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Long-term properties of the matrix of composites

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Mechanical Engineering
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Supervisor: Andreas Echtermeyer, IPM

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MASTER THESIS
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NTNU - NORWEGIAN UNIVERSITY
OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF ENGINEERING DESIGN
AND MATERIALS

MASTER THESIS SPRING 2016
FOR
STUD.TECHN. CHRISTOFFER NÆSS

Long-term properties of the matrix of composites

Langtidsegenskaper i matrisen av kompositter

This project shall investigate new methods to predict the long-term performance of composites (fiber reinforced plastics). A multiscale modeling approach will be used. Changes in material properties of the matrix will be modeled on the molecular level. The local changes will be combined to describe macroscale engineering properties.
This approach is new and requires testing in the laboratory to simulate long-term exposure and new modeling solutions to understand the results.

Formal requirements:

Three weeks after start of the thesis work, an A3 sheet illustrating the work is to be handed in. A template for this presentation is available on the IPM's web site under the menu "Masteroppgave" (https://www.ntnu.edu/web/ipm/master-thesis). This sheet should be updated one week before the master's thesis is submitted.

Risk assessment of experimental activities shall always be performed. Experimental work defined in the problem description shall be planed and risk assessed up-front and within 3 weeks after receiving the problem text. Any specific experimental activities which are not properly covered by the general risk assessment shall be particularly assessed before performing the experimental work. Risk assessments should be signed by the supervisor and copies shall be included in the appendix of the thesis.

The thesis should include the signed problem text, and be written as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents, etc. During preparation of the text, the candidate should make efforts to create a well arranged and well written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work a thorough discussion of results is appreciated.

The thesis shall be submitted electronically via DAIM, NTNU's system for Digital Archiving and Submission of Master's theses.

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Abstract

This is a study of the effects of water on the long term properties of polymer matrix reinforced composites. Water is one of the main contributors to reliability reduction in predicting the life cycle of polymer matrix composites, as the presence of water induces changes in their mechanical behaviour. The microscopic chain of events have been discussed and related to the macroscopic effect. Epoxy polymer and epoxy-based polymer matrix composite specimens were submerged in distilled water and the absorption process was investigated. In addition were desorption tests of epoxy polymer performed, and the changes in water mass uptake were monitored. Tensile tests were performed and discussed along the diffusion process.

Preface

This study comprise the effect of water absorption on the long term properties of epoxy polymers and carbon fiber reinforced epoxy polymers. It was carried out on behalf of The Department of Polymers and Composites at NTNU during the spring semester of 2016, as a part of the study program Engineering Design and Materials.

It is recommended that the readers of this report have a background in composite materials, mechanical behaviour of materials and a basic knowledge of chemistry.

Trondheim, 2016-06-10

Christoffer Næss

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C.N.

Summary and Conclusions

Water diffusion into epoxy can be looked upon on as a 3-stage process. At the beginning will the available surfaces of the material create a rapid mass uptake, due to the fact that the "surfaces" of the molecular structure comprise easily accessible chemical bonding sites for the water molecules. The second stage of water diffusion begins when these sites are spent, and the water begins to diffuse into the material. This stage in this study shows behaviour applicable to linear Fickian diffusion, as the water mass uptake were linear to the square root of time. The third stage were initiated after approximately 650 hours. At this time did the rate of water mass uptake decrease, and showed behaviour applicable to non-linear Fickian diffusion.

Diffusion coefficients for pure epoxy specimens were calculated by linear regression and compared to coefficients of carbon fibre containing epoxy specimens, which was calculated by numerical approximations. The results show that it is a faster *process* for the case of water diffusion in the transverse direction of unidirectional carbon fibre reinforced epoxy polymers in comparison to the diffusion process into pure epoxy specimens. The carbon fibre containing specimens reached mass saturation after approximately 700 hours of diffusion, whereas the pure epoxy specimens did not reach mass saturation during this study.

Desorption occurs at a much higher rate than absorption. The initial behaviour is in accordance with the initial behaviour of absorption, as a rapid mass release was experienced during the first 24 hours. After the easily available surfaces of the molecular chains had yielded their chemical bonds to the water, the rate of desorption decreases. It was observed that the desorption process moved at a rate approximately twice as fast as the absorption process.

The mechanical behaviour of the pure epoxy specimens experienced several changes during the water absorption process. During the first 120 hours of diffusion in this study the average elastic modulus decreased by 18%, whereas the average ultimate tensile strength decreased by 21%. Further, the maximum strain suffered a 13% loss. After 310 hours of absorption all three properties decreased further, although only by a small degree. At this time the specimens showed a greater plastic region, as necking was observed in the tensile test results. This plastic behaviour completely disappears after 742 hours of water absorption. Both the elastic modulus and the ultimate tensile strength remain relatively unchanged at this point, but the maximum strain have decreased.

The CF containing specimens suffered more than a 15% loss of ultimate tensile strength in the fibre direction due to the water mass uptake. They failed due to matrix cracking. Even though the strength decreased, it was observed that the elongation properties increased with a higher water mass uptake.

Oppsummering og konklusjoner

Vanndiffusjon inn i epoxy kan sees på på som en tre-trinns prosess. I begynnelsen vil de tilgjengelige overflatene av materialet skape et hurtig masseopptak, på grunn av det faktum at "overflatene" av molekylstrukturen omfatter lett tilgjengelige kjemiske bindingssteder for vannmolekylene. Den andre fasen av vanndiffusjon begynner når disse områdene er oppbrukt, og vannet begynner å diffusere inn i materialet. Dette stadiet viste oppførsel lik lineær Fickian diffusjon, ettersom vannmasse-opptaket var lineært med kvadratroten av tiden. Den tredje fasen ble initiert etter ca 650 timer. På dette tidspunktet ble hastigheten av vannmasse-opptaket redusert, og viste oppførsel anvendelig til ikke-lineær Fickian diffusjon.

Diffusjonskoeffisienter for rene epoksy-prøver ble beregnet ved hjelp av lineær regresjon og sammenlignet med koeffisientene til epoxy-prøver med karbonfiber-forsterkning, som ble beregnet ved numeriske approksimasjoner. Resultatene viser at *prosessen* er raskere for tilfellet av vann-diffusjon i tverretningen av ensrettede karbonfiberforsterket epoxy-polymerer i forhold til diffusjonsprosessen til rene epoxy-prøver. Prøvene med karbonfiber-forsterkning nådde massemetning etter ca 700 timer med diffusjon, mens de rene epoxy prøvene ikke nådde massemetning i dette studiet.

Masse-avgilvelse skjer med en mye høyere rate enn absorbering. Den innledende opptredenen er i overensstemmelse med den første opptredenen av absorbering, ettersom en hurtig masse-frigivelse ble opplevd i løpet av de første 24 timene. Etter at de lett tilgjengelige flatene til molekylkjedene hadde gitt bort sine kjemiske bindinger til vannet, ble raten av masse-avgivelse redusert. Det ble observert at masse-avgivelses-prosessen skjer med en hastighet omtrent dobbelt så fort som absorberingsprosessen.

Den mekaniske oppførselen av de rene epoxy prøvene opplevde flere endringer i løpet av vannabsorberings-prosessen. I løpet av de første 120 timene av diffusjon i dette studiet ble den gjennomsnittlige elastisitetsmodul redusert med 18%, mens den gjennomsnittlige maksimale strekkstyrken ble redusert med 21%. Videre led den maksimale strekkbelastningen et 13% tap. Etter 310 timer med absorbering reduseres alle tre egenskapene ytterligere, om enn kun i liten grad. På dette tidspunkt viste prøvene en større plastisk region, ettersom necking ble observert i strekktestresultatene. Denne plastiske oppførselen forsvinner helt etter 742 timer med vannabsorbering. Både elastisitetsmodulen og den maksimale strekkfastheten forblir forholdsvis uforandret på dette punktet, men den maksimale strekkbelastningen har gått ned.

Prøvestykkene med karbonfiber-forsterkning hadde mer enn et 15% tap av maksimal strekkstyrke i fiberretningen på grunn av vannmasse-opptaket. De feilet på grunn av sprekkdannelser i matrisen. Selv om styrken ble redusert, ble det observert at forlengelsesegenskapene økte med et høyere vannmasse-opptak.

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Nomenclature

Abbreviations

CAD	Computer aided design
CF	Carbon fiber
FRP	Fiber reinforced polymer
H-bonds	Hydrogen Bonds
MDF	Medium-density fiberboard
PMC	Polymer Matrix Composite
SG	Strain gauge
UD	Uni-directional

Symbols

$\Delta R/R_0$	Relative change of resistivity
ϵ^*	Corrected strain measurements
ϵ_{ave}	Strain in specimen
ϵ_{gauge}	Strain in gauge
γ	Individual bond strength

λ	Correction factor
Ω	Resistance
σ	Stress
σ_{ts}	Ultimate tensile strength
$\mathrm{Mol}_2(t)$	Moles of reacted water
A	Area
c	Concentration
c_∞	Saturation concentration
$C_{\mathrm{Ajovalasit}}$	Correction coefficient, as proposed by Ajovalasit
C_{Swan}	Correction coefficient, as proposed by Swan
C_{GF}	Correction coefficient
c_t	Concentration at time t
D	Diffusion Coefficient
E^*_{sg}	Reduced elastic modulus of strain gauge
E_{sg}	Elastic modulus of strain gauge
E_{spec}	Elastic modulus of specimen
F	Load
GF_{act}	Actual gauge factor
GF_{cal}	Calculated gauge factor from manufacturer
h	Specimen thickness
h_{sg}	Strain gauge thickness

J	Flux
L_E	Least square error
$m_{1,\infty}$	Mass of mobile water molecules at equilibrium.
m_1	Molecular concentration of mobile water molecules
$m_{2,\infty}$	Mass of bonded water molecules at equilibrium.
m_2	Molecular concentration of bonded water molecules
M_∞	Percentage mass increase at equilibrium
M_k	The kth point of test data for mass uptake
M_t	Percentage mass increase at time t
N	Number of test data points
r	Degradation parameter
t	Time
t_k	Time at kth point of test data
W_0	Initial weight
W_t	Weight at time t
x_i	Distance in i-direction

Chapter 1

Introduction

Polymer matrix composites (PMCs) offers an endless range of opportunities. Thousands of PMC applications can be found in the marked, and the material choice is only becoming more and more attractive. In comparison to other materials can PMCs in many cases provide a more lightweight alternative that still meets the required mechanical properties. One of the most commercialized composite compositions is the fibre reinforced epoxy polymer. Epoxy might be best known to the common man for it's presence as glue, but much due to their excellent chemical resistance, good electrical insulation properties and ease of processing they are being widely used in many demanding application fields. The chemistry of epoxies also offers a high degree of production variation in the curing process, providing the possibility to "custom-make" their mechanical properties to create the best possible fit for a specific application.

Even though PMC's are already in use in high end industries like aerospace and civil infrastructure repair, there is still a need for research on their reliability. The inability to accurately predict their lifetime still puts a damper on their application possibilities, especially regarding applications that are exposed to water.

1.1 Background

The ability to accurately predict the lifetimes of PMCs exposed to water would be of great interest to several product developers, not to mention the offshore industry. PMCs are widely known to have great corrosion resistance and specific strengths and could potentially simplify the installation process for several offshore applications. Together with their ease of processing, this would create a huge reduction in terms of cost. There are several factors to consider when evaluating a PMC's properties, especially when it comes to applications exposed to water. The presence of water is often regarded as the main reason for reliability reduction of composite materials.

Several models have been developed to analyse the water absorption process of polymers. The most commonly used view, much due to it's simplicity, is to look at it as a Fickian mass diffusion process. Previous research have found that this approach yields great approximations of one-dimensional diffusion during the early stages of absorption, but lacks the ability to translate the short term behaviour into the long term behaviour. The approach are dependent on experimental data to find the polymer's saturation weight, hence not able to predict how much time saturation will take. It is however able to approximate the diffusion coefficient during the early stages of absorption. Others suggests that the process can be looked on as a two-stage Fickian process, whereas some recognize it as non-Fickian behaviour.

One of the big challenges in predicting a PMC's life-cycle lies in relating the microscopic effect of water into the macroscopic effect. Any polymer exposed to water will at some point reach a point of equilibrium. To create a complete understanding of the microscopic effects during this process one have to know when this point is. And since the lifetime of PMCs may be several years, even decades, real life testing is basically out of the question. Tests have been developed, whereas manipulation of temperature have been used to accelerate the process. These tests exploit the fact that the chain mobility in polymeric chains are increased at higher temperatures, making it much simpler for water molecules to move in between them. Hence, easier for the water to diffuse into the material. Although this is a functioning method to accelerate the absorption process, it provides little knowledge on how the water effects the PMC's long term properties. Temperature changes are, in addition to water, also seen as one of the main contributors of reliability reduction in a PMC, creating even more factors to consider in the evaluation of the visco-elastic material.

PMC applications that are submerged in water experiences little variations in temperature. Normally the temperature of *liquid* water lies within the range of 4-35°C, hence well below the glass transition temperature of epoxy. The problem for offshore PMC applications therefore lies in predicting the water uptake, and further relate the uptake to the macroscopic mechanical properties.

1.2 Objectives

1. Present the theoretical background for water diffusion into epoxy and epoxy-based PMCs.
2. Perform experiments to examine the effects of water diffusion related to epoxy and PMC mechanical properties.
3. Link the microscopic behaviour to the macroscopic behaviour of epoxy and PMCs during water diffusion.
4. Relate the results to the long term properties of epoxy and PMCs.

1.3 Structure of the Report

The rest of the report is organized as follows. Chapter 2 gives a chemical background for the case of epoxy and PMCs. Chapter 3 provides a thorough analysis of water diffusion into polymeric materials, whereas chapter 4 describes the materials and experimental procedures used in this study. Chapter 5 displays the results of this study, and chapter 6, together with reconsiderations for further work, comprise a summary and discussion of the results.

Chapter 2

Epoxy-Based Polymer Matrix Composites

2.1 Polymer Matrix Composites

PMCs include an increasingly large material group that is quickly gaining popularity as a material choice. Depending on what needs that should be met by the product, a polymeric solution will in many cases provide a more lightweight alternative that still meets the necessary mechanical properties.

The polymeric part of PMCs can have very different structure however. What they all have in common is the fact that they are essentially the result of a repeated set of sub-units in a chemical structure, called monomers or resin. These monomers go through a polymerization, where covalent bonds are created between them. Depending on how this process is completed, the chemical structure can end up being either a very linear chain-structure or a highly cross-linked network structure. The linear structure ends up being a thermoplastic, while the latter structure becomes a thermosetting polymer. In this study the focus has been on epoxy polymers and epoxy based carbon fibre reinforced polymers (FRPs). Epoxy is most commonly known as a thermosetting polymer.

2.2 Epoxy Polymers

A solid epoxy polymer is created through solidification of two or more viscous liquid reactants. Figure 2.1 shows a schematic representation of the first reactant, a resin with epoxy groups at both ends. The *n* indicates the degree of polymerization, and can be as high as 25.

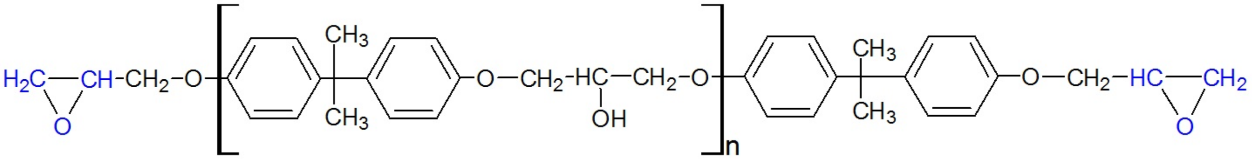


Figure 2.1: Schematic representation of epoxy resin, with epoxy groups in blue [1].

To create a solid polymer the resin are induced with a hardener, i.e. a curing agent that reacts with the epoxy-groups at the ends of the structure. This leads to crosslinking between the chains, as illustrated in figure 2.2.

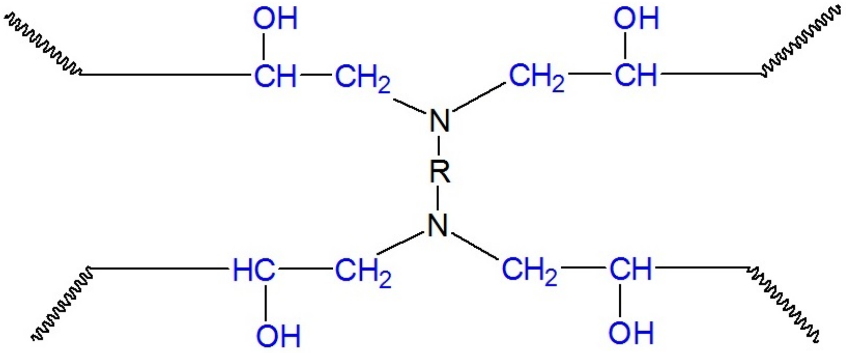


Figure 2.2: Schematic representation of crosslinking between epoxy groups and hardener during curing [adapted from 1].

Epoxy may also appear as a thermoplastic, but the focus in this study has been on the thermosetting structure. This is the standard option for most commercialized applications, including many composite materials.

2.3 Carbon Fibre - Epoxy Interface

When carbon fibre is prepared for bonding with epoxy, the focus lies on making the surface of the fibres prone to create chemical bonds between the two materials. These bonds are known as the interface. Layer C in figure 2.3 indicates the layers of interaction between carbon fibre and epoxy.

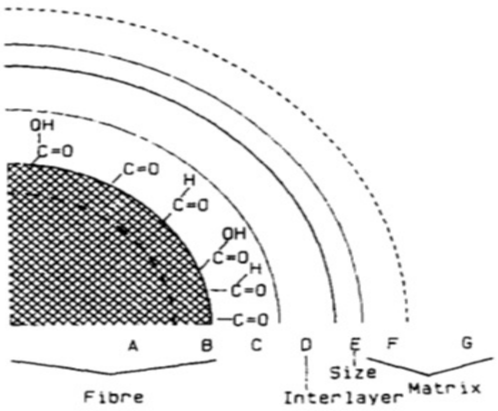


Figure 2.3: Regions of the carbon fibre epoxy interface [2].

As mentioned in section 2.1, the bonds between the monomers are covalent bonds. The bonds between the molecules in the carbon fibre are also formed of strong covalent bonds. When the epoxy and carbon fibre bond together, the chemical bonds between them consists of Van der Waals forces.

2.4 Van der Waals Forces

All atoms wants to be whole by becoming balanced molecules. In a bonding process between two atoms there is one atom that exhibits one or more electrons extra, whereas the other atom is lacking the equivalent number of electrons. Molecules are bonded by sharing of electrons. This is possible since the electrons move at such a pace around the protons that they can balance both atoms at the same time. These electrostatic forces keeps the molecule together, and are what is known as covalent and ionic bondings. Even though the molecule is in a stabilized state, the fact that the atoms originally had either too many or too few electrons leads to a difference in electron-negativity. This means that the molecule consists of an attractive positively charged side and a repulsive negatively charged side. The phenomenon when a molecule's attractive side interacts with another molecule's repulsive side is known as a Van der Waals bond, as represented in figure 2.4. Intermolecular Van der Waals bonds exist between the molecular chains in epoxy polymers. In an epoxy polymer structure, these forces consists of hydrogen bonds.

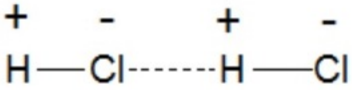


Figure 2.4: Representation of balanced molecules with an attractive and repulsive side, interacting with each other through a Van der Waals bond.

2.4.1 Hydrogen Bonds

Hydrogen bonds (H-bonds) are a strong form of Van der Waals forces. They occur when two electronegative atoms interacts with the same hydrogen atom, as shown in figure 2.5. The system comprise a donor, of which the hydrogen atom is covalently bonded with, and an acceptor. Covalent bonds are stronger than H-bonds, but the H-bonds occur due to the dipole interaction between the electronegative atoms and the proton. H-bonds can interact between several different donor and acceptor systems, but the strength between them deviates.

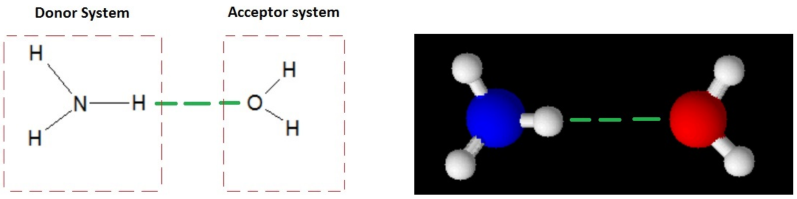


Figure 2.5: Nitrogen-Oxygen H-bond in green.

The hydrogen bond-interface in the epoxy/carbon fibre (epoxy/CF) system occur between oxygen-atoms, which are connected to carbon-atoms either by a single or a double bond. The bond type, and therefore the geometrical configuration, decides if it is a donor or acceptor system. Figure 2.6 illustrates how the carbon fibre's continuously reactive sites along its molecular structure comprise both acceptor and donor systems.

