermal conductivity compared to wool which is in accordance to literature values [17]. Wet_{ref} was measured on three different places with varying structures. Looking at the result it seems that the more loose lining that is facing towards the skin of the user does not lower the thermal conductivity. When the measurement was performed on the seam the conductivity increased significantly to 0.055 W/(m K), which can also be illustrated by Figure 16 that was taken during this measurement.

The simulated values in section 4.1 show a similar ratio between Mat_A and Wet_{ref}. However, the obtained values from the flash method are significantly lower and can most likely be described by lateral heat loss as mentioned above.

Table 8: Parameters and results from flash measurement.

	λ (W/(m K))	ρ (kg/m^3)	C_p (J/(kg K)))	Thickness (mm)
Sample 1	0.036	680	1790	3.16
Sample 2	0.030	680	1790	3.16
Sample 3	0.026	750	1860	2.24
Sample 4	0.028	750	1860	2.34
Wet$_{ref}$ w/ lining	0.046	210	2100	6.15
Wet$_{ref}$ w/o lining	0.041	210	2100	5.31
Wet$_{ref}$ seam	0.055	210	2100	7.78

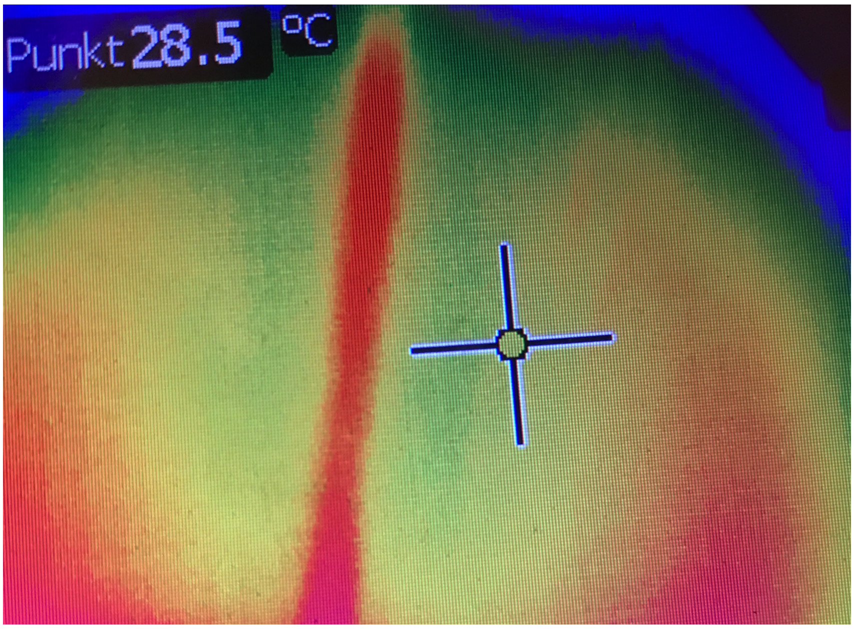


Figure 16: Picture from the heat imaging camera when performing the flash measurement on the Wet$_{ref}$ sample with seam. The red colour indicates a higher temperature meaning more heat has escaped through the seam of the sample.

4.3.3 Thermal insulation testing of wetsuit shoe in water

To analyse the thermal properties of Mat$_A$ in a situation closer to reality, the test described in section 3.5 was carried out. The sample shoes being equally thick (4.3 mm), the test once again verifies the hypothesis that Mat$_A$ will insulate better. As seen in figure 17 the temperature in the warm reservoir inside the shoe decrease slower for Mat$_A$ than for Wet$_{ref}$.

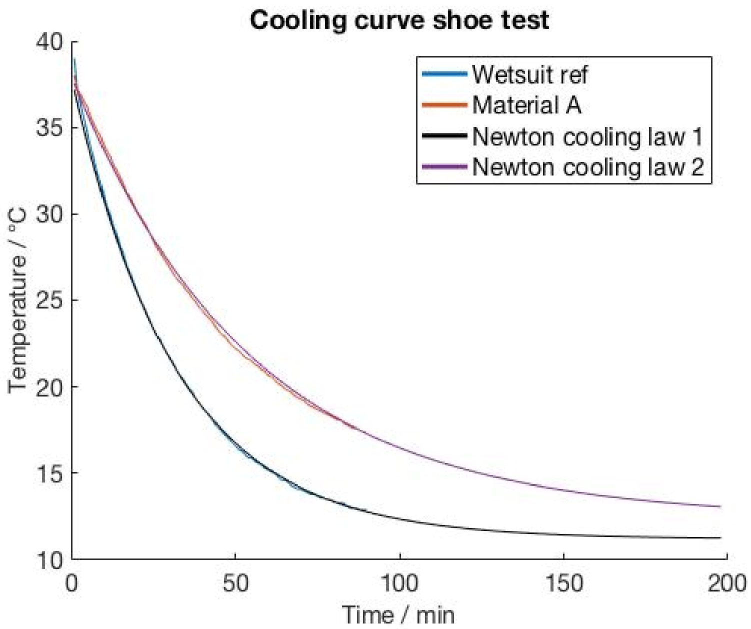


Figure 17: Cooling curve of the Wet_{ref} shoe and the shoe made from Mat_A.

In figure 17 Newton's cooling curve (see section 2.1.2) has been fitted to obtain a graph of how the measurement most likely would continue if it was carried out for a longer time. As a comparative analysis, a 1D simulation in COMSOL® was performed. Three lines were drawn to fit the measured λ value of Wet_{ref} with lining (0.046 W/mK). The cold and the hot reservoirs were drawn as 30 mm and 3 mm lines respectively while the sample was represented as a line of 4.3 mm. The same geometry was chosen for Mat_A and the thermal conductivity value was changed to fit the curve in figure 17. The obtained factor λ_{diff} between these λ values is shown below.

$$\lambda_{diff} = \frac{\lambda_{\text{Mat}_A}}{\lambda_{\text{Wet}_{ref}}} = \frac{0.024}{0.046} = 0.522 \tag{8}$$

Hence, by this comparative analysis Wet_{ref} seems to conduct heat 48% better than Mat_A. Notice that the values obtained in equation 8 are not absolute. This method can not be used to determine absolute values of the conductivity because the simulated geometry of the hot and cold reservoir are not based on the actual, quite complex experimental setup. It might be used as an indication of how much better the Wet_{ref} conducts heat in a more realistic situation. Values of density and specific heat capacities were chosen from table 8.

Performing the measurement in the same container at the same time, convection in the hot and cold reservoir is assumed to be similar for both shoes. Also, since the Wet_{ref} shoe was used as a mold to create the shoe of Mat_A, the surface areas are assumed to be equal as well.

48% is higher than was obtained by the flash method (35%) and by simulation (33%) which can be due to imperfections of the shoe made from Mat_A that probably made the shoe thicker at some areas. These parts specifically had more air trapped in the structure resulting in better insulation. The Wet_{ref} shoe also had some thicker parts with solid rubber as reinforcement, however, these areas are expected to have rather high thermal conductivity compared to the rest of the structure.

4.4 Tensile testing

Measurements of elasticity were performed using an elongation test. The results are visualised in figure 18 and 19. Figure 18 shows stress, meaning it includes the cross-section area of the specimen, see equation 6. Since the samples of Mat_A have a heterogeneous structure, the cross-section area is complicated to specify since the elasticity should only depend on the rubber layers and not on the insulating textile. The foamed neoprene depends on the amount of nitrogen bubbles because less rubber present in the structure result in reduced actual cross-section area. The thickness of foamed neoprene is measured including its nitrogen bubbles, consequently the thickness of the samples are measured including the insulating layers. Thus, adding a thicker insulating layer to Mat_A results in lower stress, while the force applied for the same strain remains unchanged. Therefore, in figure 19 the force is plotted as a function of strain. This way the samples and the Wet_{ref} can be compared with each other, even though their specific thicknesses are different. Since the thermal performance is superior in the samples from Mat_A, the thicknesses of the samples can be lower than that of a neoprene wetsuit. Consequently, comparing the Wet_{ref} with a thickness of 6.15 mm with the samples with thickness around 3 mm is reasonable as a comparison of elastic performance of a final product.

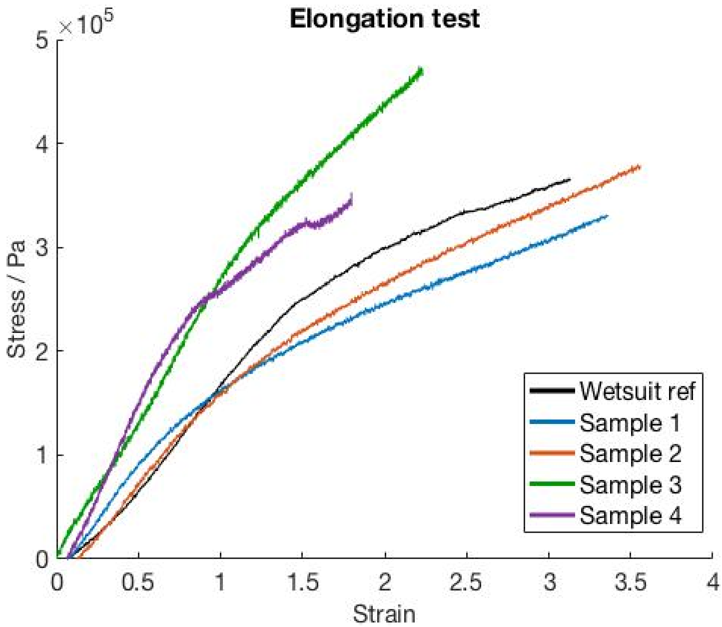
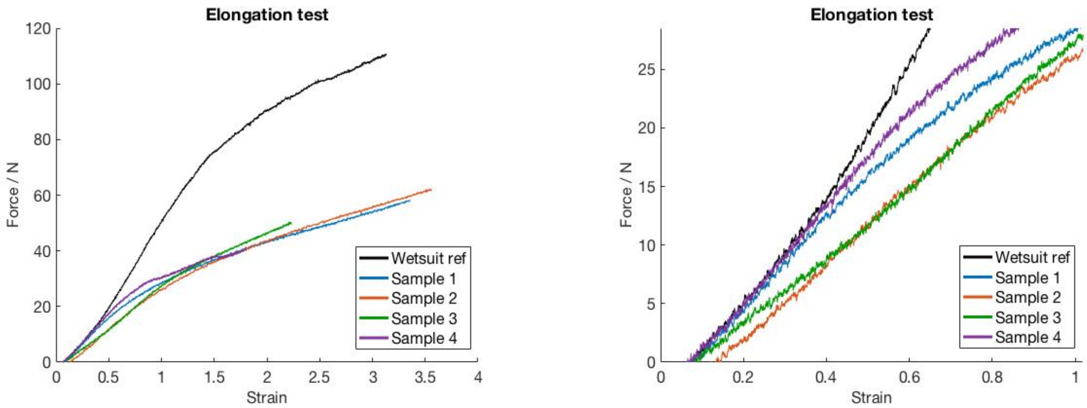


Figure 18: Stress vs. strain from elongation tests.