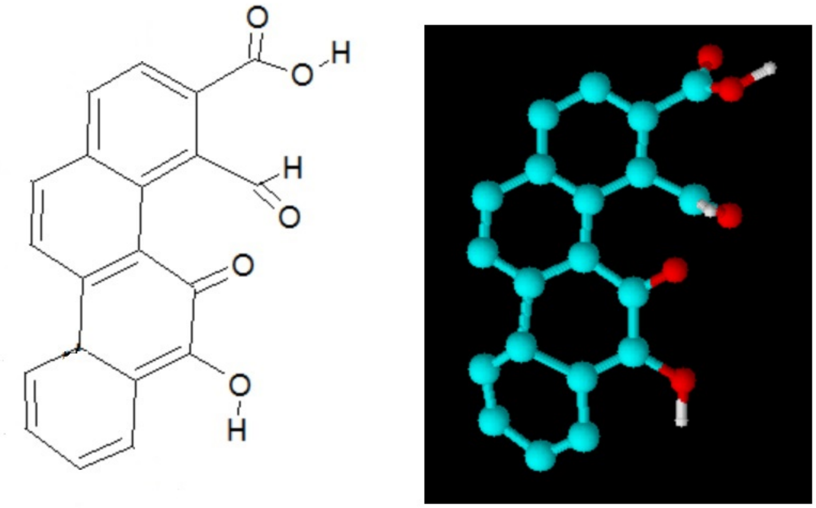


Figure 2.6: Representation of possible bonding sites along a carbon fibre's surface.

2.5 Activation Energy

Molecules possesses a certain amount of potential energy, and when they collide the kinetic energy can lead to stretching, bending and even breaking of the molecular bonds. The *activation energy* is defined as the minimum amount of energy required in order for a chemical reaction to take place. In contrast to the strong covalent bonds between the chains, the activation energy of hydrogen bonds are not substantial. Their strength are highly dependent on the molecular geometry, as the strongest among them are co-linear [3]. The shorter the bond, the stronger it is.

Chapter 3

Water Diffusion

Diffusion can be defined as molecular penetration or mass transfer from one system to another. In this study one of the systems is water while the second system is an epoxy polymer or a carbon fibre reinforced epoxy polymer, and can effectively be looked upon as an absorption process.

The polymeric part of a fibre reinforced epoxy will experience a degree of water absorption, i.e. water diffusion when exposed to water. This is of interest to a mechanical engineer because the mechanical properties of the entire FRP will suffer from this kind of moisture attack. Previous research indicates that the absorption process is a two-stage process, where the first stage can be said to follow Fickian Law.

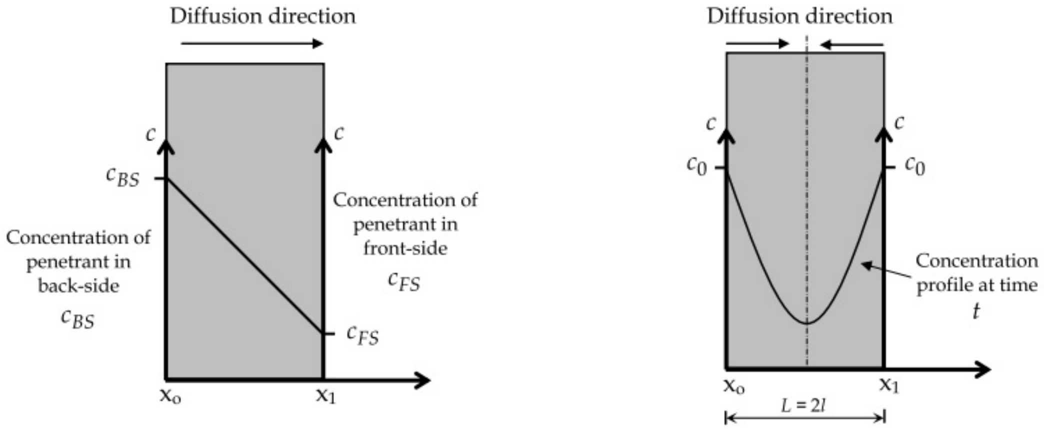
3.1 First Stage of Diffusion

3.1.1 Fickian Law

Fickian's first law, as given by equation 3.1, describes the diffusion process under steady-state circumstances, i.e., the concentration does not vary with time in the absence of temperature, stress and damage gradients.

$$J = -D\frac{\partial c}{\partial x_i} \tag{3.1}$$

Here J is the flux which gives the quantity of penetrant diffusing across unit area of medium per unit time. D is the diffusion coefficient, c is the concentration and x_i is the distance in the three dimensions $i = 1,2,3$. $\partial c/\partial x_i$ indicates the gradient of concentration along the i-direction, as indicated in the x-direction in figure 3.1a.



(a)

(b)

Figure 3.1: Concentration profile under (a) steady-state and (b) unsteady circumstances [4].

A better approximation of the work done in this study is provided by Fickian's second law. This describes the diffusion process under unsteady circumstances, and is given by equation 3.2.

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left[D\frac{\partial c}{\partial x}\right] \tag{3.2}$$

Equation 3.2 comprise the same parameters as in equation 3.1, but the new variable *time* is included. Note that this study is on one-dimensional through thickness diffusion, therefore further direction-notation is not included. With this equation, the concentration change can be modelled with respect to the time. *However*, it is important to note that this only applies to one-dimensional diffusion processes. Figure 3.1b shows the principle in the x-direction.

For the case of long time approximations, a more suitable solution is given by equation 3.3 [5].

$$\frac{c_t}{c_\infty} = 1 - \frac{4}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}\exp\left[\frac{-D(2n+1)^2\pi^2 t}{h^2}\right]\cos\left[\frac{(2n+1)\pi x}{h}\right] \tag{3.3}$$

Here c_∞ is the saturation equilibrium concentration within the material and h is the specimen thickness. Integrating equation 3.3 leaves an equation giving the mass absorbed by the material as a function of time compared to the saturation mass M_∞.

$$\frac{M_t}{M_\infty} = 1 - \sum_{n=0}^{\infty}\frac{8}{(2n+1)^2\pi^2}\exp\left[\frac{-D(2n+1)^2\pi^2 t}{h^2}\right] \tag{3.4}$$

Equation 3.4 can be simplified even further if the time spans over a short period.

$$\frac{M_t}{M_\infty} = \frac{4}{h}\left(\frac{D}{\pi}\right)^{\frac{1}{2}} t^{\frac{1}{2}} \tag{3.5}$$

By looking at the slope of the plot to M_t/M_∞ as a function of $t^{\frac{1}{2}}$, the diffusion coefficient can be approximated. An illustration of a diffusion process following Fickian law is indicated in figure 3.2.

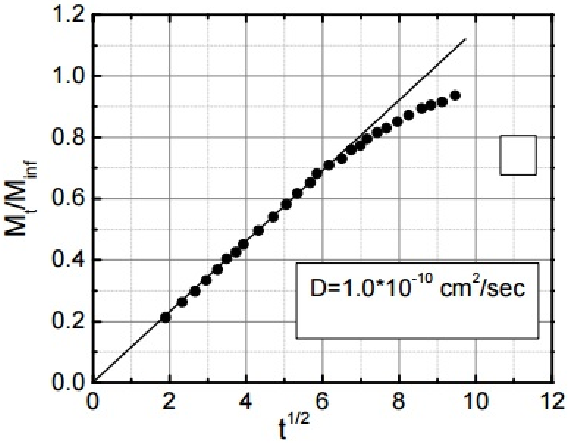


Figure 3.2: M_t/M_∞ as a function of $t^{\frac{1}{2}}$ for a typical polymer [4].

The weight gain, or mass uptake in percentage at a given time can be found from

$$M_t = \frac{W_t - W_0}{W_0} \cdot 100\% \tag{3.6}$$

where W_0 is the original dry weight and t indicates a given time. The diffusion coefficient can then be found by interpolation of the slope to equation 3.5.

$$\begin{gathered} \frac{4}{h}\left(\frac{D}{\pi}\right)^{\frac{1}{2}} = \frac{\frac{M_{t_2}}{M_\infty} - \frac{M_{t_1}}{M_\infty}}{\sqrt{t_2} - \sqrt{t_1}} \\ \Rightarrow D = \frac{\pi}{16}\frac{h^2}{M_\infty^2}\left(\frac{M_{t_2} - M_{t_1}}{\sqrt{t_2} - \sqrt{t_1}}\right)^2 \end{gathered} \tag{3.7}$$

For the case of long time diffusion processes equation 3.4 may be written as

$$\ln\left(1 - \frac{M_t}{M_\infty}\right) = \ln\left(\frac{8}{\pi^2}\right) - \frac{D\pi^2 t}{h^2} \tag{3.8}$$

3.1.2 Free Volume Theory

During water diffusion a polymer will absorb water and swell to a bigger size. Observations show that the amount of water absorbed is larger than the amount of volume increase. This phenomenon can be explained by free volume theory.

Polymeric materials inhibits an amount of holes within it's structure. Therefore it can be said that the material consists of two parts, the molecules creating the structure themselves and the empty spaces between them. This amount of empty space is commonly known as the free volume, and it heavily influences the first process of water diffusion.

Epoxy polymer chains exhibit more free volume at the ends of the chains than within the chains. When water diffuses into a polymer this free volume is the first space that the water occupies. During the process the water replace the empty spaces within the polymer, therefore the polymer does not swell. This explains how the first part of absorption follows Fickian law, as there are little or no relevant deformations or stresses created during the process.

3.2 Second Stage of Diffusion

The second stage of absorption is of interest when evaluating the long term properties of a PMC undergoing water diffusion. When the easily available free volume within the polymer matrix is spent, the water finds new ways in order to diffuse into the material.

3.2.1 Breaking of H-bonds

As mentioned in section 2.2, an epoxy polymer consists of a cross-linked covalently bonded network of monomer subunit chains. The cross-link structure gains an additional amount of strength by H-bonds that are created between the chains during curing, as illustrated in figure 3.3.

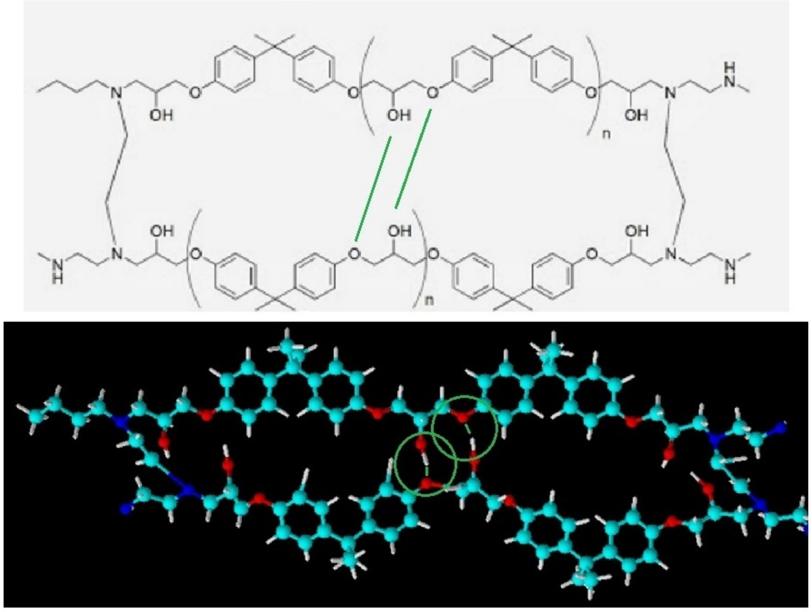
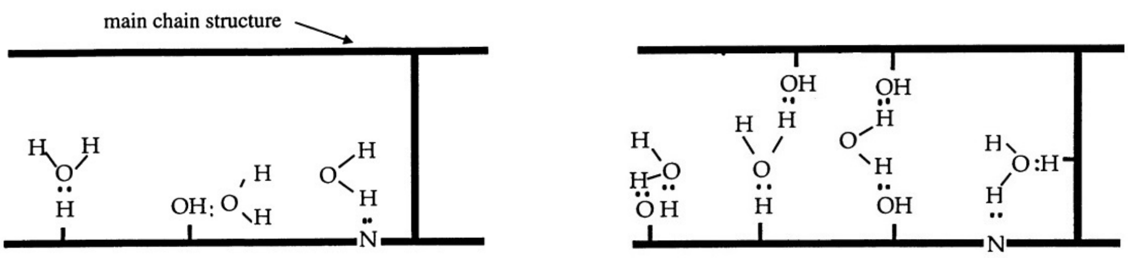


Figure 3.3: Possible H-bonds in green, occurring between the chains in a cured epoxy [adapted from 6].

Section 2.5 explains that there is a difference in strength of the different H-bonds. When the free volume within the polymer is spent, water continues to diffuse into the material because the water molecules break the existing H-bonds between the chains. This is possible because the activation energy of the original interchain Van der Waals bonds are low, and the geometrical configuration of H_2O-molecules have the possibility to create more linear H-bonds than the original bonds between the chains. Antoon and Koenig [7] propose that by doing this, as figure 3.4a illustrates, they create one H-bond of their own. In this process the water acts as a plasticizer, and will decrease the polymers *Glass Transition Temperature*. The breaking of initial Van der Waals bonds therefore results in an increase in chain segment mobility, consequently are the chains pushed apart in order to make room for the water molecules. This will increase the free volume further and induce swelling, which will lead to residual stresses and deformations.



(a)

(b)

Figure 3.4: Representation of: (a) water molecules overtaking existing H-bonds between the polymer chains and creates their own and (b) water molecules creating additional H-bonds [8].

Figure 3.4b illustrates how the water molecules that consists of both acceptor and donor systems will create more than one H-bond within the structure as more time passes by. As more bonds are created, the activation energy of the bound water molecules increases. The additional H-bonds may also interact between the main molecular chains, forming bridges between them and working as a secondary crosslinking.

3.2.2 Microcracks

When swelling occurs, the residual stresses in a PMC change. This may lead to the formation of microcracks, consequently creating faster diffusion paths for the water molecules which further may change the absorption characteristics.

3.3 Saturation of Mass

When all the free volume and available reaction sites are spent the material will become saturated and further water diffusion will stop. At this time the material's volume will have expanded, and there will be a mass of water uptake ($m_{1,\infty}$) that resides within the free volume of the material. In addition there will be a mass of water ($m_{2,\infty}$) that are bonded through H-bonds to the PMC. Samit [9] proposes a model for calculating both the saturation concentration and coefficient of diffusivity using a method of non-linear least squares technique based on Fickian's second law. Revisiting equation 3.4 and rearranging it

$$M_{t_k} = M_\infty \left[1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-(2n+1)^2 \left(\frac{\pi}{h} \right)^2 D t_k \right) \right] \tag{3.9}$$

The least square error is given by

$$L_E = \sum_{k=1}^{N} \left[M_k - M_{t_k} \right]^2 \tag{3.10}$$

where

L_E is the least square error

N is the number of test data points

M_k is the kth data point for mass uptake

t_k is the time at the kth point of data

The first variation of least-square error should be zero, in order for the error to be minimum.

$$\delta M_{t_k} = \sum_{k=1}^{N} -2 \left[M_k - M_{t_k} \right] \delta M_{t_k} = 0 \tag{3.11}$$

Further, the difference in M_{t_k} can be expressed as

$$\delta M_{t_k} = \frac{\partial M_{t_k}}{\partial M_\infty} \delta M_\infty + \frac{\partial M_{t_k}}{\partial D} \delta D \tag{3.12}$$

Substituting the expression in equation 3.12 into equation 3.11 yields

$$\delta L_E = \left\{ \sum_{k=1}^{N} \left[M_k - M(t_k) \right] \frac{\partial M_{t_k}}{\partial M_\infty} \right\} \delta M_\infty + \left\{ \sum_{k=1}^{N} \left[M_k - M(t_k) \right] \frac{\partial M_{t_k}}{\partial D} \right\} \delta D = 0 \tag{3.13}$$

δM_∞ and δD are arbitrary variations, hence must each of the terms in braces independently go to zero.

$$\sum_{k=1}^{N} \left[M_k - M(t_k) \right] \frac{\partial M_{t_k}}{\partial M_\infty} = 0 \tag{3.14}$$

$$\sum_{k=1}^{N} \left[M_k - M(t_k) \right] \frac{\partial M_{t_k}}{\partial D} = 0 \tag{3.15}$$

Expressions for the saturation mass M_∞ and diffusion coefficient may be found by expanding equations 3.14 and 3.15, respectively.

Saturation mass:

$$\sum_{k=1}^{N} \left\{ M_k - M_\infty \left[1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-(2n+1)^2 \left(\frac{\pi}{h} \right)^2 D t_k \right) \right] \right\}$$

$$- \left[1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-(2n+1)^2 \left(\frac{\pi}{h} \right)^2 D t_k \right) \right]$$

$$\Rightarrow M_\infty = \frac{\sum_{k=1}^{N} \left\{ M_k \left[1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-(2n+1)^2 \left(\frac{\pi}{h} \right)^2 D t_k \right) \right] \right\}}{\sum_{k=1}^{N} \left[1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-(2n+1)^2 \left(\frac{\pi}{h} \right)^2 D t_k \right) \right]} \tag{3.16}$$

Diffusion coefficient:

$$\sum_{k=1}^{N}\left\{M_k - M_\infty\left[1-\frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)^2\left(\tfrac{\pi}{h}\right)^2 D t_k\right)\right]\right\}$$

$$-\left[M_\infty\frac{8}{\pi^2}\sum_{n=0}^{\infty}-\frac{1}{(2n+1)^2}(2n+1)^2\left(\frac{\pi}{h}\right)^2 t_k\exp\left(-(2n+1)^2\left(\tfrac{\pi}{h}\right)^2 D t_k\right)\right]=0$$

$$\Rightarrow\sum_{k=1}^{N}\left\{\begin{array}{l} M_k M_\infty t_k\dfrac{8}{\pi^2}\displaystyle\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)^2\left(\tfrac{\pi}{h}\right)^2 D t_k\right)- \\ (M_\infty)^2\left[1-\dfrac{8}{\pi^2}\displaystyle\sum_{n=0}^{\infty}-\frac{1}{(2n+1)^2}\exp\left(-(2n+1)^2\left(\tfrac{\pi}{h}\right)^2 D t_k\right)\right] \\ \left[\dfrac{8}{\pi^2}t_k\displaystyle\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)^2\left(\tfrac{\pi}{h}\right)^2 D t_k\right)\right]\end{array}\right\}=0 \tag{3.17}$$

By substituting equation 3.16 into equation 3.17, an expression for the diffusivity coefficient related to the saturation mass for each specimen can be acquired. The iteration procedure should be solved numerically with computer aid. Note that this approach require values for the saturation mass in order to provide accurate results.

3.4 Long Term Effects

Revisiting the fact that the water that diffuses into a PMC will at all times comprise an amount that resides within the free volume (m_1) and a separate amount that are bonded to the PMC chains (m_2). As through-thickness diffusion are conducted in this study, the *molecular* concentration of water can then be expressed as a function of time and thickness [10].

$$\frac{\partial m_1}{\partial t}+\frac{\partial m_2}{\partial t}=D\frac{\partial^2 m_1}{\partial x^2} \tag{3.18}$$

The breaking of H-bonds creates more fee volume, hence one can assume that there is a relationship between the amount of reacted water molecules and the mobile molecules residing within the PMC. Samit [9] proposes a degradation parameter r as follows

$$m_2 = r m_1 \tag{3.19}$$

where r is assumed to be a material constant. By further defining

$$D^{'} = \frac{D}{1+r} \tag{3.20}$$

$$m_{1,\infty} = \frac{M_\infty \rho_{epoxy}}{(1+r)m_w} \tag{3.21}$$

where m_w is the molar mass of water and ρ_{epoxy} is the density of the epoxy resin, Samit [9] proposes a solution for equation 3.18 as the total water uptake in moles per unit surface area. The solution is given for two different sets of transverse thickness (d) as follows:

For

$$t \leq \frac{0.05d^2}{D^{'}}$$

$$\text{Mol}_2(t) = \frac{4 r m_{1,\infty}}{d}\sqrt{\frac{D^{'} t}{\pi}} \tag{3.22}$$

For

$$t > \frac{0.05d^2}{D^{'}}$$

$$\text{Mol}_2(t) = r m_{1,\infty}\left[1 - \frac{8}{\pi^2}\exp\left(-\frac{D^{'}\pi^2 t}{d^2}\right)\right] \tag{3.23}$$

Here $\text{Mol}_2(t)$ is the amount of moles of reacted water within the PMC at a given time. This can be further translated into the number of *bonds* that at are broken within the PMC by applying Avogadro's constant (N_A), leaving a number equal to $\text{Mol}_2(t) \cdot N_A$. Xiao and Shanahan [10] show an expression for the probability of a chain segment being broken Y times.

$$P\left[\text{Mol}_2(t)N_A, Y\right] = \left(\frac{1}{N_A N_0}\right)^Y \left(1 - \frac{1}{N_A N_0}\right)^{(\text{Mol}_2(t)N_A - Y)} \left(\frac{(\text{Mol}_2(t)N_A)!}{Y!(\text{Mol}_2(t)N_A - Y)!}\right) \tag{3.24}$$

Here N_0 is the initial number of network crosslinks per mole. $1/N_A N_0$ is very small in comparison to $M_2(t)N_A$, hence can equation 3.24 be simplified to

$$P\left[\mathrm{Mol}_2(t)N_A, Y\right] = \frac{\left(\frac{M_2(t)}{N_0}\right)^Y \exp\left(-\frac{M_2(t)}{N_0}\right)}{Y!} \tag{3.25}$$

Defining the probability of no bond breakage as $P(0)$, then the probability of at least one breakage is given by

$$P(Y \geq 1) = 1 - P(0)$$
$$P(Y \geq 1) = 1 - \exp\left(-\frac{M_2(t)}{N_0}\right)$$

Using this an expression for the number of moles of inter-crosslink chains that have been cut per unit volume at time t can be given as

$$R = N_0\left[1 - \exp\left(-\frac{M_2(t)}{N_0}\right)\right] \tag{3.26}$$

The remaining number of moles of inter-crosslink chains will therefore be

$$N(t) = N_0 - ZR \tag{3.27}$$

Here Z is a parameter in the range of $1 < Z < 3$, determining the type of crosslink. This study comprise a homobifunctional crosslinking agent with identical reactive groups at either ends [11], meaning $Z = 1$. Using this and combining equations 3.26 and 3.27 yields

$$N(t) = N_0\left[\exp\left(-\frac{M_2(t)}{N_0}\right)\right] \tag{3.28}$$

Further Samit [9] proposes an expression for quantifying change in crosslink density due to hygrothermal ageing as

$$S_H(t) = \frac{N(t)}{N_0} = \exp\left(-\frac{M_2(t)}{N_0}\right) \tag{3.29}$$

3.5 Individual Bond Strength

Even though the number of inter-crosslinks within the PMC decreases during water diffusion, one can assume that the *strength* of the remaining bonds stay the same. At the initial state the critical load capacity in a mole of the PMC at failure may be given as an expression of the individual bond strength (λ) as follows [9]:

$$P_{crit}(0) = \lambda N_0 \tag{3.30}$$

Further, the critical load capacity at time t may be given as

$$P_{crit} = \lambda N(t) \tag{3.31}$$

Combining equations 3.30 and 3.31 yields

$$\frac{P_{crit}(t)}{P_{crit}(0)} = \frac{N(t)}{N_0} = S_H(t) \tag{3.32}$$

3.6 Wicking

CF will create bonds with water at it's surface, but it will not absorb water. Should water diffuse through the matrix and meet an already bonded site at the CF surface it is suggested that the molecule may be transported along the interface through wicking, as illustrated by water molecule marked as 2 in figure 3.5.