The thickness of the rubber in Mat_A will remain unchanged even though the samples will be made thicker. Using as little rubber as possible is advantageous in terms of insulation and as long as the structure is considered water tight and durable, the rubber will remain thin as in figure 15. Hence, the elastic modulus will remain the same, even though the samples are made thicker by adding insulating fabric. In the stress-strain plot (figure 18), the thicknesses are measured including the insulating layer. This is the reason for the samples of Mat_A showing different values in this plot. In the force-strain plots (figure 19) one can see that all of the samples of Mat_A closely overlap. This is because the elastic behaviour only depends on the rubber layers and not the insulating layer, and all samples have similar thickness of the rubber layers.

In figure 19a the Wet_{ref} can be seen exhibiting the highest forces at all strains. This can be explained by it simply being the thickest of the specimens. The plastic behaviour is likely due to the lining's properties superseding the neoprene at strains above 1.5. All of the specimens from Mat_A exhibit similar behaviour: two elastic regions. The samples goes over to a secondary linear part after the Yield point which is not expected by elastomeric materials [18]. A possible explanation could be that for the first linear part of the curve, the yarns have a significant effect on the force necessary for deformation. After a certain strain these fibres might not adhere enough to the rubber film and only the rubber is deformed and represented in the second linear part.

Sample 1 and 2 exhibit 'softest' behaviour, i.e. lowest force for that strain, until 100% elongation (strain = 1), see figure 19b.



(a) Strains 0 to 4.

(b) Strains 0 to 1.

Figure 19: Force vs. strain from elongation tests.

The elastic modulus can be determined graphically as described in section 2.3, see resulting values in table 9. The elastic modulus of four of the specimens are within the interval 86-272 kPa mentioned in Naebe et al. [3, Results, p. 8], where 8 different wetsuits were measured. The Wet_{ref} is slightly high since it is considered a high-end wetsuit, which ranged from 86 to 128 kPa in Naebe et al. [3]. This result is highly dependent on the measured area and starting length of the material. Since the dimensions of the samples were relatively small, such an error could have big influence on the end result. The elastic modulus for the samples were higher than the Wet_{ref}, but not significantly. Even though the latex is medium modulus the samples are within the limits to be used as wetsuits. With low modulus latex the elastic modulus might be reduced to be even lower than that of Wet_{ref}.

Once again it should be noted that the result shown in table 9 is difficult to consider since the cross section areas consist of materials that do not restrict the movement during the tensile testing.

Table 9: Elastic modulus of the different specimens.

Sample	Elastic modulus (kPa)
Wet_{ref}	186
Sample 1	205
Sample 2	195
Sample 3	266
Sample 4	347

Additionally, elongation test for different directions of deformation were performed on Wet_{ref}. 0 degrees corresponds to the most elastic direction of the Wet_{ref}. Since foamed neoprene consists of homogeneous synthetic rubber with a uniform distribution of spherical nitrogen bubbles, the neoprene itself should not have different forces for different directions of deformation. Thus, the lining must account for the difference for different directions seen in figure 20. It can be seen that 45 degrees results in highest deformation forces. This is expected from a woven fabric, since the structure elongates fully in one direction (0 degrees), partially in a secondary direction (90 degrees). However, at 45 degrees the fibers get drawn closer to each other and friction inhibits further movement due to shear forces between the fibres [19].

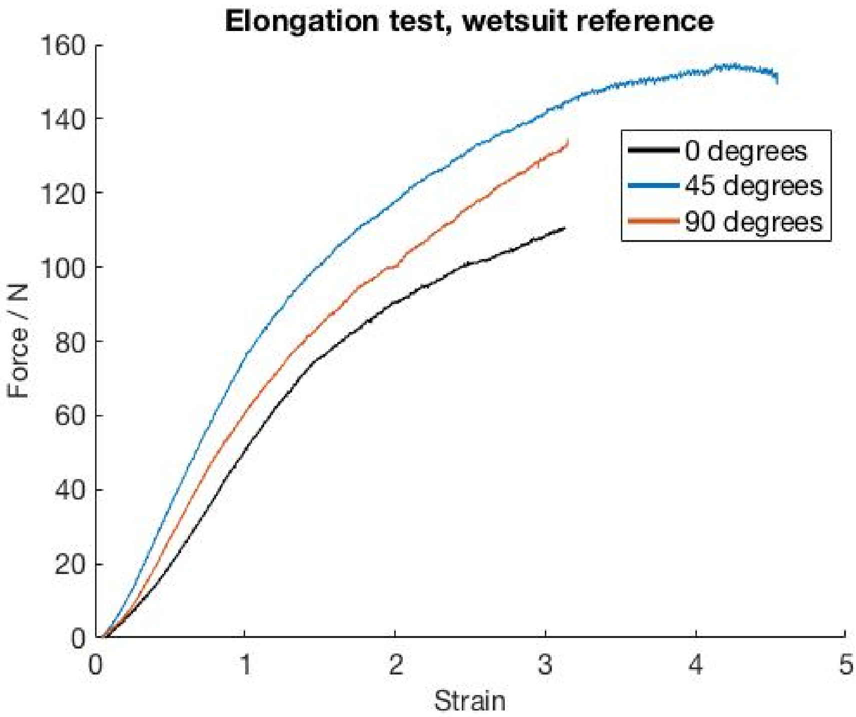


Figure 20: Force vs. strain from elongation tests of the Wet_{ref} at different angles.

5 Discussion

5.1 Sample preparation

All samples for Mat_A were prepared using a dipping method resulting in a sandwich structure shown in Figure 15. No testing on wear rate was carried out due to lack of time and it can only be said that the dimensions obtained is believed to be a good compromise between insulation, elasticity and durability. Theoretically, adding more solid rubber should make the sample more durable but both elasticity and insulation properties depend on the rubber being a small fraction of the sandwich structure.

To obtain a structure suitable for watersport users the wetsuit must be easy to put on and feel soft towards the skin. Future work will include preparing samples with fabric towards the skin as well. This could theoretically be achieved by dipping the first layer of latex on top of the soft fabric that has been applied around the metal mould. Furthermore, the suit must be possible to put on and off in a convenient way. The easiest way to work around this problem is to use zippers in the same way that is used in today's wetsuits. Using zippers is a rather cheap and established method in industry but it could also result in cold water flushing trough and the effect of using no seams could then be questioned.

5.2 Thermal analysis

The different measurements of thermal conductivity yielded highly different results. According to *Elastocon AB*, the MTPS-technique was not fully compatible with layered heterogenous materials, which most likely explains the diverse results. The flash-technique yielded similar results as the simulations in terms of ratio between Mat_A and Wet_{ref}. The absolute values obtained by the flash method is significantly lower than the simulated and literature values. This could be explained by lateral heat loss, errors in measuring densities and thicknesses and estimations of specific heat capacities. The thermal insulation test of the two shoes shows a rather high ratio between the two materials' thermal conductivity. This can possibly be explained by the non-uniform thickness of Mat_A with extra trapped air exceeding the 4.3 mm thickness that was considered in the simulation. Overall, Mat_A seems to insulate better than Wet_{ref} considering all test methods carried out in this report.

The layered rubber composite used in this report is less homogeneous than neoprene and the heat must travel between the rubber and air/fabric interface. In the more homogeneous neoprene the heat flow is restricted by the nitrogen bubbles but a difference to Mat_A is that there is a continuous path through the solid polymer for the heat to travel. This could explain the superior insulation performance for Mat_A compared to Wet_{ref}.

5.3 Tensile testing

The layered material has inferior flexibility/elasticity compared to neoprene foam. Literature values of E-modulus of high end wetsuits can be as low as 86 kPa [3], which is considerably lower than for Mat_A. It is important to note that three moduli for latex is available on the market: low, medium and high. Due to availability, only the medium module latex was tested in this report and it would for comparison be interesting to test the low modulus latex as well.

One big difference between Mat_A and the neoprene suits are the use of solid instead of foamed rubber. This might affect the module since in a foam the effective cross section area is very small (due to trapped gas bubbles) than what is accounted for in the calculations. Hence, when applying a tensile force on the foamed neoprene the experienced stress is rather low due to the very small effective cross section area. This is something that has to be accounted for when engineering a wetsuit made of Mat_A that consist of solid rubber. Interestingly, comparable thicknesses (in terms of insulation) of Mat_A and Wet_{ref} exhibits similar behaviour in the force vs strain plot. This does not generalise the tensile behaviour for the materials but it is a better comparative analyse since no effective cross section area needs to be accounted for.

In terms of tear strength foams have much lower strengths compared to solid elastomers which potentially can increase the durability of the wetsuit made out of Mat_A [20]. NR is furthermore a material with excellent tear strength [21] and it is believed that Mat_A exhibits the tear strength properties of the outer rubber layer. Also, eliminating seams should have a positive effect on increasing the durability of the wetsuit. Due to lack of time no tear strength testing was performed which would be interesting for future work.

5.4 Assessment of sustainability

When evaluating a product's sustainability there are innumerable aspects to be taken into account. This report follows Fiksel et al. [16] with three sections: *Resource and value*, *Three aspects* and *Life cycle*, see section 3.6

As the product will be offered as an alternative to current neoprene wetsuits, the assessment will use comparisons with current processes for manufacturing and materials used.

5.4.1 Resource and value

Resources can be materials, labour, energy and facilities. There are mainly two materials used in this product: NR latex (cis-1,4 isoprene), for the rubber layer, and wool/cotton for the insulating layer. Yulex® offer *Yulex Pure*™, a NR latex which is FSC®-certified. FSC® is an assessment and issuance of the Forest Stewardship Council® certification is conducted by the Rainforest Alliance, who is an FSC® accredited certifying body. This certification ensures sustainable production of the rubber. This includes the trees being irrigated by ambient rainfall, protection of the social and economic well being of forest dependant communities and that the NR is processed with recycled and recharged water supply aquifer during manufacturing [22].

The insulating layer can consist of 100% re-used cotton or wool. It is growing more common to re-use these kinds of fabrics. It is believed that using Mat_A can reduce the use of fossil fuels by offering a sustainable alternative to today's neoprene wetsuit which is a petrochemical product. Mat_A also offers better thermal properties in terms of improved thermal insulation performance. Furthermore, it is believed that the durability of Mat_A will be increased due to the elimination of seams and the use of solid instead of foamed rubber. All these aspects add value to the product.

5.4.2 Three aspects

By offering an alternative with higher durability to today's neoprene, the user will spend less money over time. All elastomers are effected by weather, UV and other factors, and every wetsuit eventually wear out. Solid rubber has an improved durability compared to foamed rubber (higher tensile tear strength) [20]. As an increase of durability will extend the life span of a product, it will also lessen the demand for material resources. For simplicity it is assumed that wetsuits are trashed because they are no longer functional. However, there are certainly cases where the user purchases a new wetsuit because of other reasons, for instance because there are new models on the market. In addition to higher durability, as the thermal performance is improved, less material is needed per product; further reducing material consumption. Higher durability also results in an lower overall cost for the customer.