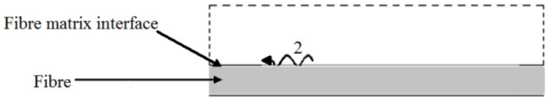


Figure 3.5: Representation of wicking at the CF/epoxy interface [adapted from 12].

Chapter 4

Materials and Experimental Procedure

4.1 Mould Preparation

To accelerate the time to reach saturation, i.e., diffusion equilibrium in the specimens, the thickness needs to be as thin as possible with a large area of exposure. The size of the specimens should also be as equal as possible. The pure epoxy specimens were therefore made in a home-made mould. The blue cavities shown in figure 4.1 illustrates where the epoxy specimens cured.

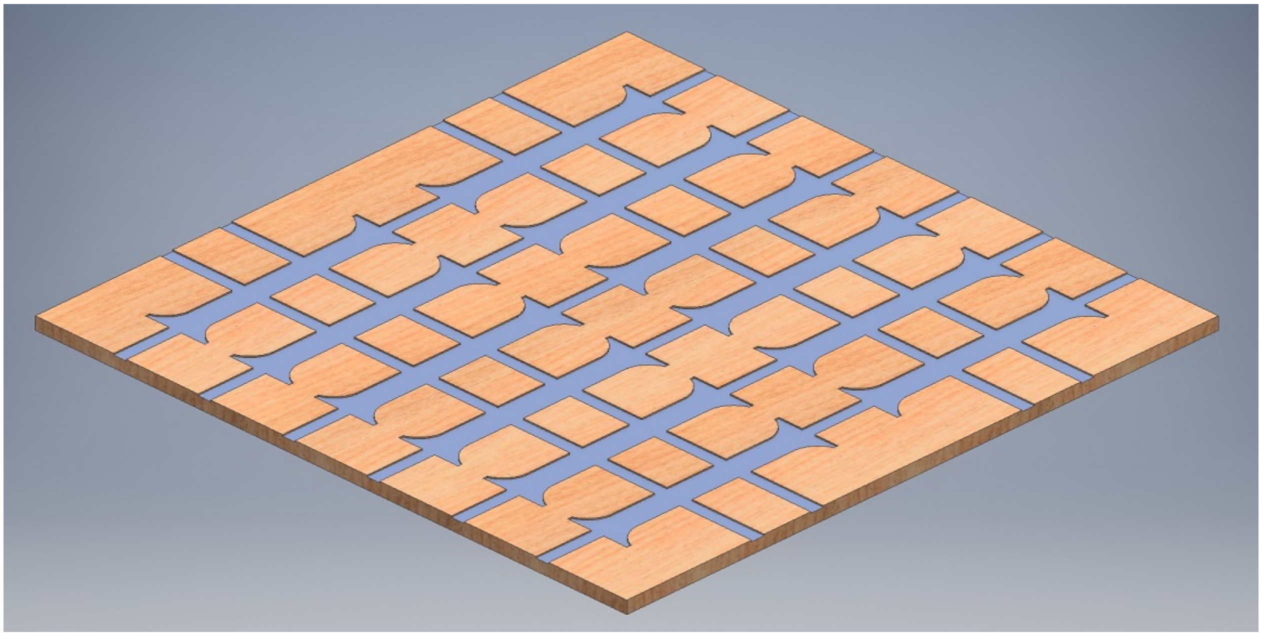


Figure 4.1: CAD model of mould.

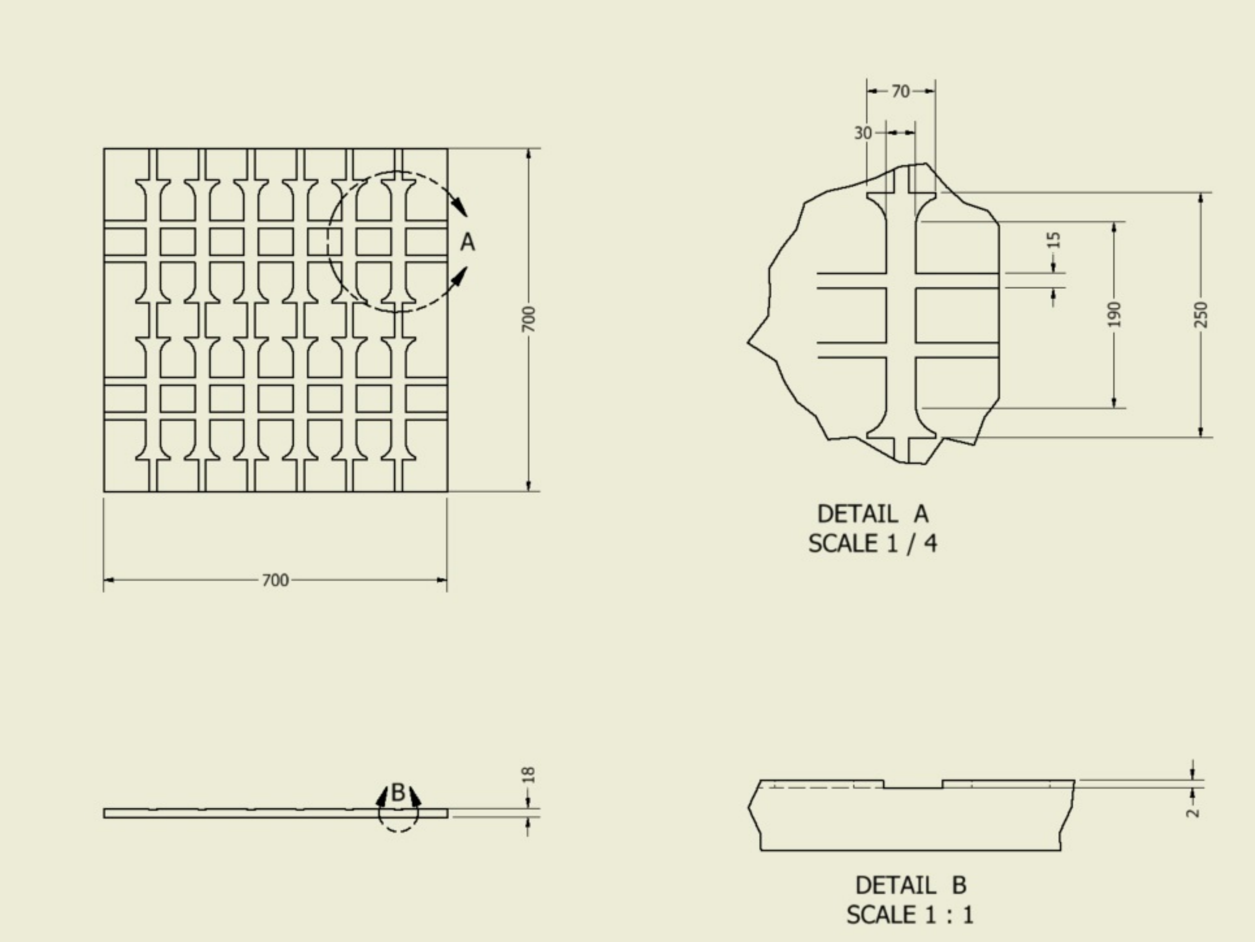


Figure 4.2: Mould measurements in a scale of 1/8.

The mould was made of MDF and cut by computer aid. This made every cavity for the specimen of equal size, as indicated in the specific measurements in figure 4.2. In order to be able to remove the thin specimens after curing without breaking them, the following preparation was performed:

1. The MDF was sanded down using P400 sanding paper, taking especially into account the cavities.
2. The mould was brushed with a couple of thin layers of epoxy. Most of the epoxy was absorbed by the mould, and it was left to cure for 24 hours creating a thin epoxy surface.
3. The surface was sanded down, using P1200 wet sanding paper.

4. Using 2-component Polyuretan, the mould was lacquered. This was then left to cure for 30 hours.

5. The surface was sanded down again with wet P1200 sanding paper.

6. The ends of the mould were sealed by using sticky-tape before casting in order to create specimens with even thickness, as shown in figure 4.3.

7. Right before pouring the epoxy resin in the mould, it was brushed in with RenLease release agent.

8. After the epoxy had cured for 24 hours, the mould was put in an oven at 80°C for 1 hour of post-curing to simplify the release of the specimens.

Section notes:

A complete set of mould CAD-models is found in appendix A.1.

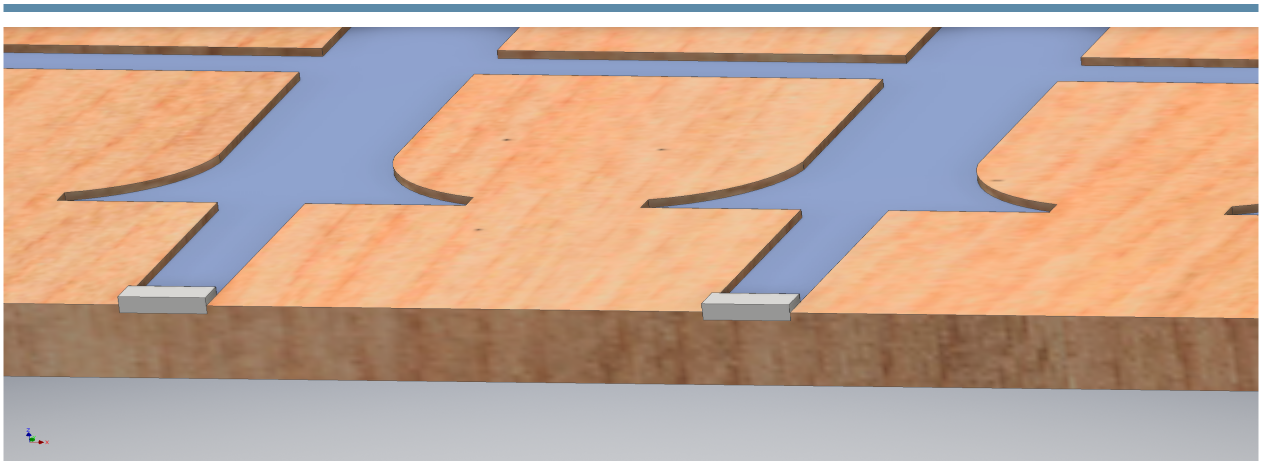


Figure 4.3: Sticky tape at the ends of the mould during casting.

4.2 Material

4.2.1 Epoxy Specimens

The epoxy-system used in this study consists of EPIKOTE Resin MGS RIMR 135 and EPIKURE Curing Agent MGS RIMH137. The test specimens were prepared using the following procedures:

1. The resin and curing agent were mixed thoroughly with a mixing ratio of 3:1
2. The mixture were degassed for 15 minutes
3. The degassed mixture was poured into the mould from a small bucket by hand
4. After curing it was removed from the mould and left in an oven at 80°C for 15 hours of post-curing.
5. The specimens were left for 24 hours at a table to cool down to room temperature. The entire curing cycle is shown in figure 4.4.
6. The specimens were then cut into equal rectangular sizes, and the thickness and edges were sanded down by hand. The end result was specimens of dimensional parameters of 150mmX30mmX2mm.

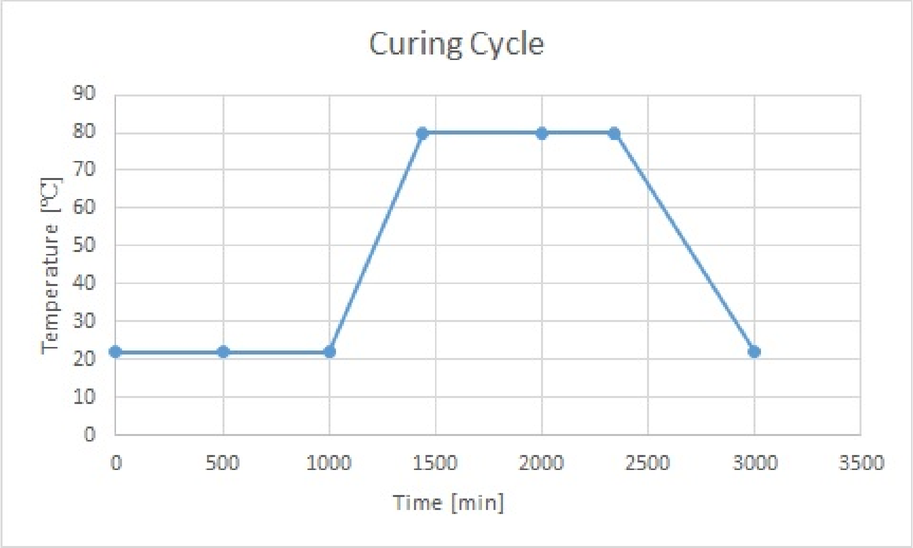


Figure 4.4: Curing cycle of epoxy specimens.

4.2.2 Carbon Fibre Reinforced Epoxy Specimens

The same epoxy-system were used for the specimens containing carbon fibre, including the same mixture procedures for the epoxy resin. But the degassed mixture were used in a vacuum infusion process, where a thin rectangular plate became the product. After curing for 24 hours and post-curing for 15 hours in the oven at 80°C, the plate was cut into smaller rectangular pieces that matched the size of the pure epoxy specimens. The end products are four unidirectional (UD) carbon fiber reinforced epoxy specimens.

4.3 Coating

To best simulate how epoxy would be exposed to liquids in real life, diffusion should only occur from two sides. The test specimens are very thin in comparison to the length and width, and is arguably negligible in the diffusion process. To ensure this the specimens were coated along the edges, as shown in figure 4.5. The diffusion tests are therefore applicable with Fickian law under unsteady circumstances, as illustrated in figure 3.1b. 13 pure epoxy specimens, in addition to 3 carbon fibre containing epoxy specimens, were coated, then measured, weighed and labelled before continuing with the water diffusion process.

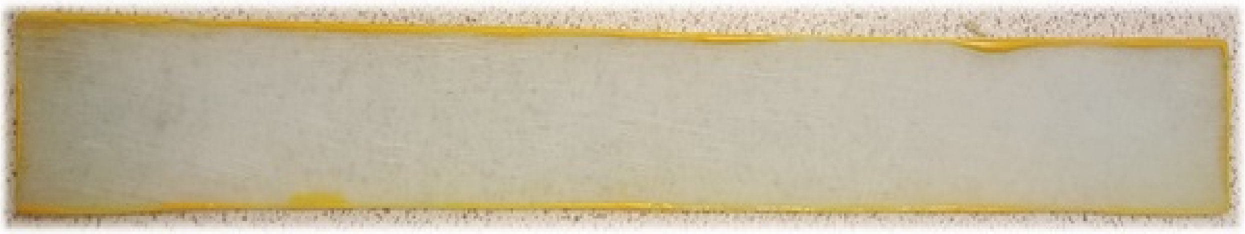


Figure 4.5: Coated specimen ready for labelling and water diffusion process.

4.4 Diffusion Process

Distilled water was used to induce water diffusion in this study. The 13 pure epoxy specimens and the 3 specimens containing carbon fibre were placed together in a box with water, stacked in a matter ensuring a big area of exposure for each specimen. The distilled water was changed regularly, to better simulate a real submerged environment where the water continuously change and new available molecules are constantly present. The temperature of the distilled water was kept at room temperature in the range of 23-28°C.

The specimens were weighed periodically during the diffusion process. After being removed from the distilled water, the surface water present was brushed away with a linen cloth. Before weighing they were allowed to air-dry for 2 minutes. The accuracy of the weight used in this study was down to 1/1000 gram.

4.5 Strain Gauge

Half-bridged two-wire strain gauges with length equal to 6mm and 120Ω resistance were used to correct the strain measurements during static tensile testing. They are constructed from thin metallic grid enclosed between polymer films, as illustrated in figure 4.6. The principle of this device incorporates the change of electrical resistance in the metal part linearly with its deformation [13]. The change is measured and further converted into the strain value using the *Gauge factor*.

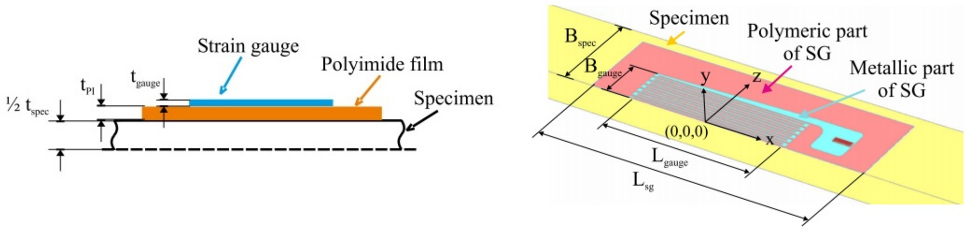


Figure 4.6: Illustration of strain gauge on a specimen [14].

4.5.1 Correction of Gauge Factor

As the strain gauge includes a thin metal grid, there is a stiffness mismatch between the strain gauge and the more compliant specimens used in this study. Due to this, the strain gauge may act as a reinforcement during tensile testing. To avoid errors in the strain gauge measurements, a calibration of the gauge factor was made. The manufacturer provides the following calculated gauge factor:

$$GF_{cal} = \frac{\Delta R/R_0}{\epsilon_{gauge}} \tag{4.1}$$

Here $\Delta R/R_0$ is the relative change of resistivity, while ϵ_{gauge} is the strain in the gauge. However, this is calculated without a stiffness mismatch. By defining a correction coefficient C_{GF}, adjustments to the provided gauge factor was made.

$$C_{GF} = \frac{GF_{act}}{GF_{cal}} \tag{4.2}$$

where GF_{act} is the actual gauge factor. By combining equations 4.1 and 4.2 the correction coefficient can be expressed as follows:

$$C_{GF} = \frac{GF_{act}}{GF_{cal}} = \frac{\Delta R/R_0}{\epsilon_{gauge}} \frac{\epsilon_{ave}}{\Delta R/R_0} \Rightarrow C = \frac{\epsilon_{ave}}{\epsilon_{sg}} \tag{4.3}$$

Here ϵ_{ave} is the strain in the specimen, whereas ϵ_{sg} is the strain experienced by the strain gauge. Equation 4.3 can therefore be expressed as the ratio of E_{sg} and E_{spec}, which are the elastic modulus of the strain gauge and the specimen, respectively.

$$C_{GF} = \frac{\epsilon_{ave}\sigma}{\epsilon_{sg}\sigma} = \frac{E_{sg}}{E_{spec}} \tag{4.4}$$

The error in measurements are dependent on the geometrical properties of both the strain gauges and the specimens. The most significant dimensions is found to be the specimen thickness and the strain gauge length. As the specimens in this study comprise an initial thickness in the range $1.4\text{mm} \leq h \leq 1.85\text{mm}$ the reinforcement from the strain gauge may have an impact. The strain gauges that were used had a length equal to 6mm, which lead to additional adjustment of the strain gauges elastic modulus. An analytical model with the reduced Young's modulus E^*_{sg} was derived by Ajovalasit et al. [15, 16] as follows:

$$C_{\text{Ajovalasit}} = \frac{\epsilon_{ave}}{\epsilon_{sg}} = 1 + \frac{E^*_{sg}}{E_{spec}} \tag{4.5}$$

Here E^*_{sg} takes the strain gauge stiffness, thickness (h_{sg}) and length into account. Using this train of thought, an improvement of the correction gauge factor can be determined based on the model proposed by Swan [17].

$$C_{\text{Swan}} = 1 + \frac{2E_{sg}h_{sg}}{E_{spec}h} \tag{4.6}$$

4.6 Tensile Testing

Gripping paper were used to avoid slipping in the grips during tensile testing of the pure epoxy specimens, as shown in figure 4.7. To not break the specimens during fastening, the grip clamps were set to a pressure of 200psi. For the case of the CF/Epoxy specimens, no gripping paper were used during testing. Instead the pressure of the clamps were set to 600psi. The speed was set to 2 mm/min for both types of specimen. The variables measured comprise time, load, strain and strain gauge measurements. The stress was found by

$$\sigma = \frac{\text{F}}{\text{A}} \tag{4.7}$$

where F is the load applied and A the area of the specimen.