The negative environmental and societal aspects should be minimised when using the FSC®-certified NR latex: sustainably grown rubber trees with proper production processes and waste handling. It also ensures that working conditions are of a sufficient standard. Positive societal aspects should be observed by increased possibility for employment when production is increased.

All production of fabrics have environmental costs. For instance, cotton is highly water intensive, using about 9000 litres for producing 1 kg of cotton. Cotton cultivation occupies 2.5% of the earth's farmed land but consumes 25% of the pesticides used [23]. Similarly, wool production requires enormous lands for grazing the sheep. To produce the clean fibres, the wool (and cotton) needs to be processed by using water, energy and chemicals. Since the recycled cotton showed superior thermal properties this could be an alternative path for lowering the global footprint.

5.4.3 Life cycle

Manufacturing NR will have less environmental impact due to it being harvested from a renewable resource compared to petroleum-derived neoprene. Even though there still exist a few problems with the production of NR, such as wastewater treatment, high levels of Polycyclic aromatic hydrocarbon (PAH)-concentrations in the working environment to name a few, the FSC®-certification will not include these issues. The NR is primarily grown in Asia, where Thailand is the world leader. Thus, the rubber material needs to be imported from this part of the world to where the production plant is placed. The transportation has certain environmental impact. However, this is common for manufacturing companies, which is why this impact is considered average. There is a great environmental gain in using NR instead of a petroleum product.

As previously mentioned: recycled fabrics can be used in the final product to lessen the environmental impact by reducing material consumption.

The use of the product does not have a negative environmental impact of its own. However, using a wetsuit for two years or using it for four years has a drastic difference of environmental impact, since the material consumption is doubled. Thus, the durability of the wetsuit is of great importance. The material studied in this report: solid NR generally has higher tensile tear strength than foamed neoprene [20], most often meaning it is more durable. As mentioned earlier, this analysis assumes that the wetsuit is trashed because of the low durability and not other choices made by the user.

The end stage of wetsuits can be drastically improved. Most wetsuits are thrown away, exiting the life cycle. However, there are organisations devoted to recycling old wetsuits. They usually create products where quality of the material is of less importance: camera cases, laptop protections, yoga mats, etc. [24].

There's great difficulty to recycle wetsuits to new wetsuits due to crosslinks in the rubber material, i.e. intermolecular covalent bonds, which are complicated and energy expensive to break up. There are methods to deal with this called *de-vulcanisation*: chemical, mechanical, thermo-mechanical to name a few. However, they generally result in rubber with lesser quality due to cleavage of the main chains of the macromolecules. This issue also exist for NR, meaning there's no environmental improvement for the disposition of the product [25].

5.5 Cost analysis

Table 10 was constructed using the same salaries, electricity rates and shoe geometry ($0.06\,m^2$ surface area [26]). Estimations and references are shown in Appendix C. The result presented can work as a first comparative estimation between the two products from an economical point of view. Material costs seems to have a bigger impact on the dipped product than for the neoprene shoe. In general the salaries contribute to the biggest cost for both products in this analysis. It should be noted that electricity costs and labour costs are estimated using rates in China. In total it is estimated that the neoprene shoe is slightly cheaper to produce.

A big advantage of using the dipping method is that the same operator can from raw materials finish the wetsuit shoe in a couple of dipping sequences. The neoprene shoe is usually sent between different operators handling different tasks such as sewing, gluing and cutting [27]. Another aspect to consider is the required time for the dipped product to vulcanise in the oven and being dried in the drying machine to get rid of all moisture. Depending on the size of the factory and its capacity this might limit how many shoes that can be produced. Also, the need for these machines require more factory space, costs of purchasing the machines and reparation of them.

Scaling the dipping process to full wetsuits both mean higher complexity and higher costs of production. First of all when dipping such a big mould in latex it will have significant different thickness depending on which part that has been in the latex longer time. It will also need complex machinery systems carrying out the dipping that is not yet developed like for shoes and gloves. The weight of the mould will contribute to high machinery costs and the big volume will require even more factory space and storage. The scaling of neoprene wetsuits is more straight forward but it does probably imply more complexity when putting the wetsuit together. More neoprene sheets are used and the end product probably depends more strongly on the precision when attaching the sheets together.

As a final aspect, it is believed that the dipping method can more easily be automatised using less workers in production. Most stages in the process could theoretically be carried out using

Table 10: Cost evaluation

	Details	Wet_{ref} shoe (SEK)	Mat_A shoe (SEK)
	Material		
	Neoprene sheet	1.15	
	Reinforcement rubber	3	
	Neoprene tape	0.39	
	Latex		4.8
	Insulating sock		1.8
	Sock toward skin		1.8
	SUB-TOTAL	4.5	8.4
	Production		
Salary	Cut neoprene	2.6	
	Glue neoprene	4.3	
	Sew neoprene	2.6	
	Latex dipping		8.6
Machinery	Sewing machine	0.003	
	Oven		0.63
	Drying machine		0.62
	TOTAL	18.6	26.7

machines which would in the long run decrease both costs and errors in production. The neoprene wetsuits require fine precision when sewing and gluing and to this date it is still humans that carry out the production.

6 Conclusion

A wetsuit made with Mat_A is certainly viable as an alternative to the neoprene wetsuits used today. It displayed 35% lower thermal conductivity compared to the current neoprene wetsuits. Also, a wetsuit with no seams could drastically reduce heat loss from the body. However, it did show higher elastic modulus compared to current commercial wetsuits, making it less flexible, which was one of the most important aspects for the users. This could easily be improved by exchanging the medium modulus latex to low modulus latex. Additionally, the process could be optimised to allow thinner rubber layers, without water-leakage, further improving the elastic behaviour. Further testing will possibly yield even better elastic performance to make a wetsuit with Mat_A competitive to Wet_{ref}.

Durability has not been tested in this report, but solid rubber as well as natural rubber have higher tear strength than foamed neoprene [20][21], which is an indication for longer life-span of the material.

Regarding the sustainability of the material it is clear that many aspects are similar for both Mat_A and neoprene such as transportation, disposition of the product etc. But one large environmental gain is that the NR is from a renewable resource with a FSC®-certification, meaning it is produced responsibly in all three aspects: economically, environmentally and socially. Considering the fabric, cotton is known for its intense water consumption, but since recycled cotton is used this report the water consumption is drastically reduced.

The cost for producing Mat_A is equal or slightly higher than that of neoprene, which is important for competitive pricing. The dipping method used to produce the samples in this report is believed to be easier to automate but there are certain complexity problems when scaling up production to full wetsuits.

The material investigated in this report is promising as an alternative for neoprene to be used in wetsuits. However, further tests must be performed to ensure proper durability and elasticity.

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References

[1] SeventhWave. Neoprene: a brief history. https://www.seventhwave.co.nz/wetsuits101/Neoprene+Info/Neoprene+a+brief+history.html. Accessed: 2018-09-17.

[2] All about the seam. http://www.millerslocal.co.za/blog/all-about-the-seam. Accessed: 2018-12-07.

[3] Maryam Naebe, Nicholas Robins, Xungai Wang, and Paul Collins. Assessment of performance properties of wetsuits. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, (4):255–264. ISSN 17543371. doi: 10.1177/1754337113481967.

[4] John H Lienhard IV and John H Lienhard V. A heat transfer textbook, third edition. 2000.

[5] C-Therm. Modified transient plane source (mtps) technique. https://ctherm.com/products/tci_thermal_conductivity/how_the_tci_works/mtps/. Accessed: 2018-11-10.

[6] Ch.S.S.R. Kumar and A.M. Nijasure. Vulcanization of Rubber. How to Alter Molecular Structure and Influence Physical Properties. *Resonance*, 2(4):55–59, 1997. ISSN 0035-9475. doi: 10.5254/1.3546569. URL http://www.ias.ac.in/article/fulltext/reso/002/04/0055-0059.

[7] Robert Groves and Alexander F. Routh. Film deposition and consolidation during thin glove coagulant dipping. *Journal of Polymer Science, Part B: Polymer Physics*, 55(22): 1633–1648, 2017. ISSN 10990488. doi: 10.1002/polb.24290.

[8] Valerio Marra. Thermal insulation with bubbles is better. https://www.comsol.com/blogs/thermal-insulation-with-bubbles-is-better/. Accessed: 2018-10-01.

[9] Engineering ToolBox. Specific heat of common substances. https://www.engineeringtoolbox.com/specific-heat-capacity-d_391.html, . Accessed: 2018-11-21.

[10] MakeItFrom.com. Isoprene (natural) rubber (ir, nr). https://www.makeitfrom.com/material-properties/Isoprene-Natural-Rubber-IR-NR, . Accessed: 2018-10-01.

[11] polymerdatabase.com. Polyisoprene. https://polymerdatabase.com/polymers/polyisoprene.html, . Accessed: 2018-11-12.

[12] AZO Materials. Titanium dioxide - titania (tio2). https://www.azom.com/properties.aspx?ArticleID=1179. Accessed: 2018-10-01.

[13] Course Hero. Cr (chloroprene rubber - neoprene). https://www.coursehero.com/file/18781343/CR-Chloroprene-Rubber-Neoprene/. Accessed: 2018-11-12.

[14] MakeItFrom.com. Chloroprene rubber (cr, neoprene). https://www.makeitfrom.com/material-properties/Chloroprene-Rubber-CR-Neoprene, . Accessed: 2018-10-01.

[15] polymerdatabase.com. Polychloroprene. http://polymerdatabase.com/polymers/polychloroprene.html, . Accessed: 2018-11-12.

[16] Joseph Fiksel, Jeff McDaniel, and David Spitzleyn. Measuring product sustainability. *Journal of Sustainable Product Design*, October 19(7):60, 1998. ISSN 13676679. doi: 10.1056/NEJM197207272870401.

[17] Mehedi Hashan, K M Faridul Hasan, and Fazle Rabbi Khandaker. Functional Properties Improvement of Socks Items Using Different Types of Yarn. 6(2):34–42, 2017. doi: 10.5923/j.textile.20170602.02.

[18] Kraton. A review of synthetic latices in surgical glove use. http://www.kraton.com/products/cariflex/synthetic_latices.pdf. Accessed: 2018-12-07.

[19] Rainer Blum, Heidrun Bögner, and Guy Némoz. Material Properties and Testing. *European Design Guide for Tensile Surface Structures*, pages 219–242, 2004.

[20] M. F. Ashby. Material and process selection charts. *The CES EduPack Resource Booklet 2*, page 42, 2010. URL http://www.grantadesign.com/download/pdf/teaching{_}resource{_}books/2-Materials-Charts-2010.pdf.