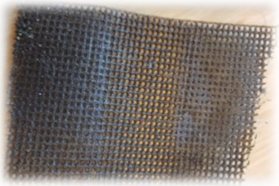


Figure 4.7: Gripping paper to fasten epoxy specimens during tensile testing.

Chapter 5

Results

5.1 Water Absorption

The weights of the specimens were measured regularly over a period of 742 hours. By exploiting equation 3.6 the percentage increase over time was calculated, of which the total amount of mass uptake is shown in figure 5.1. A complete list of the weight increase progress for the specimens is found in appendix A.2. The results from the graph can be divided into three stages.

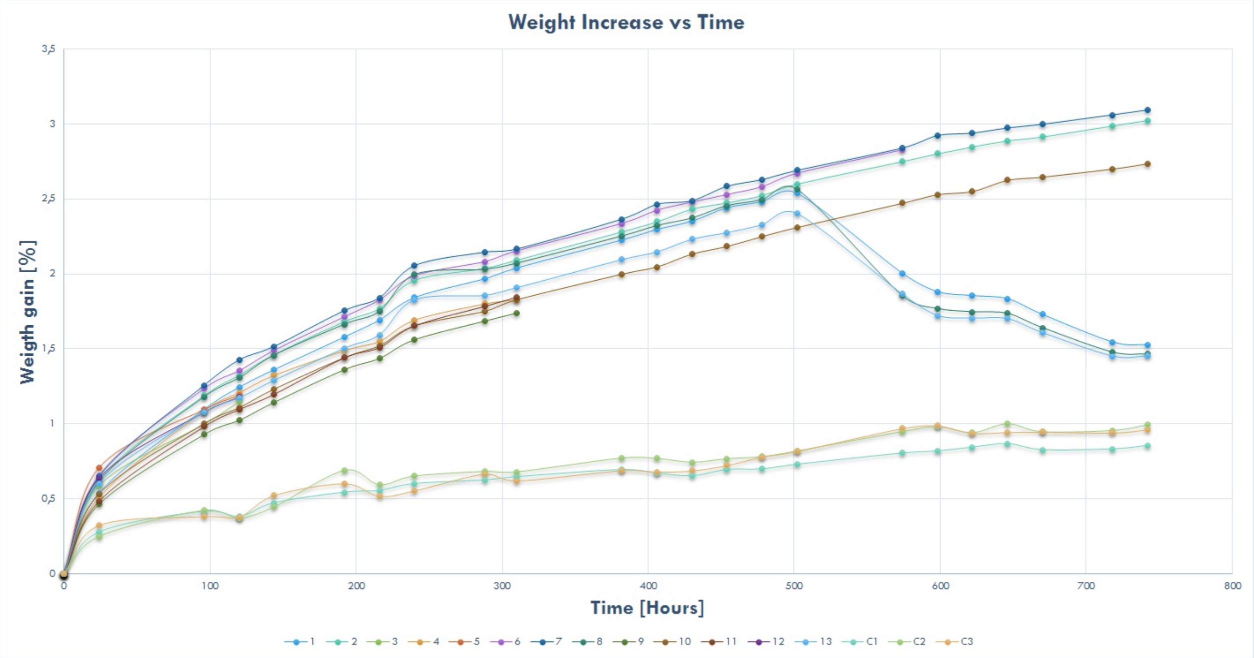


Figure 5.1: Weight increase during water diffusion.

5.1.1 Initial Stage of Absorption

The graph in figure 5.2 shows a steep growth during the initial 24 hours. This stage of absorption is rarely mentioned in previous research, but can be explained in terms of the molecular chains of epoxy resin. The ends of the molecular chains, as well as at least two available chain surfaces consists of easily accessible reaction sites for the water molecules. There are no inter-chain Van der Waals forces to overtake, hence the activation energy required for the water to bond is very small.

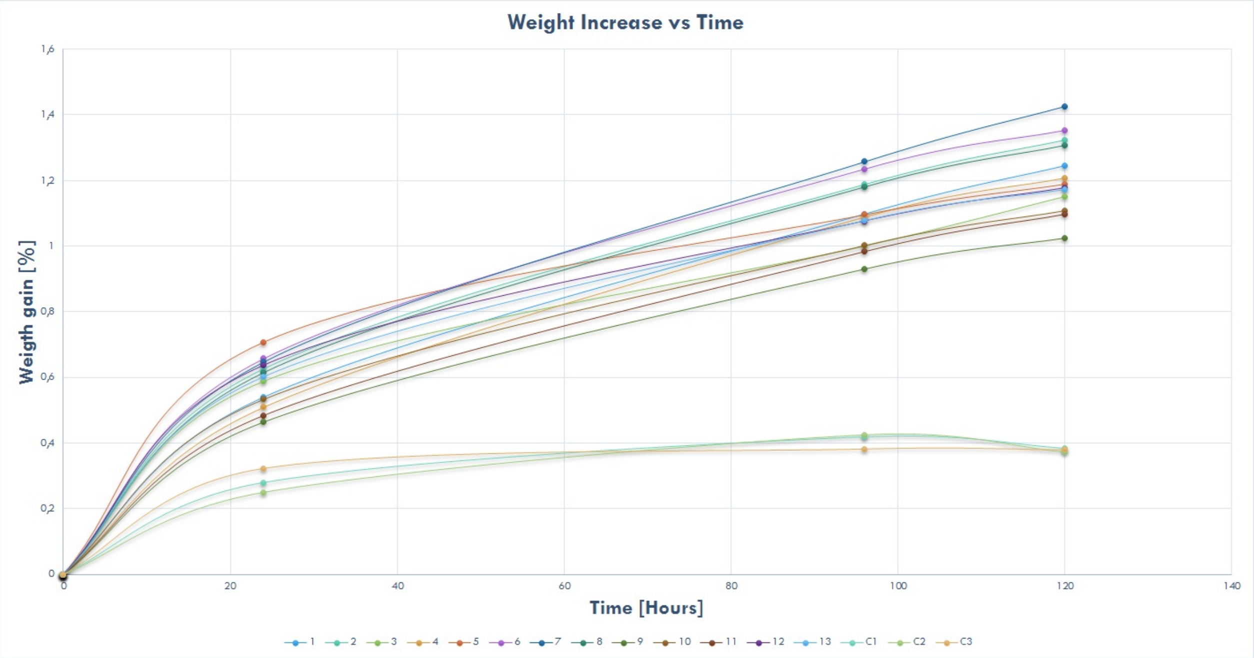


Figure 5.2: Initial weight increase during water diffusion.

Even though they contain a lesser amount of epoxy resin, it can be argued from the results that the amount of initial water uptake in percentage are greater for the CF/Epoxy specimens. This may be explained by the fact that the CF/Epoxy-specimens in this study have visible carbon fibre "stitches" at the surface, as shown in figure 5.3. As mentioned in section 2.3, the preparation of CF consists of making them prone to make H-bonds. Assuming that a negligible amount of epoxy has bonded at the surface of these stitches, the amount of initial easily available reaction sites for the water molecules is therefore very high.

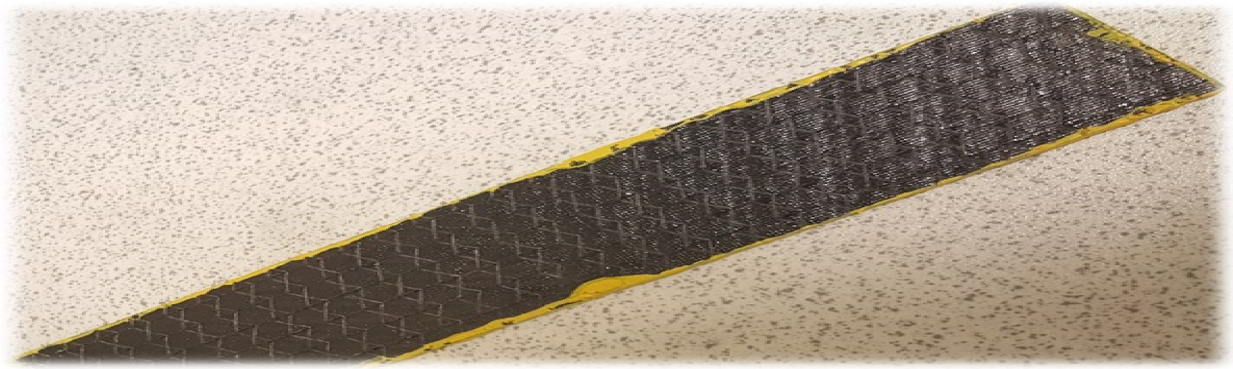
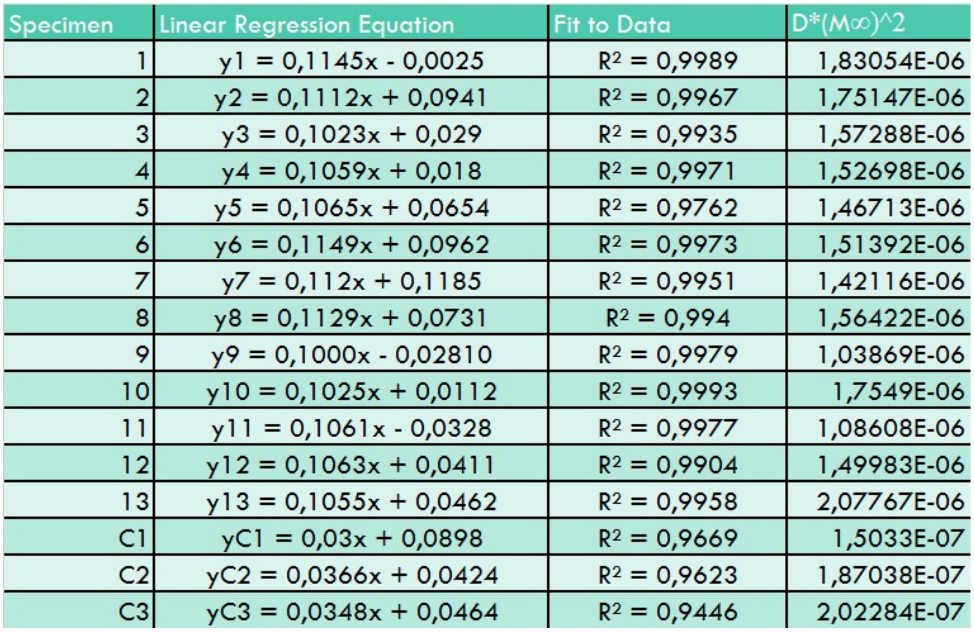


Figure 5.3: Visible carbon fiber stitches at epoxy/CF specimen surface.

5.1.2 First Stage of Absorption

Plotting the weight increase results versus the square root of time gives a graph with near linear behaviour during the first 650 hours. By exploiting curve fitting in Microsoft Excel the author obtained equations fitted to the regression line of each specimen. R^2 indicates how well the linear curve fit the data. The closer to 1, the better. As seen in figure 5.4 the linear curve of the epoxy specimens fit well during the first 650 hours, whereas the curve of the CF/Epoxy specimens are more inaccurate.

Table 5.1: $D \cdot M_{\infty}^2$ using linear regression.



Specimen	Linear Regression Equation	Fit to Data	D*(M∞)^2
1	y1 = 0,1145x - 0,0025	R² = 0,9989	1,83054E-06
2	y2 = 0,1112x + 0,0941	R² = 0,9967	1,75147E-06
3	y3 = 0,1023x + 0,029	R² = 0,9935	1,57288E-06
4	y4 = 0,1059x + 0,018	R² = 0,9971	1,52698E-06
5	y5 = 0,1065x + 0,0654	R² = 0,9762	1,46713E-06
6	y6 = 0,1149x + 0,0962	R² = 0,9973	1,51392E-06
7	y7 = 0,112x + 0,1185	R² = 0,9951	1,42116E-06
8	y8 = 0,1129x + 0,0731	R² = 0,994	1,56422E-06
9	y9 = 0,1000x - 0,02810	R² = 0,9979	1,03869E-06
10	y10 = 0,1025x + 0,0112	R² = 0,9993	1,7549E-06
11	y11 = 0,1061x - 0,0328	R² = 0,9977	1,08608E-06
12	y12 = 0,1063x + 0,0411	R² = 0,9904	1,49983E-06
13	y13 = 0,1055x + 0,0462	R² = 0,9958	2,07767E-06
C1	yC1 = 0,03x + 0,0898	R² = 0,9669	1,5033E-07
C2	yC2 = 0,0366x + 0,0424	R² = 0,9623	1,87038E-07
C3	yC3 = 0,0348x + 0,0464	R² = 0,9446	2,02284E-07

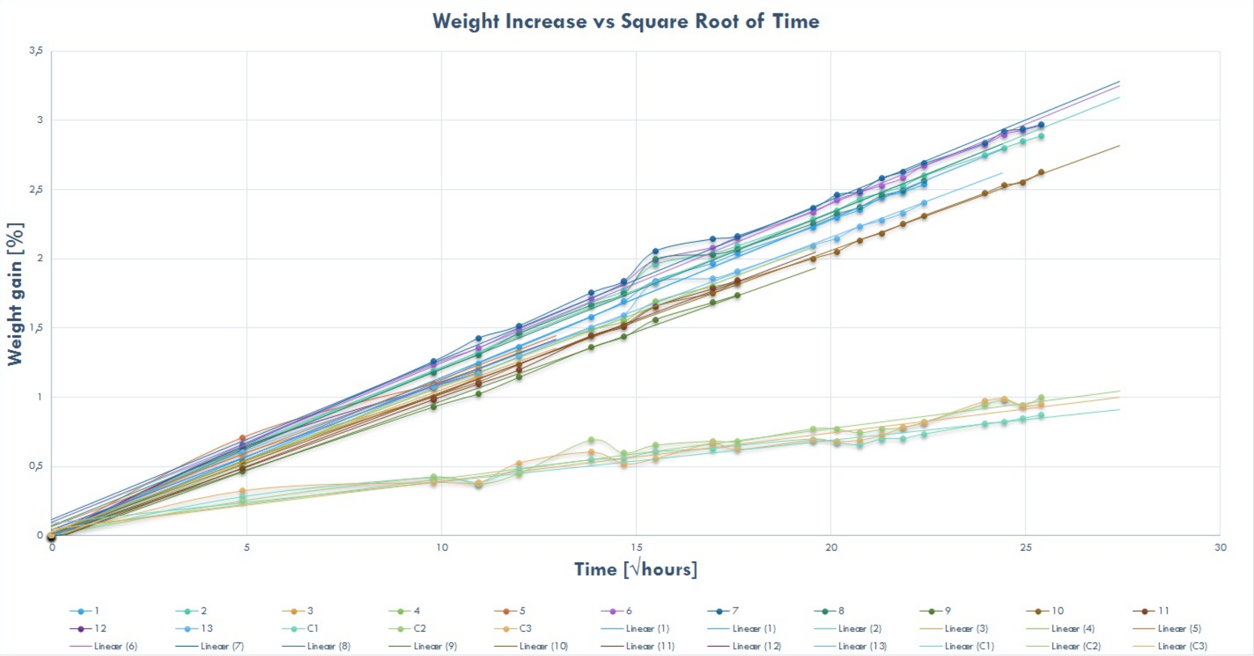


Figure 5.4: Linear regression of weight percentage increase plotted against $\sqrt{\text{time}}$.

The results are applicable with Fickian diffusion. With this behaviour the data from figure 5.4 together with equation 3.7 can provide an approximation for the diffusion coefficient multiplied by M_∞^2. The calculations for each specimen are shown in table 5.1.

5.1.3 Second Stage of Absorption

After approximately 650 hours the rate of water absorption begin to decrease for the case of the pure epoxy specimen. At this point the approximations for the diffusion coefficient acquired by linear regression yields less accurate results, as indicated by the deviations between the data and the linear regression curves towards the end in figure 5.5. As the rate decreases the behaviour are changing applicable to non-linear Fickian diffusion.

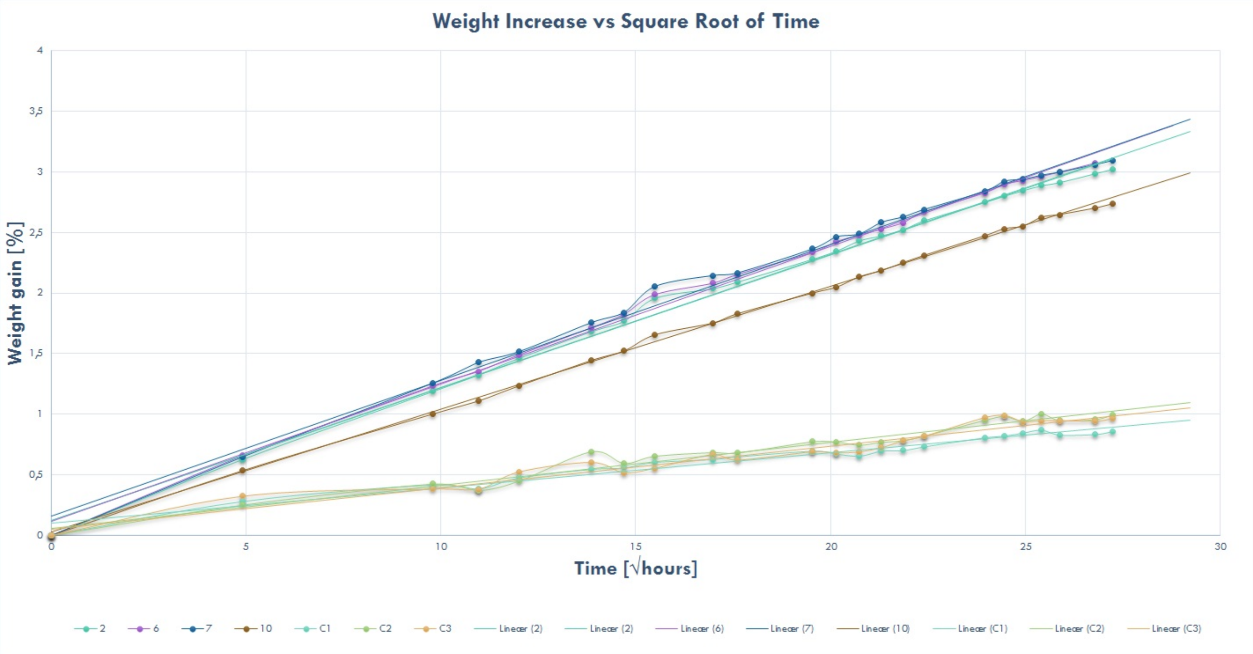


Figure 5.5: Failure of linear regression approximation, shown in plot of weight increase against $\sqrt{\text{time}}$.

5.1.4 Mass equilibrium

The linear regression line provided by Microsoft Excel showed good approximations of the diffusion coefficient for the pure epoxy specimens, hence the need for numerical approximations for the diffusivity proved unnecessary for these. Mass equilibrium was only achieved by the CF containing specimens during this study. As the results using linear regression for the diffusivity of these specimens proved less accurate, numerical approximations were acquired with the help of the math-tool Matlab and equation 3.17. A qualified guess of the pure epoxy specimens mass saturation is at least 4%, based on previous research. In best case scenario is the saturation mass of epoxy 3% according to this study. With this background, the calculation of the diffusivity results in a faster diffusion coefficient for the CF containing specimens, in comparison to the pure epoxy specimens.

5.1.5 Desorption

Three specimens were removed from the water diffusion process after 500 hours, and left in a dry environment at room-temperature for 250 hours. Figure 5.6 shows the progression of the desorption process. It can be seen that the initial stage of desorption inhibits the same behaviour as the initial stage of the absorption process. There is a rapid decrease during the first 24 hours, consistent with the fact that the water molecules that have bonded at the molecular chain surfaces and ends require little activation energy to break. These water molecules are tied to the *edges* of the epoxy only by one singular H-bond, and are the first molecules to "disappear" during the desorption process.