[21] R.L. Hudson & Company. Tear resistance. https://web.archive.org/web/20120525103424/http://www.rlhudson.com/O-Ring%20Book/selecting-physical6.html. Accessed: 2018-12-27.

[22] Yulex. Sustanability commitment: Yulex specialty natural rubber is produced using environmentally and socially responsible manufacturing practices. http://yulex.com/about/sustainability-commitment/. Accessed: 2018-12-08.

[23] Hallå Konsument. Oberoende vägledning genom Konsumentverket. Bomull och miljö. https://www.hallakonsument.se/miljo-och-hallbarhet/handla-hallbart/textilier-och-miljon/miljoaspekter-pa-olika-textiltyper/bomull/. Accessed: 2018-12-03.

[24] Professional Association of Diving Instructors (PADI). Article: Recycle old wetsuits (2018-09-06). https://www2.padi.com/blog/2018/09/06/recycle-old-wetsuit/. Accessed: 2018-12-04.

[25] Jozef T. Haponiuk M. K. Aswathi Sabu Thomas Jin Kuk Kim, Prosenjit Saha. *Rubber Recycling: Rubber Recycling*. Royal Society of Chemistry, 2018. ISBN 9781788010849.

[26] Chi-yuang Yu and Hsin-hung Tu. Foot surface area database and estimation formula Foot surface area database and estimation formula. *Applied Ergonomics*, 40(4):767–774, 2017. ISSN 0003-6870. doi: 10.1016/j.apergo.2008.08.004.

[27] How products are made. Wet suits. http://www.madehow.com/Volume-4/Wet-Suit.html. Accessed: 2018-12-20.

[28] Engineering ToolBox. Thermal conductivity of common materials and gases. https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html, . Accessed: 2018-10-31.

Appendix

A Market Research

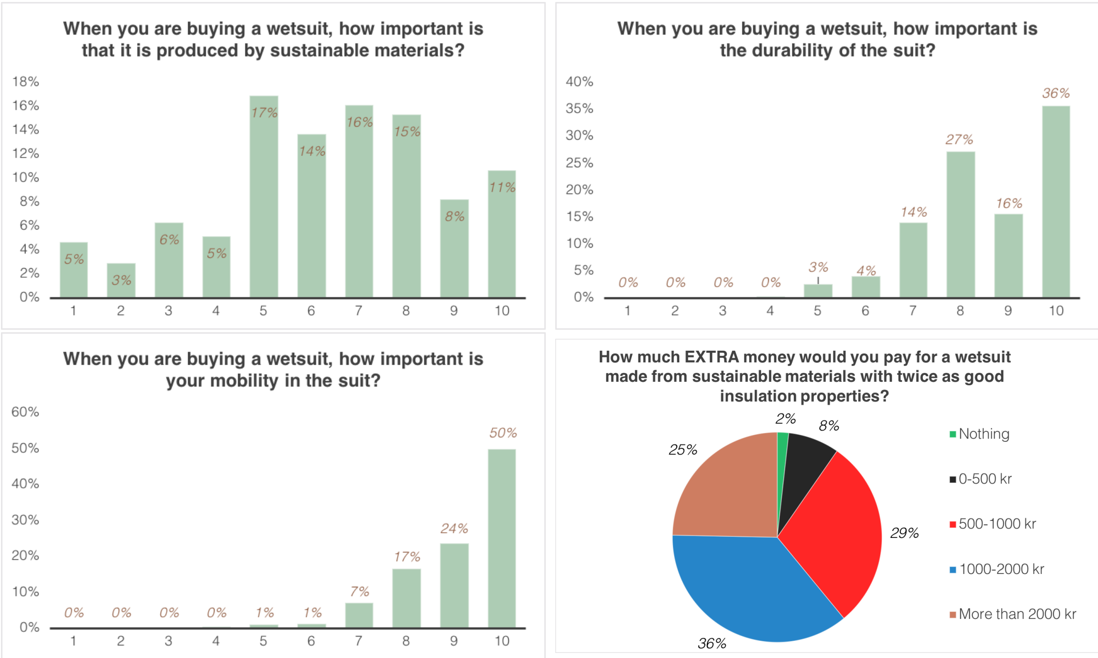
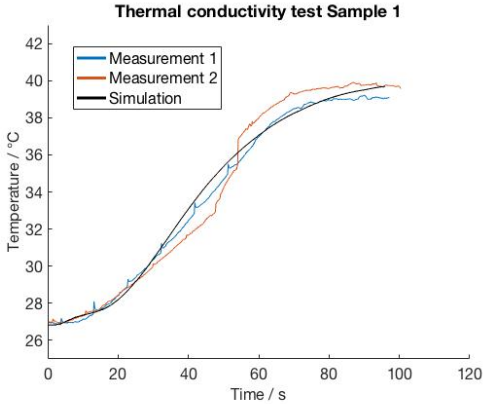
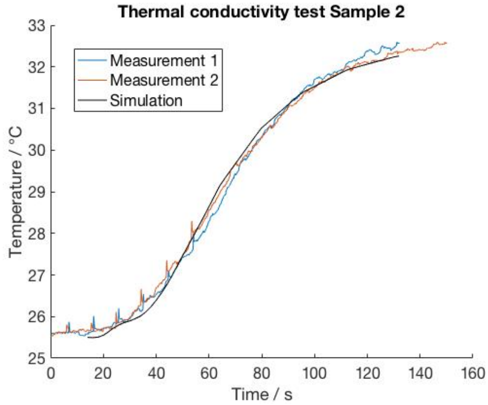
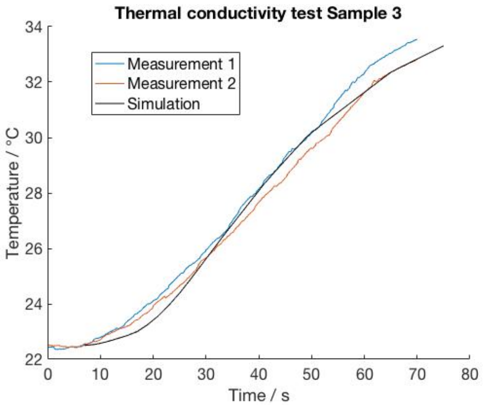