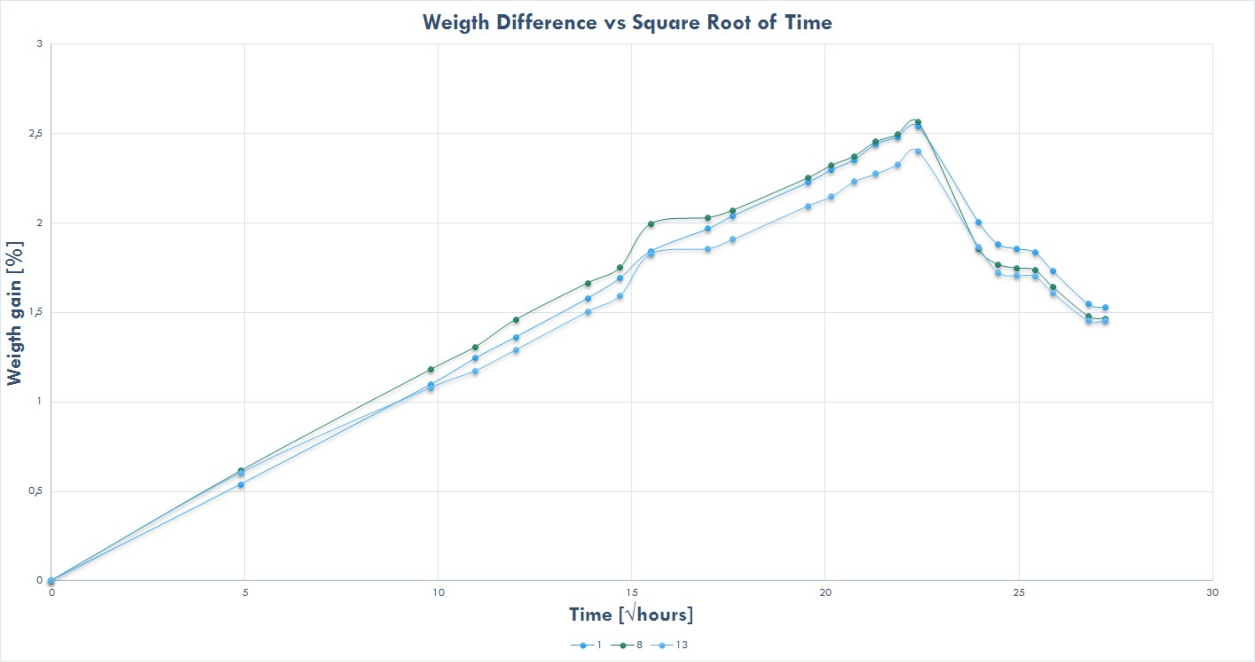


Figure 5.6: Weight percentage difference during water absorption and desorption, plotted against $\sqrt{\text{time}}$.

The results show that the absorption process occurs at a speed approximately twice as high as the absorption process. As the specimens did not reach mass saturation before the desorption process, one can assume that there was not a dominating amount of crosslinking between the epoxy chains caused by the formation of several H-bonds between the water molecules. Hence the majority of the residual water consists of single H-bonded water molecules, which are easily broken.

Reference values for density and typical number of the initial number of epoxy network crosslinks were found, and an attempt to investigate if crosslinking had already occurred after 500 hours of diffusion was done by using the approach by [9], as shown in section 3.4. The attempt proved to be unsuccessful, giving results that no crosslinking by water molecules had occured. This may be due to either wrong reference values or the fact that the model can not be used unless both complete mass saturation and complete desorption data have been acquired.

The curve in figure 5.6 further shows some interesting behaviour. The way it decreases, then stabilizes before decreasing again, indicates that water molcules are "trapped" within the specimens. These molecules are most likely residing within the free volume, and requires the breakage of H-bonds in order to be free to diffuse out of the specimens.

5.2 Tensile Testing

5.2.1 Reference Values

Thirteen epoxy specimens and three CF/Epoxy specimens were made to go through the water diffusion process. In addition there were made three epoxy specimens and one CF/Epoxy specimens which did not undergo water diffusion. These were used to create reference values for the strength and elongation properties for the specimens, as shown in table 5.2. The results of the tensile test is shown in figure 5.7, which were further used to establish a reference value for the tensile elastic modulus by introducing Hooke's Law as follows:

$$E = \frac{\sigma}{\epsilon^*} \tag{5.1}$$

Here ϵ^* represents the corrected strain measurements, which was found by introducing a correction factor (λ) based on the corrected strain gauge measurements. By using equation 4.6 the correction of the GF because of the reinforcement was found by using parameters for the elastic modulus and thickness of the strain gauge provided by Ajovalasit et al. [16] as follows:

$$E_{sg} = 7449\text{MPa}$$

$$t_{sg} = 74.5\mu\text{m}$$

$$C_{Swan,\text{Specimen 11}} = 2.703$$

$$\Rightarrow GF_{act,\text{Specimen 11}} = GF_{cal} \cdot C_{Swan,\text{Specimen 11}} = 2.12 \cdot 2.703 = 5.732 \tag{5.2}$$

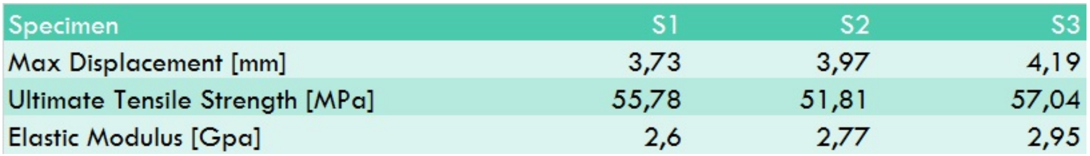
By further applying the corrected GF (GF_{act}) to the strain gauge measurements and comparing the results to the specimen measurements, the correction factor λ can be found by

$$\lambda = \frac{\epsilon_{sg}}{\epsilon_{ave}} = 0.615 \tag{5.3}$$

and the corrected strain measurements can be expressed as

$$\epsilon^* = \epsilon_{ave} \cdot \lambda \tag{5.4}$$

Table 5.2: Mechanical properties of dry specimens.



Specimen	S1	S2	S3
Max Displacement [mm]	3,73	3,97	4,19
Ultimate Tensile Strength [MPa]	55,78	51,81	57,04
Elastic Modulus [Gpa]	2,6	2,77	2,95

The correction factor (C_{Swan}) was calculated for several specimens and yielded values for λ that showed to be consistent, only varying in the range of 0.615 ± 0.01. The tensile elastic modulus values were a bit lower than expected, which can be explained by the fact that the specimens did not inhibit uniform thickness along the length. Consequently the measurements may include a small error. The deviation from the expected values were however consistent for the specimens throughout this study, which in turn created acceptable comparisons.

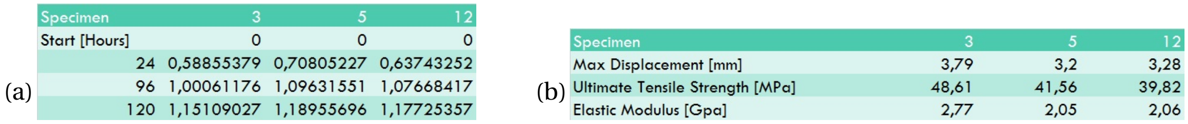
Figure 5.7: Reference stress and strain values from dry specimens tensile test.

5.2.2 Hour 120 of Water Absorption

Three epoxy specimens were tested after being submerged in water for 120 hours. It can be seen from table 5.3a that the weight percentage increase at this time was in the range of 1.15-1.19%.

Figure 5.8 shows that specimens 5 and 12, with their respective maximum values shown in table 5.3b, have suffered more than 20% loss of ultimate tensile strength (σ_{ts}). Specimens 5 and 12 have in addition suffered more than 10% loss of maximum strain. Specimen 3 however seems to be unaffected by it's water uptake. One explanation of this may be that the initial amount of free volume present in specimen 3 was higher than in specimens 5 and 12, and no residual stresses or deformations had occurred. Another possibility is that the specimen contained less microcracks. Figure 5.8 also shows how the affected specimens 5 and 12 have suffered more than 25% decrease in their tensile elastic modulus. The results also indicates that the water-containing specimens have become more brittle, as the small amount of plastic region found in the dry specimen graphs have disappeared.

Table 5.3: Values for (a) weight percentage increase and (b) mechanical properties of specimens after 120 hours of water diffusion.



(a)

Specimen	3	5	12
Start [Hours]	0	0	0
24	0,58855379	0,70805227	0,63743252
96	1,00061176	1,09631551	1,07668417
120	1,15109027	1,18955696	1,17725357

(b)

Specimen	3	5	12
Max Displacement [mm]	3,79	3,2	3,28
Ultimate Tensile Strength [MPa]	48,61	41,56	39,82
Elastic Modulus [Gpa]	2,77	2,05	2,06

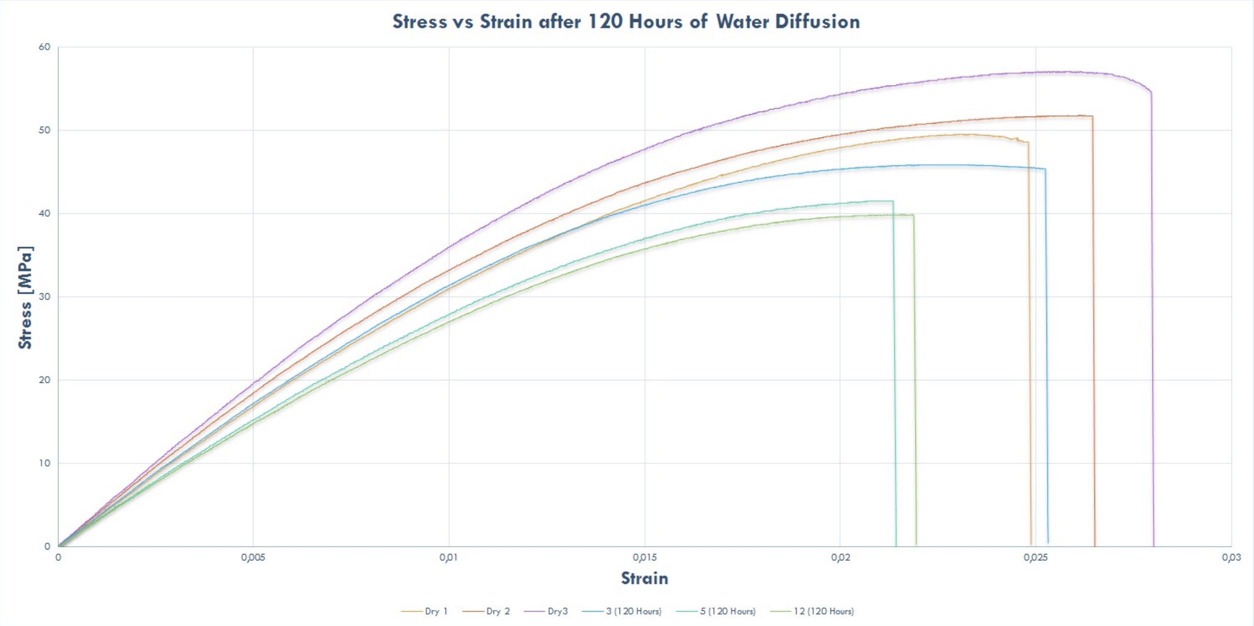


Figure 5.8: Tensile test results after 120 hours of diffusion, compared to reference values.

5.2.3 Hour 310 of Water Absorption

After being submerged in water for 310 hours, the ultimate strength and maximum strain of the specimens have decreased even more. The weight increase for specimens 4, 9 and 11 was now approximately 1.83%, 1.73% and 1.85%, respectively. At this point the specimens show a much higher degree of necking, as indicated by the curves before failure in figure 5.9. This indicates that the specimens have become more plasticized due to the formation of singular H-bonds between the water molecules and the epoxy chains, consequently creating a more ductile fracture. The elastic modulus however remains relatively unchanged in comparison to the results after 120 hours of absorption.

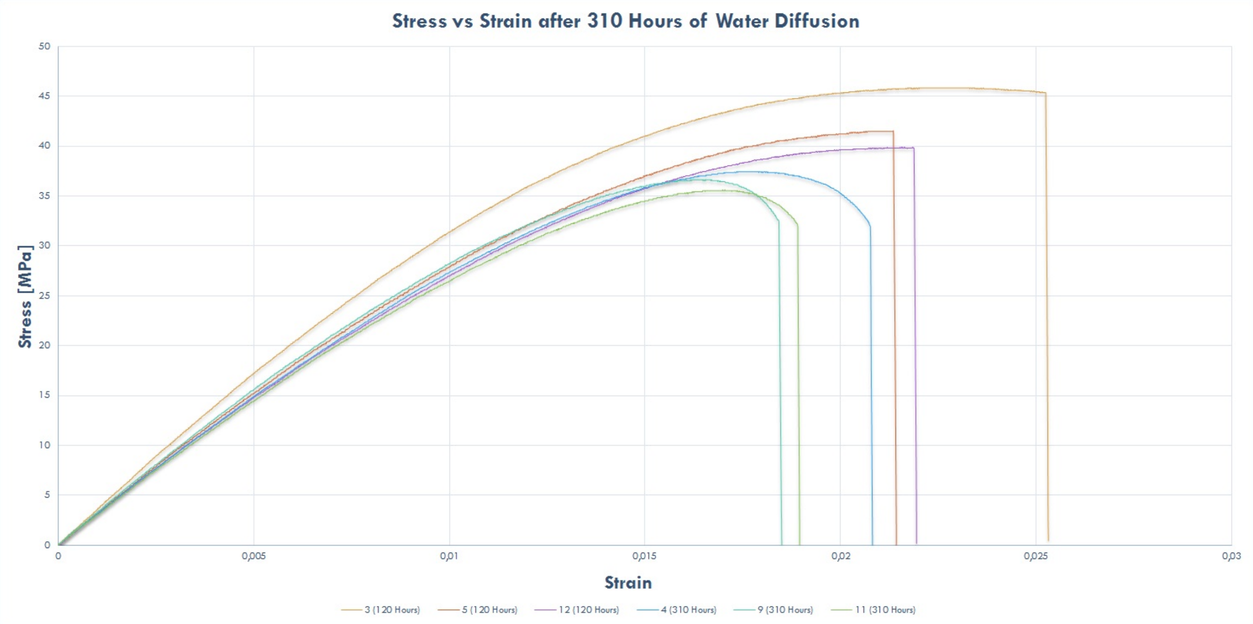


Figure 5.9: Tensile test results after 310 hours of diffusion, compared to results after 120 hours of diffusion.

5.2.4 Hour 742 of Water Absorption

Specimens number 2, 6, 7 and 10, i.e. the last 4 pure epoxy specimens, were removed from the distilled water after 742 hours. Their percentage mass uptake were now 3.02, 3.10, 3.09 and 2.74, respectively. The deviation in uptake between specimen number 10 and the others can be clearly viewed by the results shown in figure 5.10, as both it's tensile strength and elongation properties are higher than the other three specimens. They are also higher than the results after 310 hours of water diffusion. This again indicates that there was either a huge amount of free volume, or a lot less microcracks within this specimen in comparison to the majority of the others.

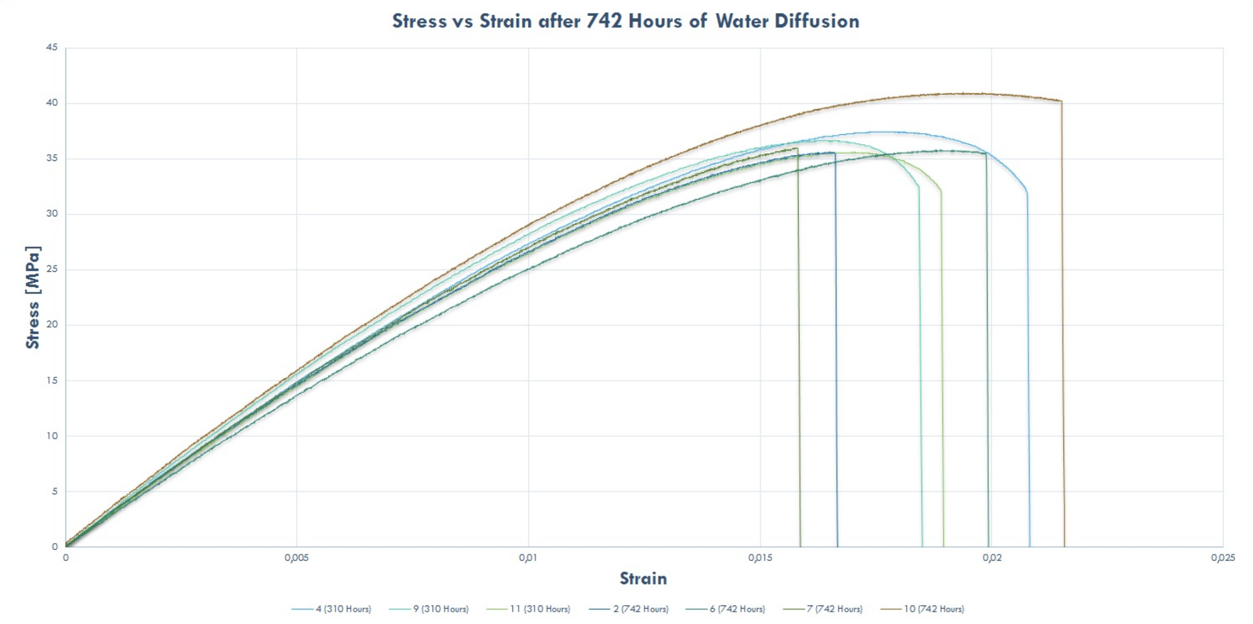


Figure 5.10: Tensile test results after 742 hours of diffusion, compared to results after 310 hours of diffusion.

The tensile elastic modulus remains relatively unchanged from the tests after 310 and 120 hours of water diffusion. Figure 5.11 shows the main difference in the results at this time by comparing specimen number 2, which was removed from water after 742 hours, and specimen number 11, which was tested after 310 hours of water diffusion. The curves are initially near identical but deviates greatly from another towards the end, meaning that necking did not occur for the case of the specimens that underwent 742 hours of water diffusion. Even though the ultimate tensile strength is equal for the two specimens the fracture have changed from ductile to brittle, consequently reducing specimen number 2's maximum elongation properties. Section 5.1.3 shows how the rate of the water absorption curve had started to decrease at this time, indicating that the formation of multiple H-bonds between the water molecules have started to occur. The results show that the new developments have unplasticised the epoxy, rendering it unable to plastically deform.

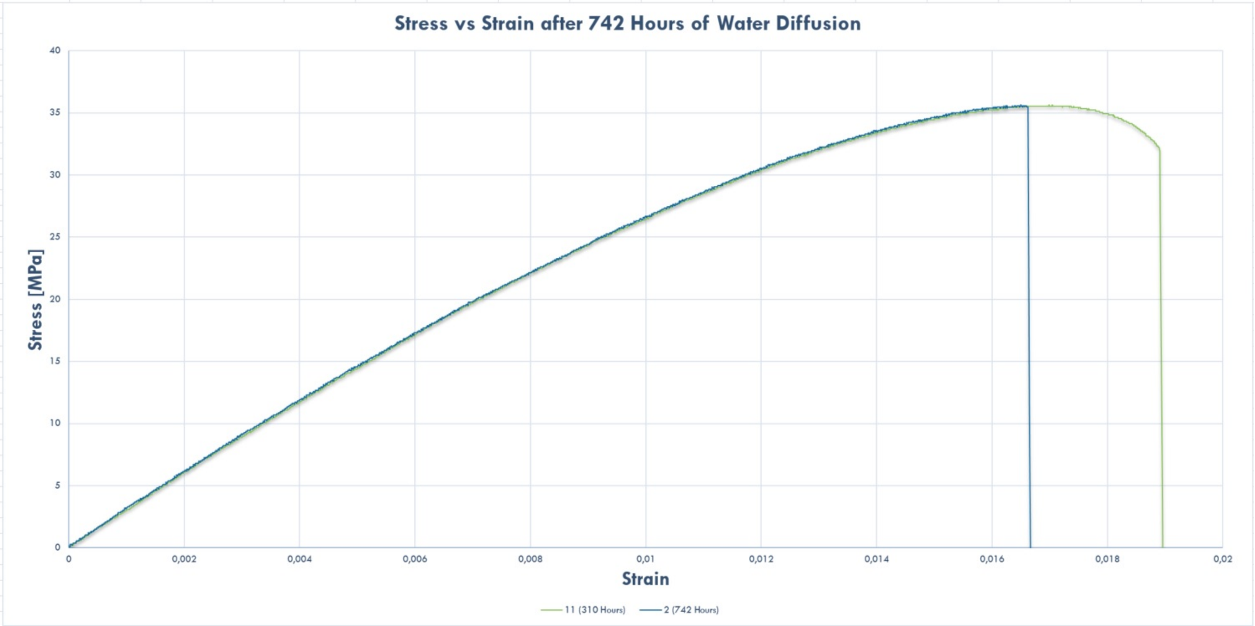


Figure 5.11: Tensile test of specimen 2, compared to tensile test of specimen 11.

5.2.5 Progress of Mechanical Behaviour During Water Absorption

Diffused specimens number 12, 11 and 2, together with dry specimen number 1, show a good representation of the mechanical behaviour of epoxy during a water diffusion process. The progress is shown in figure 5.12, but the following comparisons are based on the average values along the process.

The initial percentage water uptake during the first 120 hours, that on average was 1.17%, shows to have an impact on several mechanical properties. The tensile elastic modulus, along with both tensile strength and maximum tensile strain, have decreased significantly. In comparison to the dry specimens is the average ultiamte tensile strength reduction 21%, and the elastic modulus have decreased by 18%. The maximum strain have suffered a 13% loss on average. In addition have the small amount of plastic region that existed in the dry specimens disappeared, and the fracture have become more brittle.

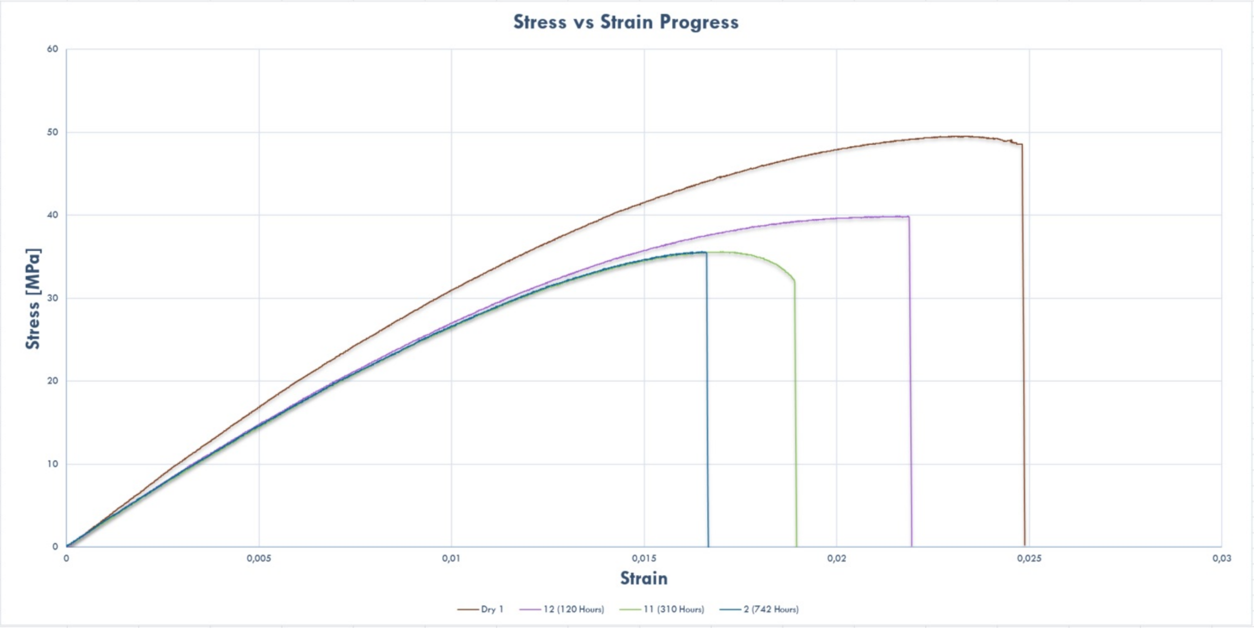


Figure 5.12: Representation of the changes in mechanical behaviour of Epoxy specimens during water diffusion process.

As the percentage water uptake increases to an average of 1.81% after 320 hours, the elastic modulus remains the same compared to the properties after 120 hours. There is an additional decrease in both average ultimate tensile strength and average maximum strain equal to 15%, but the main difference at this point is the plasticity properties. The fracture mode has changed from completely brittle to more ductile.

After 742 hours of water diffusion have the ultimate tensile strength only suffered slightly, deviating only 2% from the results after 310 hours of diffusion. At an average weight percentage increase of 2.99% the maximum strain properties have decreased by 5% on average, but the results show a complete reverse in terms of plasticity. The ductile behaviour that occurred after 310 hours are gone, and the fracture mode have gone back to being brittle without necking. It can be calculated, if compared to the reference results, that the ultimate tensile strength of the specimens have decreased by 35%, whereas the maximum tensile strain properties have decreased by 30%.

5.2.6 Tensile Testing of Carbon Fibre/Epoxy Specimens

Initial desorption is a quick process for the case of CF/Epoxy specimens. Therefore were the tensile tests in the fibre direction of the CF containing specimens performed without the use of tabs to distribute the pressure at the clamps, as the curing time to successfully bond the tabs to the specimens would significantly alter the absorption content properties. This approach provided good results for the water containing specimens, due to the fact that the water had made them softer. Hence they were easy to grip. As shown in figure 5.13, the dry specimen however did not fare as well during testing. The grips did not perform properly, and the results for the dry specimen show values that are too low. They were therefore disregarded as reference values and values were found from [18], giving the tensile strength in fibre direction as 600MPa.

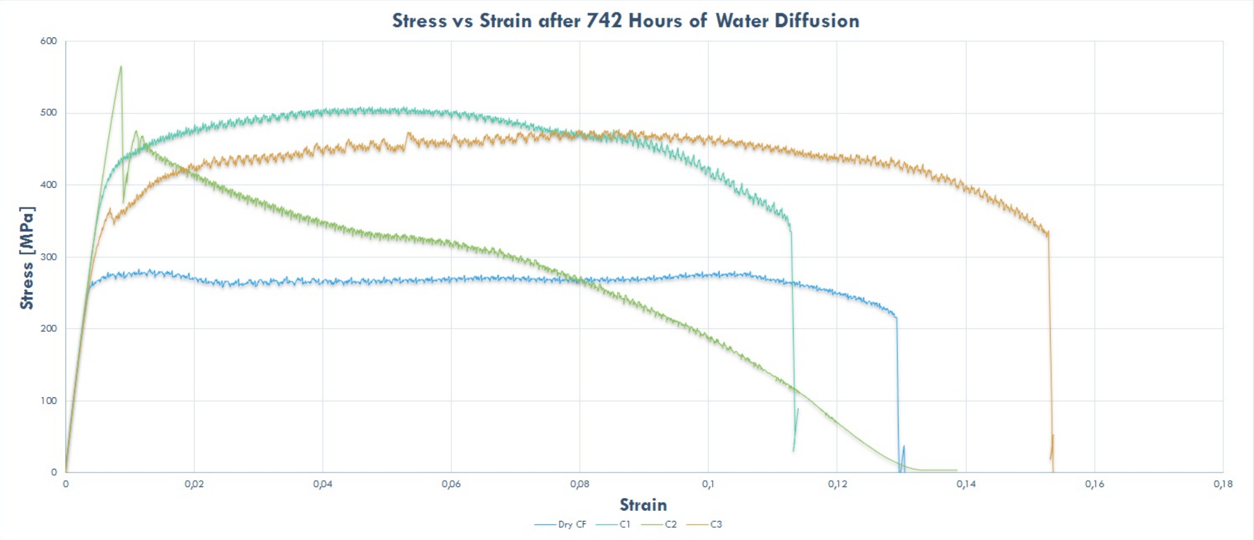


Figure 5.13: Tensile test results for CF/Epoxy specimens after 742 hours of diffusion.

Specimens C1 and C3 show similar behaviour. Crack initiation begins at approximately the same amount of strain, although at a different level of stress. The strength of both specimens have decreased significantly in comparison to the reference strength property of 600MPa. As both failures indicates matrix cracking, the deviations between the two can be explained from the percentage water uptake. At this time specimen C1's water uptake was 0.86%, whereas the uptake of specimen C3 was 0.96%. The results show how more water uptake leads to less strength but increases the maximum elongation properties of CF reinforced epoxy. Specimen 2 however experienced that the matrix cracked without any crack initiation, hence showed relaxing behaviour during the rest of the tensile test. The author chose to disregard this test result, since the crack had occurred in the clamps.

Chapter 6

Summary and Recommendations for Further Work

This study comprise a 742 hour test of water diffusion into epoxy and epoxy based PMCs. The mechanical behaviour of the specimens were tested during the absorption process, providing mechanical properties at different levels of water mass uptake. A 300 hour desorption test was conducted, monitoring the weight change along the process. Further were the macroscopic results relation to the microscopic chain of events discussed.

6.1 Summary and Conclusions

Water diffusion into epoxy can be looked upon on as a 3-stage process. The first stage is the initial reaction, where the ends and available surfaces of the molecular chains bond with the water molecules. These easily accessible reaction sites, where no existing bonds and a larger amount of free volume exists, are the first to yield place for the water. This explains the rapid mass uptake that both the epoxy and CF/epoxy specimens experienced during the first 24 hours of absorption, whereas the process then stabilized and initiated stage two of the process. This stage showed linear Fickian behaviour, which lasted for the next 600 hours. The third stage, as the rate of water absorption decreased, showed non-linear Fickian behaviour.

Diffusion coefficients for the pure epoxy specimens were calculated by linear regression based on Fickian's second law, as the absorption process proved to act linearly Fickian during the first 650 hours. The specimens containing CF reached their saturation mass during the 742 hour diffusion experiment. Hence providing results that show that the diffusion *process* is more accelerated in the transverse direction of a UD CF/epoxy in comparison to a pure epoxy specimen. According to Fickians second law should the diffusivity eventually slow down, but in this study the curves were near linear until the CF containing specimens reached mass saturation. Accordingly have some mechanism within the specimens provided an accelerated diffusion path, which may be an indication that wicking have occurred.

Desorption occurs at a much higher rate than absorption. The initial behaviour is in accordance with the initial behaviour of absorption, as a rapid mass release was experienced during the first 24 hours. After the easily available surfaces and ends of the molecular chains had yielded their H-bonds the rate of desorption decreases. It was observed that the desorption process was approximately twice as fast as the absorption process.

The mechanical behaviour of the pure epoxy specimens experienced several changes during the water absorption process. During the first 120 hours of diffusion in this study the average elastic modulus decreased by 18%, whereas the average ultimate tensile strength decreased by 21%. Further, the maximum strain suffered a 13% loss. After 310 hours of absorption all three properties decreased further, although only by a small degree. At this time the specimens showed a greater plastic region, as necking was observed in the tensile test results. These results show how water acts as a plasticiser, effectively increasing the material's ductility. This plastic behaviour completely disappears after 742 hours of water absorption. Both the elastic modulus and the ultimate tensile strength remain relatively unchanged, but the maximum strain have decreased. This is a clear indication that the formation of multiple H-bonds between the molecules have begun.

The CF containing specimens suffered more than a 15% loss of ultimate tensile strength in the fibre direction due to the water mass uptake. Although de-lamination may be an issue when the interface gets saturated, was the failure of the specimens due to matrix cracking. Even though the strength decreased, it was observed that the elongation properties increased with a higher water mass uptake.

6.2 Oppsummering og konklusjoner

Vanndiffusjon inn i epoxy kan sees på som en tre-trinns prosess. Det første trinnet er den initielle reaksjonen, hvor endene og tilgjengelige overflater av molekylkjedene bindes sammen med vannmolekyler. Disse lett tilgjengelige reaksjons-områdene, hvor ingen eksisterende bindinger og en større mengde fritt volum eksisterer, er de første til å gi plass for vannet. Dette forklarer det raske masseopptaket som både epoxy og CF/epoxy prøvene opplevde i løpet av de første 24 timene av absorbering, mens prosessen deretter stabiliserte seg og begynte trinn to av prosessen. Dette trinnet viste lineær Fickian-oppførsel, som varte de neste 600 timene. Den tredje fasen, når raten av vannabsorbering ble redusert, viste ikke-lineær Fickian-oppførsel.

Diffusjonskoeffisienter for de rene epoxy-prøvene ble beregnet ved lineær regresjon basert på Fickians andre lov, da absorberings-sprosessen viste seg å virke lineært i løpet av de første 650 timene. Prøvene med CF-innhold nådde sin metningsmasse i løpet av det 742 timer lange diffusjons-eksperimentet. Derav gir resultater som viser at *prosessen* er mer akselerert i tverretningen av en UD CF/epoxy i forhold til diffusjonsprosessen til en ren epoxy prøve. Ifølge Fickians andre lov skal diffusivitet etter hvert avta, men i denne studien var kurvene nær lineære inntil prøvene med karbonfiber nådde metningsmasse. Følgelig har en mekanisme i prøvene gitt en akselerert diffusjons-sti. Dette kan være en indikasjon på at "wicking" har foregått.

Masse-avgivelse skjer med en høyere rate enn absorbering. Den innledende opptredenen er i overensstemmelse med den første opptredenen av absorbering, ettersom en stor andel av vannmasse ble avgitt i løpet av de første 24 timene. Etter at de lett tilgjengelige flatene og endene av molekylkjedene hadde gitt bort sine H-bindinger reduseres raten av masse-avgivelse. Det ble observert at masseavgivelses-prosessen var omtrent dobbelt så rask som absorberings-prosessen.

Den mekaniske oppførselen av de rene epoxy prøvene opplevde flere endringer i løpet av vannabsorberings-prosessen. I løpet av de første 120 timene av diffusjon i dette studiet ble den gjennomsnittlige elastisitetsmodul redusert med 18%, mens den gjennomsnittlige maksimale strekkstyrken ble redusert med 21%. Videre led den maksimale strekkbelastningen et 13% tap. Etter 310 timer med absorbering reduseres alle tre egenskapene ytterligere, om enn kun i liten grad. På dette tidspunktet viste prøvene en større plastisk region, ettersom necking ble observert i strekktest-resultatene. Disse resultatene viser hvordan vann fungerer som en mykgjører, som effektivt øker materialets duktilitet. Denne plastiske oppførselen forsvinner helt etter 742 timer med vannabsorbering. Både elastisitetsmodulen og den maksimale strekkfastheten forblir forholdsvis uforandret, men den maksimale strekkbelastningen har gått ned. Dette er en klar indikasjon på at formering av doble eller flere hydrogenbindinger har begynt mellom vannmolekylene.

De CF-inneholdende prøvestykkene hadde mer enn et 15% tap av strekkstyrke ved brudd i fiberretningen på grunn av vannmasse-opptaket. Selv om delaminering kan bli et problem når grensesnittet er blitt mettet feilet prøvene på grunn av sprekkdannelser i matrisen. Selv om styrken ble redusert ble det observert at forlengelsesegenskapene økte med et høyere vannmasse-opptak.

6.3 Discussion

The water diffusion process in this study comprise accurate results. As the weights of the specimens were periodically and accurately performed, it is a clear indication that the behaviour of the absorption process in epoxy behaves linearly Fickian during the initial and first stage of diffusion. It is important to note however, that Fickians second law is based on one-dimensional assumptions. Diffusion will also have occurred in the transverse direction after the water penetrated the two exposed surfaces of the specimens in this study.

The CF containing specimens showed linear Fickian behaviour from start to mass saturation. This behaviour is most likely due to the orientation of the fibres, as fillers or diffusion in the fibre direction should normally show a decreasing rate as the uptake is close to saturation. The orientation of the fibres is therefore most likely the reason that the diffusivity of the CF containing specimens in this study showed higher results than the diffusivity of the pure epoxy specimens.

Some of the epoxy specimens deviated greatly in terms of mechanical properties in comparison to their equally diffused opponents. To provide more accurate results and discussion should the amount of initial free volume and microcracks within the specimens be measured prior to the water absorption process. Minimization of the deviations during the production of specimens will in turn provide less scattered end results. Hence decreasing the safety factor needed for the potential epoxy application.

Temperature changes, as well as induced strain or stress during the absorption process, were not a part of this study. It is worth noting that in the presence of raised temperatures the diffusion process will accelerate, due the increase of segment chain mobility. The presence of induced strain or stress would most likely change the diffusion behaviour from linear Fickian to non-Fickian behaviour.

It is widely known that water absorption may work as a plasticiser in the matrix of composites. What is interesting in this study are the results showing how plasticising occurs, but then disappears later on in the absorption process. This is a clear indicator that the formation of multiple H-bonds between the water molecules have begun. The results also show that the introduction of plasticising does not promote an increased strain to failure for the pure epoxy specimens, even though the specimens felt more pliant during the process. The strain to failure due to water uptake show opposite results for the CF containing specimens. This may indicate that it is the presence of an interface that promotes this sort of behaviour.

The results from the tensile tests are based on parameters acquired externally. These may not be completely accurate for the equipment used in this study, which may induce errors in the results found. The error may be consistent throughout this study, but the results are based on comparisons between the specimens. In addition are not the mechanical behaviour affected by these errors. The author have therefore not found this to be an issue. *However*, the specimens in this study did not exhibit uniform thickness. This may have an impact, as measurements performed of the area may include a small error.

Distilled water was used to induce water diffusion in this study. Should epoxy be exposed to salt-water will the process most likely be slower, but the end result may be worse in terms of mechanical properties as salt water contains several other molecules, such as chlorine.

For the case of the long term properties of PMCs, one can assume that a great amount of the water molecules within the material have created multiple H-bonds. Further will all original Van der Waals forces between the epoxy chains have disappeared, and there will be a high amount of crosslinked bridges formed by the water. The bridges will strengthen the structure, but since the material has swelled will the length of the bridges be longer in comparison to the original Van der Waals forces. Hence will the activation energy to break them be less in comparison, and the macroscopic strength will decrease until saturation is reached. It can be argued that this behaviour will increase the elongation properties of the material, although at a lower amount of stress.

Further assuming that all available reaction sites at the interface have been saturated, de-lamination may be a long term consequence. It seems however from the results in this study that the effects on the matrix is more severe, and matrix cracking will occur prior to de-lamination.

6.4 Recommendations for Further Work

The author reccomends that further tests of water diffusion into epoxy-based PMCs should be performed, where both complete mass saturation and complete desorption is reached. By using this complete set of data, one can evaluate if the degradation model that [9] proposes holds merit through the entire absorption process. If the model proves to show equal results at an early stage of absorption as it does at the end of the process can future predictions of the long term strength degradation be evaluated at a much earlier stage. Hence removing the need to perform real life long term tests.

Further diffusion tests should also be performed to create a relationship between the behaviour of diffusion at the interface in comparison to the behaviour of water diffusion between polymeric chains. Tests to determine the amount of microcracks should be performed prior to diffusion tests, in order to better evaluate the available water diffusion paths.

Appendix A

Additional Information

A.1 Mould CAD-models

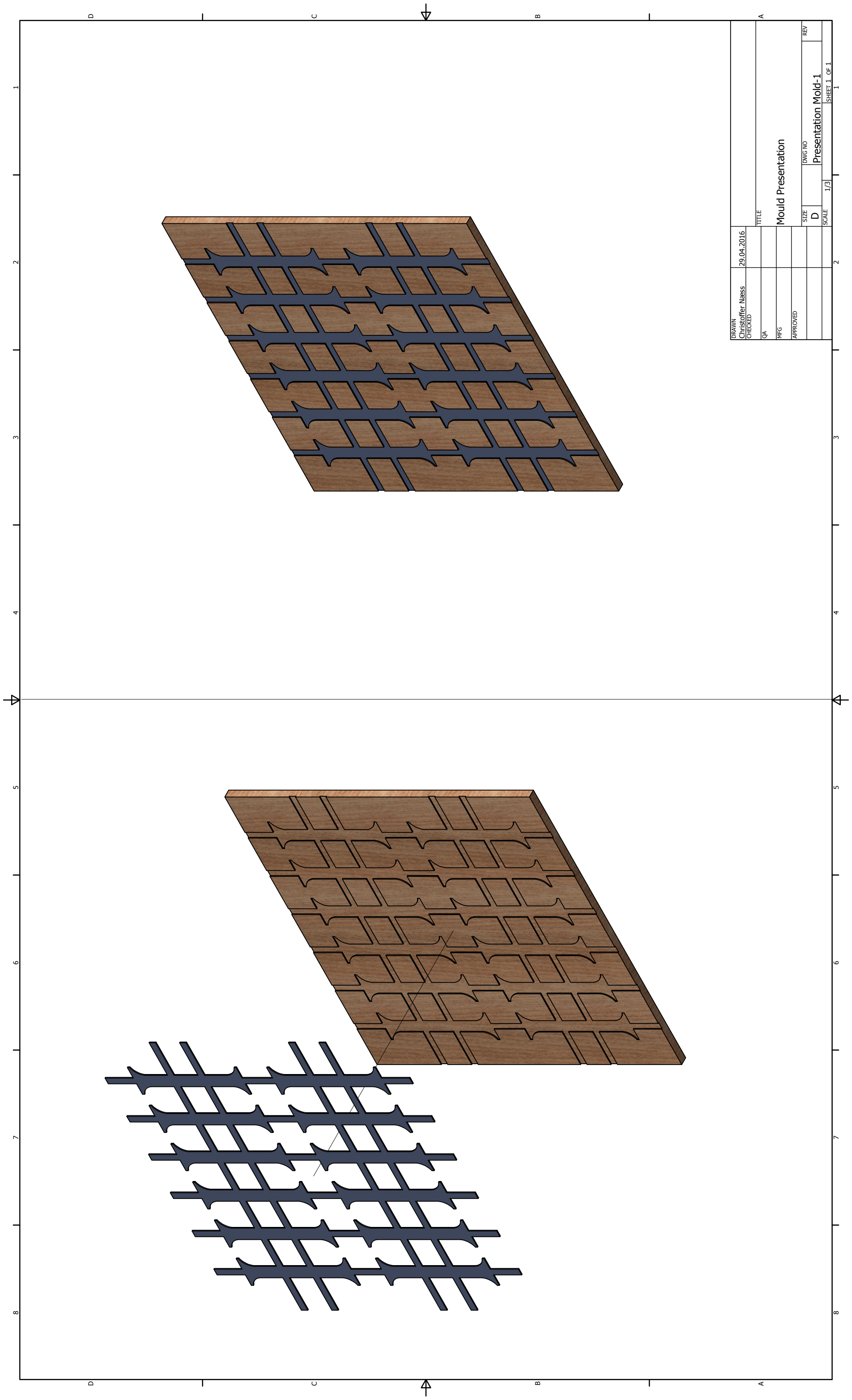


Figure A.1: Illustration of mould with cured epoxy specimens.