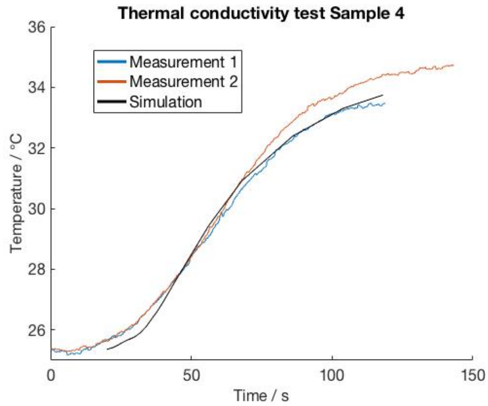
Figure 21: Answers from a survey conducted through several Swedish water sport forums with 621 participants.

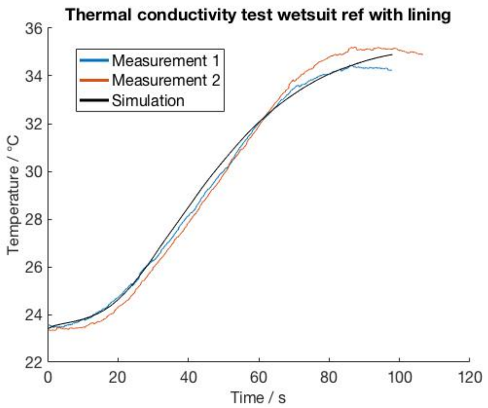
B Thermal conductivity measurements, flash method

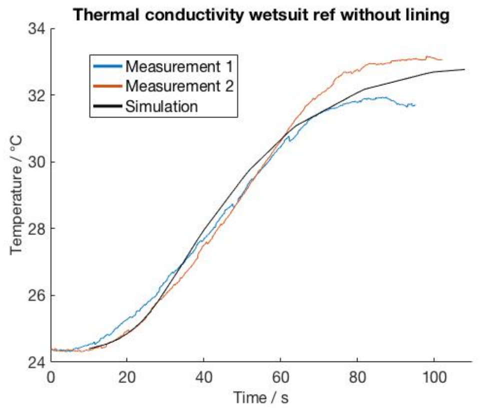


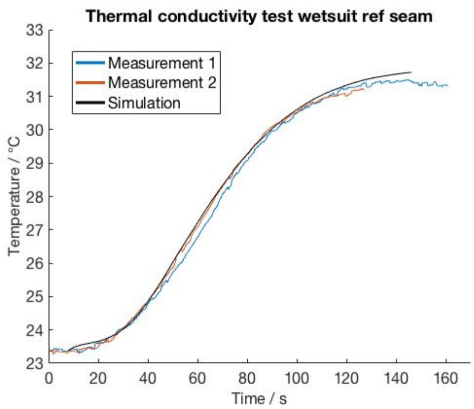












C Cost analysis

Details	Area price (SEK/m2)	Volume price (SEK/m3)	Price per shoe (SEK)	Length price (SEK/m)	Length (m)	Area (m2)	Volume (m3)	Labour costs China (SEK/h)	El. (W)	Space machine (number)	Electricity price (SEK/kWh)	Time (s/shoe)
Neoprene sheet	19.2[a]					0.06[b]						
Reinforcement rubber			3[c]									
Neoprene tape				1.3[d]	0.3							
Latex		80000[e]					0.0006[b]					
Insulating sock			1.8[f]									
Sock towards skin			1.8[f]									
Cut neoprene								57[g]				180
Glue neoprene								57[g]				300
Sew neoprene								57[g]				180
Latex dipping								57[g]				600
Sewing machine									100[h]		0.69[i]	180
Oven									2400[j]	5	0.69[i]	6900
Drying machine									3000[j]	10	0.69[i]	10800

[a] https://www.alibaba.com/product-detail/wetsuit-surf-neoprene-neoprene-wetsuit-material_60710870060.html?spm=a2700.7724857.normalList.92.25507ecfBObtGf

[b] https://linkinghub.elsevier.com/retrieve/pii/S0003687008001294

[c] https://www.alibaba.com/showroom/anti-slip-sole-pad_2.html?spm=a2700.7724857.pagination.1.14af5e53UTqhKX

[d] https://www.alibaba.com/countrysearch/CN/neoprene-tape.html

[e] Local distributor *Svenska Latex AB*

[f] https://www.alibaba.com/countrysearch/CN/recycled+cotton+sock.html?fsb=y&IndexArea=product_en&CatId=&SearchText=recycled+cotton+sock&isGalleryList=G

[g] https://www.statista.com/statistics/744071/manufacturing-labor-costs-per-hour-china-vietnam-mexico/

[h] https://absak.com/library/power-consumption-table/

[i] https://www.ceicdata.com/en/china/electricity-price

[j] http://energyusecalculator.com/electricity_clothesdryer.htm