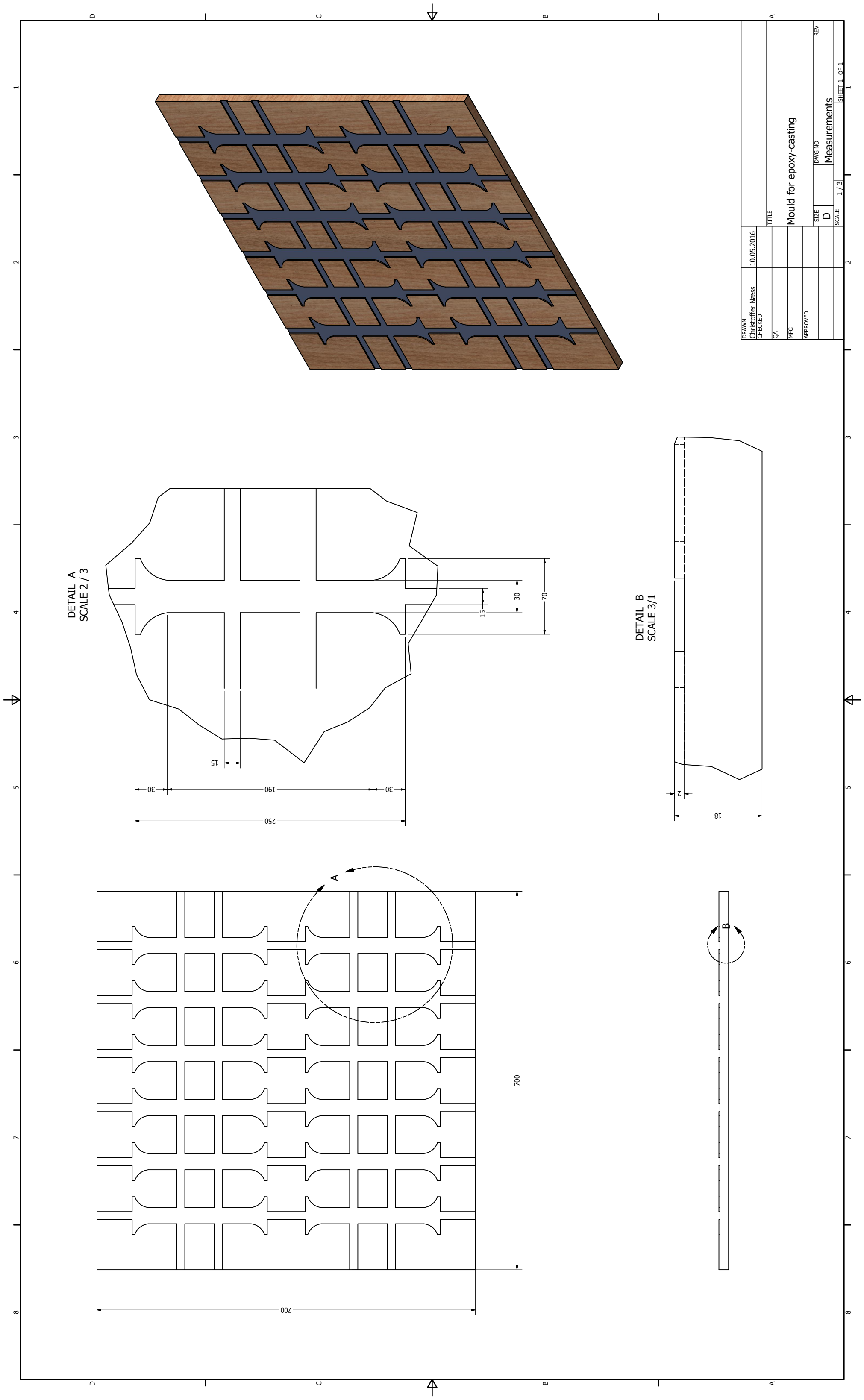


Figure A.2: Mould measurements.

A.2 Weight Percentage Increase

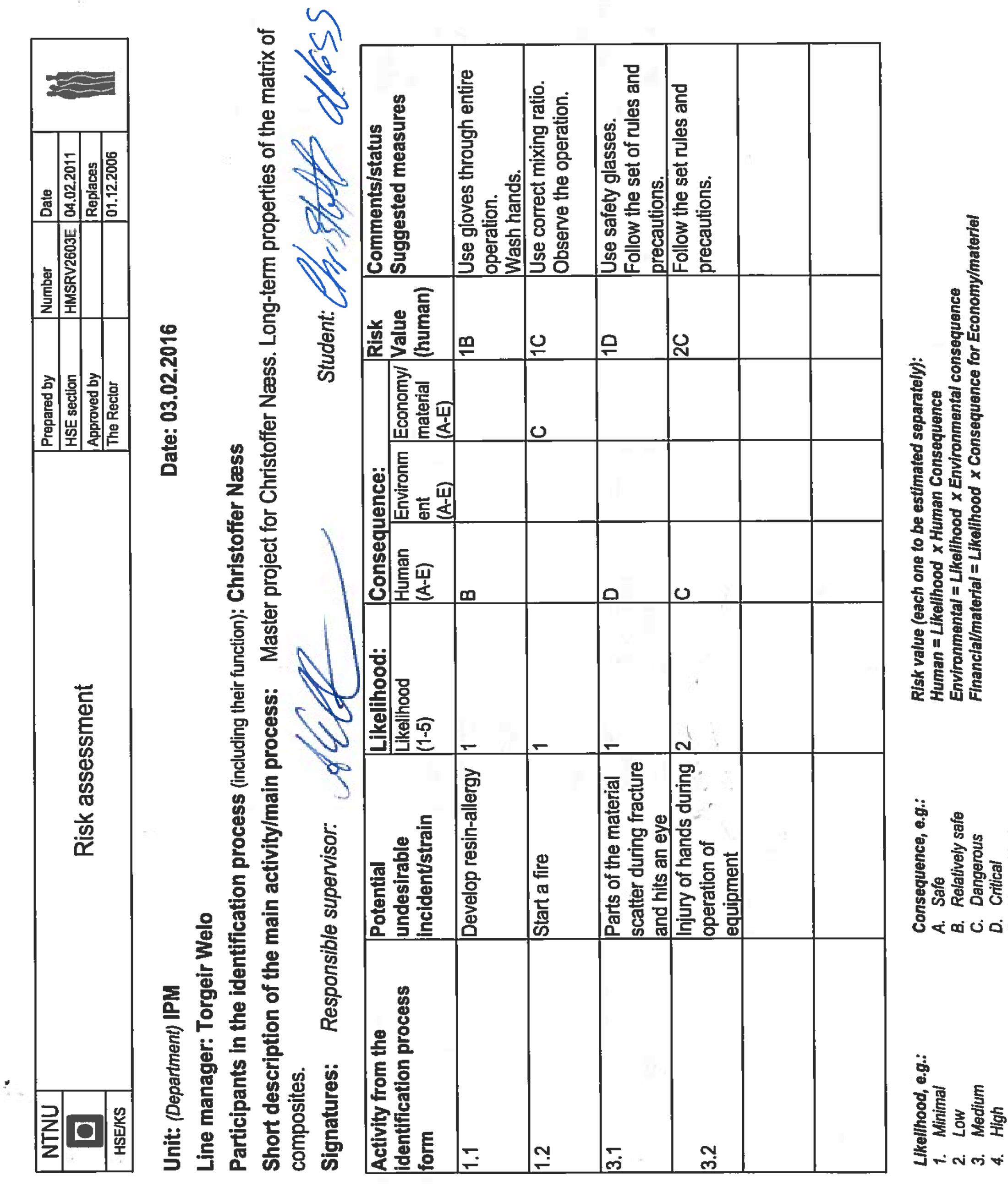
Table A.1: Weight percentage increase during absorption process.

Specimen	1	2	3	4	5	6	7	8	9	10	11	12	13	C1	C2	C3
Hours																
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0,53970234	0,62694344	0,58855379	0,50917751	0,70805227	0,65724507	0,64723793	0,6143937	0,463958	0,53359222	0,48426766	0,63743252	0,60300964	0,27952836	0,24983768	0,3229468
96	1,0967306	1,18917556	1,00061176	1,088846	1,09631551	1,23516747	1,25793823	1,1795421	0,92950218	1,00199123	0,9829531	1,07668417	1,07862288	0,41820347	0,42415944	0,38226356
120	1,2440009	1,32448105	1,15109027	1,20792784	1,18955696	1,35334208	1,42670726	1,30617286	1,02387996	1,1082845	1,0965991	1,17725357	1,17359111	0,38335318	0,37193349	0,38006664
144	1,36181714	1,46314816		1,32427216		1,49013323	1,51718138	1,45859878	1,14442973	1,23300193	1,19921974		1,29095022	0,47483519	0,44886091	0,52359855
192	1,57925741	1,68249433		1,48989173		1,7135318	1,75554589	1,66339667	1,36173655	1,44275399	1,44177763		1,50404966	0,54526181	0,69093527	0,60195526
216	1,69274217	1,76989663		1,55148579		1,8260405	1,84080035	1,74938053	1,43708016	1,52141101	1,51047409		1,59361319	0,55687858	0,59565819	0,5177401
240	1,84174507	1,95814774		1,69315211		1,98711411	2,05480644	1,99482534	1,56159538	1,65463191	1,65549996		1,82755932	0,60261958	0,65353019	0,55435539
288	1,96735797	2,03798639		1,80128389		2,08100626	2,14441061	2,03000055	1,6861106	1,75100447	1,78610805		1,85689909	0,62657915	0,68387771	0,66639815
310	2,03926053	2,09261282		1,82865903		2,15304421	2,1661592	2,07064746	1,73924767	1,82824425	1,84717157		1,90785766	0,64836058	0,68105468	0,6209952
382	2,22638044	2,28170434				2,33597203	2,36537625	2,25121354		1,9990221			2,09470571	0,69555368	0,77350874	0,68983194
406	2,29568411	2,34809648				2,42419827	2,46367986	2,3207823		2,04720838			2,14566428	0,67232016	0,77139147	0,68031196
430	2,35199335	2,43297756				2,47761967	2,48803828	2,37159094		2,13295162			2,23059521	0,65416897	0,74527849	0,68763502
454	2,44122182	2,4749979				2,52861282	2,58373206	2,45366643		2,18397239			2,27460488	0,69555368	0,7692742	0,723518
478	2,48107143	2,52374149				2,58041539	2,62809917	2,49275		2,24987422			2,32710764	0,69990997	0,78268357	0,78063784
502	2,53738067	2,5993781				2,67026047	2,68986516	2,56231875		2,31010707			2,40200128	0,73113002	0,8207944	0,81798543
574	2,00460869	2,75065132				2,82647759	2,83949543	1,85334282		2,47167284			1,86539219	0,80591293	0,95065353	0,97103731
598	1,88246097	2,80191613				2,8968967	2,92214006	1,76892231		2,52907121			1,7233259	0,81970784	0,98382407	0,98934495
622	1,8556058	2,8481385				2,92846389	2,93866899	1,74703551		2,55032986			1,70556761	0,84511951	0,94289021	0,93881586
646	1,8348147	2,88847802				2,96245933	2,97259678	1,73609211		2,62473515			1,70170711	0,86907908	1,00217373	0,94540661
670	1,7299929	2,91537104				2,99888301	2,99782514	1,64072821		2,64670243			1,60828308	0,82842041	0,94924202	0,94687122
718	1,54633817	2,98848643				3,07173037	3,06046107	1,47814056		2,70055769			1,452319	0,83350274	0,95771109	0,94174508
742	1,52641336	3,02462392				3,10491639	3,09264898	1,46563382		2,73528015			1,4538632	0,85673627	0,99511617	0,96224964

Appendix B

Risk Assessments

B.1 Initial Risk Assessment



NTNU	Risk assessment	Prepared by	Number	Date
		HSE section	HMSRV2603E	04.02.2011
		Approved by		Replaces
HSE/KS		The Rector		01.12.2006

Unit: *(Department)* **IPM** **Date: 03.02.2016**

Line manager: Torgeir Welo

Participants in the identification process (including their function)**: Christoffer Næss**

Short description of the main activity/main process: Master project for Christoffer Næss. Long-term properties of the matrix of composites.

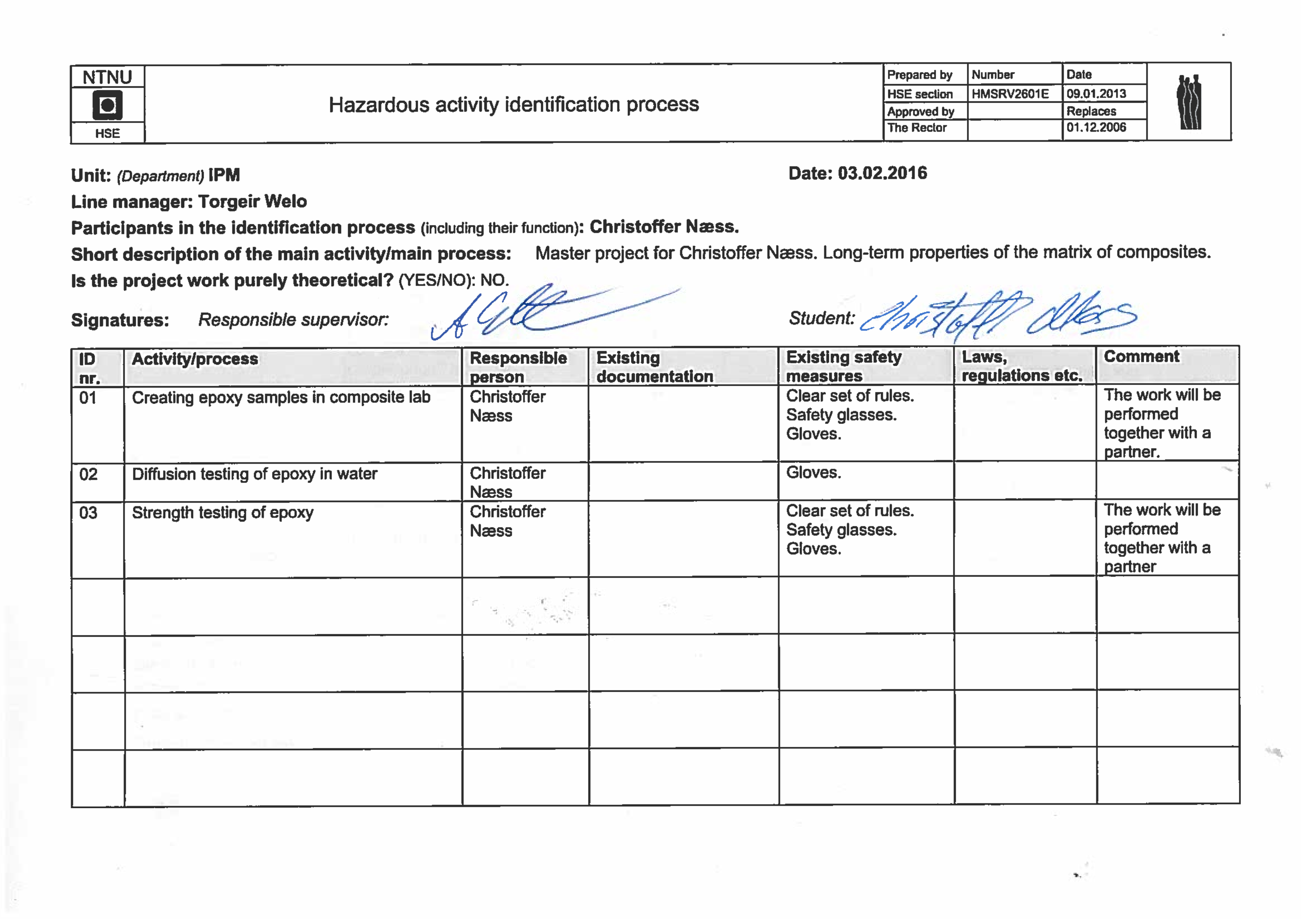
Signatures: *Responsible supervisor:* *Student:*

Activity from the identification process form	Potential undesirable incident/strain	Likelihood:	Consequence:			Risk Value (human)	Comments/status Suggested measures
		Likelihood (1-5)	Human (A-E)	Environment (A-E)	Economy/ material (A-E)		
1.1	Develop resin-allergy	1	B			1B	Use gloves through entire operation. Wash hands.
1.2	Start a fire	1			C	1C	Use correct mixing ratio. Observe the operation.
3.1	Parts of the material scatter during fracture and hits an eye	1	D			1D	Use safety glasses. Follow the set of rules and precautions.
3.2	Injury of hands during operation of equipment	2	C			2C	Follow the set rules and precautions.

Likelihood, e.g.:
1. *Minimal*
2. *Low*
3. *Medium*
4. *High*
5. *Very high*

Consequence, e.g.:
A. *Safe*
B. *Relatively safe*
C. *Dangerous*
D. *Critical*
E. *Very critical*

Risk value (each one to be estimated separately):
Human = Likelihood x Human Consequence
Environmental = Likelihood x Environmental consequence
Financial/material = Likelihood x Consequence for Economy/materiel



NTNU HSE	Hazardous activity identification process	Prepared by	Number	Date
		HSE section	HMSRV2601E	09.01.2013
		Approved by		Replaces
		The Rector		01.12.2006

Unit: *(Department)* **IPM**

Date: 03.02.2016

Line manager: Torgeir Welo

Participants in the identification process (including their function)**: Christoffer Næss.**

Short description of the main activity/main process: Master project for Christoffer Næss. Long-term properties of the matrix of composites.

Is the project work purely theoretical? (YES/NO): NO.

Signatures: *Responsible supervisor:*

Student: Christoffer Næss

ID nr.	Activity/process	Responsible person	Existing documentation	Existing safety measures	Laws, regulations etc.	Comment
01	Creating epoxy samples in composite lab	Christoffer Næss		Clear set of rules. Safety glasses. Gloves.		The work will be performed together with a partner.
02	Diffusion testing of epoxy in water	Christoffer Næss		Gloves.		
03	Strength testing of epoxy	Christoffer Næss		Clear set of rules. Safety glasses. Gloves.		The work will be performed together with a partner

B.2 Mould Forming

Detaljert Risikorapport

ID	7010	**Status**	**Dato**
Risikoområde	Risikovurdering: Helse, miljø og sikkerhet (HMS)	Opprettet	14.04.2016
Opprettet av	Christoffer Næss	Vurdering startet	14.04.2016
Ansvarlig	Christoffer Næss	Tiltak besluttet	
		Avsluttet	14.04.2016

Bearbeiding av tre-form

Gyldig i perioden:

4/14/2016 - 4/14/2019

Sted:

3 - Gløshaugen / 307 - Verkstedteknisk / 1010 - 1. etasje / 148A

Mål / hensikt

Klargjøre tre-form for kompositt.

Bakgrunn

Rutinemessig risikovurdering.

Beskrivelse og avgrensninger

Kun meg selv som berøres av arbeidet. Skal kutte i eksisterende tre-form for hånd. Tar lite plass med minimal mulighet for personskade.

Forutsetninger, antakelser og forenklinger

[Ingen registreringer]

Vedlegg

[Ingen registreringer]

Referanser

[Ingen registreringer]

Oppsummering, resultat og endelig vurdering

I oppsummeringen presenteres en oversikt over farer og uønskede hendelser, samt resultat for det enkelte konsekvensområdet.

Farekilde: **Personskade**

Uønsket hendelse: **Kutt**

Konsekvensområde: Helse Risiko før tiltak: 🟢 Risiko etter tiltak: ⚪

Uønsket hendelse: **Spon i øyet**

Konsekvensområde: Helse Risiko før tiltak: 🟢 Risiko etter tiltak: ⚪

Endelig vurdering

Enkelt generelt arbeid som skal utføres. Ingen usikkerhet i vurderingen.

Oversikt involverte enheter og personell

En risikovurdering kan gjelde for en, eller flere enheter i organisasjonen. Denne oversikten presenterer involverte enheter og personell for gjeldende risikovurdering.

Enhet /-er risikovurderingen omfatter

- Institutt for produktutvikling og materialer

Deltakere

[Ingen registreringer]

Lesere

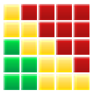
[Ingen registreringer]

Andre involverte/interessenter

[Ingen registreringer]

Følgende akseptkriterier er besluttet for risikoområdet Risikovurdering: Helse, miljø og sikkerhet (HMS):

Helse



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🟩	🟨	🟨	🟥	🟥
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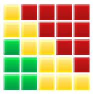
🟩	🟩	🟨	🟨	🟨

Materielle verdier



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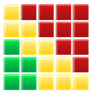
Omdømme



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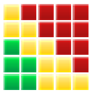
Ytre miljø



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🟨	🟨	🟥	🟥	🟥
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🟩	🟩	🟨	🟨	🟥
🟩	🟩	🟨	🟨	🟨

Oversikt over eksisterende, relevante tiltak som er hensyntatt i risikovurderingen

I tabellen under presenteres eksisterende tiltak som er hensyntatt ved vurdering av sannsynlighet og konsekvens for aktuelle uønskede hendelser.

Farekilde	Uønsket hendelse	Tiltak hensyntatt ved vurdering
Personskade	Kutt	
	Spon i øyet	Personlig verneutstyr

Eksisterende og relevante tiltak med beskrivelse:

Personlig verneutstyr
Vernebriller

Risikoanalyse med vurdering av sannsynlighet og konsekvens

I denne delen av rapporten presenteres detaljer dokumentasjon av de farer, uønskede hendelser og årsaker som er vurdert. Innledningsvis oppsummeres farer med tilhørende uønskede hendelser som er tatt med i vurderingen.

Følgende farer og uønskede hendelser er vurdert i denne risikovurderingen:

- **Personskade**
  - Kutt
  - Spon i øyet

Oversikt over besluttede risikoreduserende tiltak med beskrivelse:

Personskade (farekilde)

Personskade/Kutt (uønsket hendelse)

Mulighet for å kutte meg selv i hånden.

Årsak: Lite fokus

Beskrivelse:

Hendelse kan inntreffe dersom jeg ikke har fokus på arbeidet.

Samlet sannsynlighet vurdert for hendelsen: Svært lite sannsynlig (1)

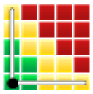
Kommentar til vurdering av sannsynlighet:

Arbeidet kan ikke utføres uten fokus.

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Svært lite sannsynlig (1)

Vurdert konsekvens: Liten (1)



Kommentar til vurdering av konsekvens:

Utstyret som skal brukes til å gjennomføre arbeidet er ikke sterkt nok til å skape dype kutt.

Personskade/Spon i øyet (uønsket hendelse)

Ved kutting kan spon fly i øynene mine.

Årsak: Spon flyr ved kutting

Beskrivelse:

Samlet sannsynlighet vurdert for hendelsen: Svært lite sannsynlig (1)

Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Svært lite sannsynlig (1)

Vurdert konsekvens: Middels (2)

Kommentar til vurdering av konsekvens:

Kan irritere øyet.

Oversikt over besluttede risikoreduserende tiltak:

Under presenteres en oversikt over risikoreduserende tiltak som skal bidra til å reduseres sannsynlighet og/eller konsekvens for uønskede hendelser.

Oversikt over besluttede risikoreduserende tiltak med beskrivelse:

Detaljert Risikorapport

Norges teknisk-naturvitenskapelige universitet (NTNU)	**Utskriftsdato:**	**Utskrift foretatt av:**	**Side:**
Unntatt offentlighet jf. Offentlighetsloven § 14	14.04.2016	Christoffer Næss	7/7

B.3 Specimen Casting

Detaljert Risikorapport

ID	8043	**Status**	**Dato**
Risikoområde	Risikovurdering: Helse, miljø og sikkerhet (HMS)	Opprettet	27.04.2016
Opprettet av	Christoffer Næss	Vurdering startet	27.04.2016
Ansvarlig	Christoffer Næss	Tiltak besluttet	
		Avsluttet	27.04.2016

Støping av epoxy

Gyldig i perioden:

4/27/2016 - 4/27/2019

Sted:

3 - Gløshaugen / 307 - Verkstedteknisk / 1010 - 1. etasje / 104

Mål / hensikt

Støpe epoxy-eksemplarer

Bakgrunn

Rutinemessig risikovurdering

Beskrivelse og avgrensninger

Arbeid gjennomføres i samarbeid med partner. Skal støpe epoxy i eksisterende form. Tar lite plass med minimal mulighet for personskade.

Forutsetninger, antakelser og forenklinger

[Ingen registreringer]

Vedlegg

[Ingen registreringer]

Referanser

[Ingen registreringer]

Oppsummering, resultat og endelig vurdering

I oppsummeringen presenteres en oversikt over farer og uønskede hendelser, samt resultat for det enkelte konsekvensområdet.

Farekilde: **Innånding av epoxy**

Uønsket hendelse: **Innånding**

Konsekvensområde: Helse — Risiko før tiltak: 🟢 Risiko etter tiltak: ⚪

Farekilde: **Epoxy i øyet**

Uønsket hendelse: **Epoxy-sprut**

Konsekvensområde: Helse — Risiko før tiltak: 🟢 Risiko etter tiltak: ⚪

Endelig vurdering

Generell art. Liten usikkerhet ved vurderingen.

Oversikt involverte enheter og personell

En risikovurdering kan gjelde for en, eller flere enheter i organisasjonen. Denne oversikten presenterer involverte enheter og personell for gjeldende risikovurdering.

Enhet /-er risikovurderingen omfatter

- Institutt for produktutvikling og materialer

Deltakere

[Ingen registreringer]

Lesere

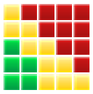
[Ingen registreringer]

Andre involverte/interessenter

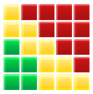
[Ingen registreringer]

Følgende akseptkriterier er besluttet for risikoområdet Risikovurdering: Helse, miljø og sikkerhet (HMS):

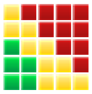
Helse



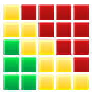
Materielle verdier



Omdømme



Ytre miljø



Oversikt over eksisterende, relevante tiltak som er hensyntatt i risikovurderingen

I tabellen under presenteres eksisterende tiltak som er hensyntatt ved vurdering av sannsynlighet og konsekvens for aktuelle uønskede hendelser.

Farekilde	Uønsket hendelse	Tiltak hensyntatt ved vurdering
Innånding av epoxy	Innånding	Luftavsug
Epoxy i øyet	Epoxy-sprut	Verneutstyr
	Epoxy-sprut	Øyeskyll-stasjon

Eksisterende og relevante tiltak med beskrivelse:

Luftavsug
Finnes luftavsug i rommet.

Verneutstyr
Vernebriller og hansker på plass i rommet.

Øyeskyll-stasjon
Er øyeskyll-stasjon i rom.

Risikoanalyse med vurdering av sannsynlighet og konsekvens

I denne delen av rapporten presenteres detaljer dokumentasjon av de farer, uønskede hendelser og årsaker som er vurdert. Innledningsvis oppsummeres farer med tilhørende uønskede hendelser som er tatt med i vurderingen.

Følgende farer og uønskede hendelser er vurdert i denne risikovurderingen:

- **Innånding av epoxy**
  - Innånding
- **Epoxy i øyet**
  - Epoxy-sprut

Oversikt over besluttede risikoreduserende tiltak med beskrivelse:

Innånding av epoxy (farekilde)

Kan puste inn epoxy under blandeproses

Innånding av epoxy/Innånding (uønsket hendelse)

Innånding av epoxy-blanding

Årsak: Blandeprosess

Beskrivelse:

Det vil bli litt avgasser under blandeprosessen.

Samlet sannsynlighet vurdert for hendelsen: Lite sannsynlig (2)

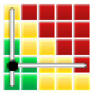
Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Lite sannsynlig (2)

Vurdert konsekvens: Liten (1)



Kommentar til vurdering av konsekvens:

Er svært lite epoxy som brukes, og avgassene blir dermed også små. I tillegg brukes luftavsugstasjon i rom under blanding.

Epoxy i øyet (farekilde)

Kan sprute epoxy i øynene.

Epoxy i øyet/Epoxy-sprut (uønsket hendelse)

Kan sprute epoxy ut av bøtte under blanding

Årsak: Blander for fort

Beskrivelse:

Kan røre sammen blandingen for fort slik at sprut ut av bøtte oppstår.

Samlet sannsynlighet vurdert for hendelsen: Svært lite sannsynlig (1)

Kommentar til vurdering av sannsynlighet:

Har vernebriller på, og er fokusert på oppgaven da blandeforhold spiller en rolle videre.

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Svært lite sannsynlig (1)

Vurdert konsekvens: Middels (2)

Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Oversikt over besluttede risikoreduserende tiltak:

Under presenteres en oversikt over risikoreduserende tiltak som skal bidra til å reduseres sannsynlighet og/eller konsekvens for uønskede hendelser.

Oversikt over besluttede risikoreduserende tiltak med beskrivelse:

B.4 Specimen Brushing

Detaljert Risikorapport

ID	8036	**Status**	**Dato**
Risikoområde	Risikovurdering: Helse, miljø og sikkerhet (HMS)	Opprettet	22.04.2016
Opprettet av	Christoffer Næss	Vurdering startet	22.04.2016
Ansvarlig	Christoffer Næss	Tiltak besluttet	
		Avsluttet	22.04.2016

Smøring av treform

Gyldig i perioden:

4/22/2016 - 4/22/2019

Sted:

3 - Gløshaugen / 307 - Verkstedteknisk / 1010 - 1. etasje / 104

Mål / hensikt

Klargjøre treform for kompositt

Bakgrunn

Rutinemessig risikovurdering

Beskrivelse og avgrensninger

Kun meg selv som berøres av arbeidet. Skal pensle på tynne lag med epoxy, sealing agent og release agent for hånd. Minimal mulighet for personskade.

Forutsetninger, antakelser og forenklinger

[Ingen registreringer]

Vedlegg

[Ingen registreringer]

Referanser

[Ingen registreringer]

Oppsummering, resultat og endelig vurdering

I oppsummeringen presenteres en oversikt over farer og uønskede hendelser, samt resultat for det enkelte konsekvensområdet.

Farekilde: **Luktfare**

Uønsket hendelse: **Avgass**

Konsekvensområde: Helse Risiko før tiltak: 🟢 Risiko etter tiltak: ⚪

Endelig vurdering

Vurderingen er av generell art, og det er svært liten usikkerhet ved vurderingen.

Oversikt involverte enheter og personell

En risikovurdering kan gjelde for en, eller flere enheter i organisasjonen. Denne oversikten presenterer involverte enheter og personell for gjeldende risikovurdering.

Enhet /-er risikovurderingen omfatter

- Institutt for produktutvikling og materialer

Deltakere

[Ingen registreringer]

Lesere

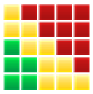
[Ingen registreringer]

Andre involverte/interessenter

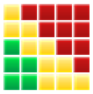
[Ingen registreringer]

Følgende akseptkriterier er besluttet for risikoområdet Risikovurdering: Helse, miljø og sikkerhet (HMS):

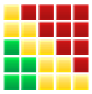
Helse



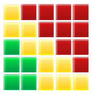
Materielle verdier



Omdømme



Ytre miljø



Oversikt over eksisterende, relevante tiltak som er hensyntatt i risikovurderingen

I tabellen under presenteres eksisterende tiltak som er hensyntatt ved vurdering av sannsynlighet og konsekvens for aktuelle uønskede hendelser.

Farekilde	Uønsket hendelse	Tiltak hensyntatt ved vurdering
Luktfare	Avgass	Avtrekk

Eksisterende og relevante tiltak med beskrivelse:

Verneutstyr
Vernebriller

Verneutstyr
Engangshansker

Avtrekk
Luktavtrekk-skap på lab.

Risikoanalyse med vurdering av sannsynlighet og konsekvens

I denne delen av rapporten presenteres detaljer dokumentasjon av de farer, uønskede hendelser og årsaker som er vurdert. Innledningsvis oppsummeres farer med tilhørende uønskede hendelser som er tatt med i vurderingen.

Følgende farer og uønskede hendelser er vurdert i denne risikovurderingen:

- **Luktfare**
    - Avgass

Oversikt over besluttede risikoreduserende tiltak med beskrivelse:

Luktfare (farekilde)

Kan lukte inn gass fra epoxy-blanding under laging.

Luktfare/Avgass (uønsket hendelse)

Mulighet for å innhalere avgass fra epoxy-blanding

Årsak: Blanding

Beskrivelse:

Det vil bli gasser når epoxy resin og curing agent blandes sammen.

Samlet sannsynlighet vurdert for hendelsen: Sannsynlig (3)

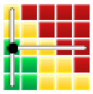
Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Sannsynlig (3)

Vurdert konsekvens: Liten (1)



Kommentar til vurdering av konsekvens:

Til penslingen brukes svært lite epoxy, så avgassene som kommer vil være begrenset

Oversikt over besluttede risikoreduserende tiltak:

Under presenteres en oversikt over risikoreduserende tiltak som skal bidra til å reduseres sannsynlighet og/eller konsekvens for uønskede hendelser.

Oversikt over besluttede risikoreduserende tiltak med beskrivelse:

Detaljert Risikorapport

Norges teknisk-naturvitenskapelige universitet (NTNU)	**Utskriftsdato:**	**Utskrift foretatt av:**	**Side:**
Unntatt offentlighet jf. Offentlighetsloven § 14	22.04.2016	Christoffer Næss	7/7

B.5 Specimen Coating

Detaljert Risikorapport

ID	8063	**Status**	**Dato**
Risikoområde	Risikovurdering: Helse, miljø og sikkerhet (HMS)	Opprettet	12.05.2016
Opprettet av	Christoffer Næss	Vurdering startet	12.05.2016
Ansvarlig	Christoffer Næss	Tiltak besluttet	
		Avsluttet	12.05.2016

Coating av epoxy specimens

Gyldig i perioden:

5/12/2016 - 5/12/2019

Sted:

3 - Gløshaugen / 307 - Verkstedteknisk / 1010 - 1. etasje / 104

Mål / hensikt

Coate kantene på epoxy-specimens

Bakgrunn

Rutinemessig sikkerhetsvurdering

Beskrivelse og avgrensninger

Arbeid utføres i samarbeid med partner.

Forutsetninger, antakelser og forenklinger

[Ingen registreringer]

Vedlegg

[Ingen registreringer]

Referanser

[Ingen registreringer]

Detaljert Risikorapport

Oppsummering, resultat og endelig vurdering

I oppsummeringen presenteres en oversikt over farer og uønskede hendelser, samt resultat for det enkelte konsekvensområdet.

Farekilde: **Løsemiddelskade**

Uønsket hendelse: **Løsemiddelskade**

Konsekvensområde: Helse Risiko før tiltak: 🟢 Risiko etter tiltak: ⚪

Farekilde: **Brann**

Uønsket hendelse: **Brann**

Konsekvensområde: Materielle verdier Risiko før tiltak: 🟢 Risiko etter tiltak: ⚪

Endelig vurdering

Liten usikkerhet ved vurderingen.

Oversikt involverte enheter og personell

En risikovurdering kan gjelde for en, eller flere enheter i organisasjonen. Denne oversikten presenterer involverte enheter og personell for gjeldende risikovurdering.

Enhet /-er risikovurderingen omfatter

- Institutt for produktutvikling og materialer

Deltakere

[Ingen registreringer]

Lesere

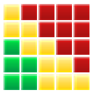
[Ingen registreringer]

Andre involverte/interessenter

[Ingen registreringer]

Følgende akseptkriterier er besluttet for risikoområdet Risikovurdering: Helse, miljø og sikkerhet (HMS):

Helse



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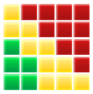
Materielle verdier



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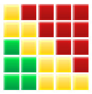
Omdømme



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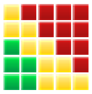
Ytre miljø



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Oversikt over eksisterende, relevante tiltak som er hensyntatt i risikovurderingen

I tabellen under presenteres eksisterende tiltak som er hensyntatt ved vurdering av sannsynlighet og konsekvens for aktuelle uønskede hendelser.

Farekilde	Uønsket hendelse	Tiltak hensyntatt ved vurdering
Løsemiddelskade	Løsemiddelskade	Verneutsyr
	Løsemiddelskade	Gassmaske
	Løsemiddelskade	Verneutsyr
Brann	Brann	Verneutsyr
	Brann	Gassmaske
	Brann	Verneutsyr

Eksisterende og relevante tiltak med beskrivelse:

Verneutsyr
Vernebriller

Gassmaske
Maske for å unngå avgasser.

Verneutsyr
Hansker

Risikoanalyse med vurdering av sannsynlighet og konsekvens

I denne delen av rapporten presenteres detaljer dokumentasjon av de farer, uønskede hendelser og årsaker som er vurdert. Innledningsvis oppsummeres farer med tilhørende uønskede hendelser som er tatt med i vurderingen.

Følgende farer og uønskede hendelser er vurdert i denne risikovurderingen:

- **Løsemiddelskade**
  - Løsemiddelskade
- **Brann**
  - Brann

Oversikt over besluttede risikoreduserende tiltak med beskrivelse:

Løsemiddelskade (farekilde)

Ved lang eksponering av komponentene kan løsemiddelskader oppstå.

Løsemiddelskade/Løsemiddelskade (uønsket hendelse)

Kan blir løsemiddelskadet under lang eksponering av komponentene i bruk.

Årsak: Blandeprosess

Beskrivelse:

Det vil bli avgasser under blanding.

Samlet sannsynlighet vurdert for hendelsen: Svært lite sannsynlig (1)

Kommentar til vurdering av sannsynlighet:

Det brukes gassmaske, og prosessen er over på kort tid.

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen): Svært lite sannsynlig (1)

Vurdert konsekvens: Middels (2)

Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Brann (farekilde)

Ved feil mikse-ratio kan blandingen bli veldig varm.

Brann/Brann (uønsket hendelse)

Ved feil blandeforhold vil blnadingen bli veldig varm.

Årsak: Blandeforhold

Beskrivelse:

Feil blandeforhold av komponenter.

Samlet sannsynlighet vurdert for hendelsen: Svært lite sannsynlig (1)

Kommentar til vurdering av sannsynlighet:

Blandingen blir utført med svært god nøyaktighet, med informasjon om korrekt blandeforhold.

Vurdering av risiko for følgende konsekvensområde: Materielle verdier

Vurdert sannsynlighet (felles for hendelsen): Svært lite sannsynlig (1)

Vurdert konsekvens: Middels (2)

Kommentar til vurdering av konsekvens:

[Ingen registreringer]

Oversikt over besluttede risikoreduserende tiltak:

Under presenteres en oversikt over risikoreduserende tiltak som skal bidra til å reduseres sannsynlighet og/eller konsekvens for uønskede hendelser.

Oversikt over besluttede risikoreduserende tiltak med beskrivelse:

B.6 Specimen Tensile Test

Detaljert Risikorapport

ID	8062	**Status**	**Dato**
Risikoområde	Risikovurdering: Helse, miljø og sikkerhet (HMS)	Opprettet	12.05.2016
Opprettet av	Christoffer Næss	Vurdering startet	12.05.2016
Ansvarlig	Christoffer Næss	Tiltak besluttet	
		Avsluttet	12.05.2016

Strekktest av epoxy

Gyldig i perioden:

5/12/2016 - 5/12/2019

Sted:

3 - Gløshaugen / 307 - Verkstedteknisk / 1010 - 1. etasje / 102F

Mål / hensikt

Strekkteste epoxy-biter.

Bakgrunn

Rutinemessig risikovurdering

Beskrivelse og avgrensninger

Arbeid utføres i samarbeid med en partner. Skal teste preparerte epoxy-eksemplarer.

Forutsetninger, antakelser og forenklinger

[Ingen registreringer]

Vedlegg

[Ingen registreringer]

Referanser

[Ingen registreringer]

Oppsummering, resultat og endelig vurdering

I oppsummeringen presenteres en oversikt over farer og uønskede hendelser, samt resultat for det enkelte konsekvensområdet.

Farekilde: **Flygende epoxy-biter under failure**

Uønsket hendelse: **Flygende biter treffer personer**

Konsekvensområde: Helse Risiko før tiltak: 🟢 Risiko etter tiltak: ⚪

Endelig vurdering

Liten usikkerhet ved vurderingen.

Oversikt involverte enheter og personell

En risikovurdering kan gjelde for en, eller flere enheter i organisasjonen. Denne oversikten presenterer involverte enheter og personell for gjeldende risikovurdering.

Enhet /-er risikovurderingen omfatter

- Institutt for produktutvikling og materialer

Deltakere

[Ingen registreringer]

Lesere

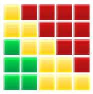
[Ingen registreringer]

Andre involverte/interessenter

[Ingen registreringer]

Følgende akseptkriterier er besluttet for risikoområdet Risikovurdering: Helse, miljø og sikkerhet (HMS):

Helse



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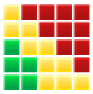
Materielle verdier



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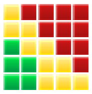
Omdømme



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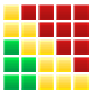
Ytre miljø



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Oversikt over eksisterende, relevante tiltak som er hensyntatt i risikovurderingen

I tabellen under presenteres eksisterende tiltak som er hensyntatt ved vurdering av sannsynlighet og konsekvens for aktuelle uønskede hendelser.

Farekilde	Uønsket hendelse	Tiltak hensyntatt ved vurdering
Flygende epoxy-biter under failure	Flygende biter treffer personer	Beskyttelses-skjerm

Eksisterende og relevante tiltak med beskrivelse:

Verneutstyr
Vernebriller

Beskyttelses-skjerm
[Ingen registreringer]

Risikoanalyse med vurdering av sannsynlighet og konsekvens

I denne delen av rapporten presenteres detaljer dokumentasjon av de farer, uønskede hendelser og årsaker som er vurdert. Innledningsvis oppsummeres farer med tilhørende uønskede hendelser som er tatt med i vurderingen.

Følgende farer og uønskede hendelser er vurdert i denne risikovurderingen:

- **Flygende epoxy-biter under failure**
  - Flygende biter treffer personer

Oversikt over besluttede risikoreduserende tiltak med beskrivelse:

Flygende epoxy-biter under failure (farekilde)

Flygende epoxy-biter under failure/Flygende biter treffer personer (uønsket hendelse)

Årsak: Failure

Beskrivelse:

Testen kjøres frem til failure, når specimen ryker vil det fly biter.

Samlet sannsynlighet vurdert for hendelsen:	Svært lite sannsynlig (1)

Kommentar til vurdering av sannsynlighet:

[Ingen registreringer]

Vurdering av risiko for følgende konsekvensområde: Helse

Vurdert sannsynlighet (felles for hendelsen):	Svært lite sannsynlig (1)
Vurdert konsekvens:	Middels (2)

Kommentar til vurdering av konsekvens:

Små biter som flyr, ikke stor nok kraft til å være veldig skadelig.

Detaljert Risikorapport

Oversikt over besluttede risikoreduserende tiltak:

Under presenteres en oversikt over risikoreduserende tiltak som skal bidra til å reduseres sannsynlighet og/eller konsekvens for uønskede hendelser.

Oversikt over besluttede risikoreduserende tiltak med beskrivelse:

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