Moisture Content and Mould Risk in Concrete Outer Walls

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Preface

This master thesis is the final part of the two year master program in Civil and Architectural Engineering at the KTH Royal Institute of Technology, Stockholm. The project is equivalent of 30 ECTS and was completed during the spring term of 2018.

The project has been carried out in cooperation with the Department of Construction Research at the Innovation Center Iceland in Reykjavík. The tasks of the department include research projects and services, quality certification, formal reports, education and publications. It has provided valuable advice to the construction industry in Iceland through publications of construction instruction pamphlets with information on maintenance and building technology.
Acknowledgements

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Our co-workers at the Innovation Center Iceland receive gratitude for all the help we have received during the construction of the experiment. Special thanks to Hafsteinn Hilmarsson who was crucial during the construction of the T-beam and to Björn Hjartarson for his assistance with the measurement equipment.

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Finally, we would like to thank our family for their endless love and support during our thesis work.
Abstract

Previous studies on the typical Icelandic external wall have shown that condensation occurs at the interior surface of the concrete and field inspections have supported this conclusion. The primary objective of this study is to analyse the hygrothermal behaviour of the typical Icelandic wall and evaluate the mould risk at the interior surface of the concrete.

A comparative study is performed to compare the hygrothermal performance and mould growth risk of two concrete outer wall structures with interior and exterior insulation, by performing a parametric study using the simulation program WUFI® Pro. Additional parametric studies are performed in order to analyse the effect of various material properties of the Icelandic building materials on the hygrothermal behaviour of the wall. This part also utilized WUFI® Pro.

To investigate the thermal bridge of the Icelandic wall, simulations were conducted with the COMSOL Multiphysics software to evaluate the linear thermal bridge and the risk of condensation at the joint. Lastly, an experiment was set up at the Innovation Center Iceland to model the interior insulated wall-slab section. The experimental set-up was completed during this time but the results will be analysed further after the thesis work.

The results from this study indicate that the typical Icelandic wall is more sensitive to rain than to interior moisture load and that no condensation occurs within the wall structure. As concrete is inorganic, the risk of mould growth in the wall structure is limited, however, with increased driving rain load the mould risk increases. The results also revealed that the moisture content of the interior insulated wall was a great deal higher compared to the exterior insulated wall. Furthermore, the humidity level at the interior surface of the concrete in the interior insulated wall exceeded the recommended critical humidity level based on general suggestions. Finally, results indicated that using a more dense concrete resulted in higher relative humidity at the interior surface but a lower total water content of the wall.
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**Nomenclature**

**Moisture mechanics**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V$</td>
<td>Volume</td>
<td>$m^3$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Bulk density</td>
<td>$kg/m^3$</td>
</tr>
<tr>
<td>$u$</td>
<td>Absolute humidity</td>
<td>$kg/m^3$</td>
</tr>
<tr>
<td>$x$</td>
<td>Humidity ratio</td>
<td>$kg/kg$</td>
</tr>
<tr>
<td>$RH$</td>
<td>Relative humidity</td>
<td>%</td>
</tr>
<tr>
<td>$w$</td>
<td>Mass concentration of water</td>
<td>$kg/m^3$</td>
</tr>
<tr>
<td>$u$</td>
<td>Moisture ratio of water to dry matter</td>
<td>$kg/kg$</td>
</tr>
<tr>
<td>$n$</td>
<td>Porosity</td>
<td>%</td>
</tr>
<tr>
<td>$\rho_{\text{particle}}$</td>
<td>Packed density</td>
<td>$kg/m^3$</td>
</tr>
<tr>
<td>$S$</td>
<td>Degree of saturation</td>
<td>%</td>
</tr>
<tr>
<td>$S_{\text{cap}}$</td>
<td>capillary saturation ratio</td>
<td>%</td>
</tr>
<tr>
<td>$m_w$</td>
<td>Water mass absorption</td>
<td>$kg/m^2$</td>
</tr>
<tr>
<td>$A$</td>
<td>Water absorption coefficient</td>
<td>$kg/m^2 s^{0.5}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Water vapour diffusion resistance factor</td>
<td>[-]</td>
</tr>
<tr>
<td>$sd$</td>
<td>Vapour diffusion thickness</td>
<td>[m]</td>
</tr>
<tr>
<td>$g_w$</td>
<td>Liquid transport flux density</td>
<td>$kg/m^2 s$</td>
</tr>
<tr>
<td>$D_w$</td>
<td>Liquid transport coefficient</td>
<td>$m^2/s$</td>
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<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
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<tr>
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<td>-------------------------------------</td>
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</tr>
<tr>
<td>$w_{bm}$</td>
<td>Built-in moisture</td>
<td>$kg/m^3$</td>
</tr>
<tr>
<td>$v$</td>
<td>Vapour content</td>
<td>$kg/m^3$</td>
</tr>
<tr>
<td>$n$</td>
<td>Air change rate</td>
<td>$s^{-1}$</td>
</tr>
<tr>
<td>$C_{RP}$</td>
<td>Driving rain protection coefficient</td>
<td>-</td>
</tr>
<tr>
<td>$G$</td>
<td>Moisture production</td>
<td>$kg/s$</td>
</tr>
<tr>
<td>$R_{L}$</td>
<td>Air flow rate</td>
<td>$m^3/s$</td>
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**Mould**

<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>$a_w$</td>
<td>Water activity</td>
<td></td>
</tr>
<tr>
<td>$M$</td>
<td>Mould Index</td>
<td>$[-]$</td>
</tr>
<tr>
<td>$M_{max}$</td>
<td>Largest possible mould Index</td>
<td>$[-]$</td>
</tr>
<tr>
<td>$R_{H_{crit}}$</td>
<td>Critical relative humidity</td>
<td>$%$</td>
</tr>
<tr>
<td>$w/b$</td>
<td>Water-to-binder ratio</td>
<td></td>
</tr>
<tr>
<td>$w/c$</td>
<td>Water-to-cement ratio</td>
<td></td>
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**Thermal mechanics**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>$\lambda$</td>
<td>Thermal conductivity</td>
<td>$W/mK$</td>
</tr>
<tr>
<td>$R$</td>
<td>Thermal resistance</td>
<td>$m^2K/W$</td>
</tr>
<tr>
<td>$U$</td>
<td>Thermal transmittance</td>
<td>$W/m^2K$</td>
</tr>
<tr>
<td>$\Psi$</td>
<td>Linear thermal bridge value</td>
<td>$W/mK$</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td>$^\circ C$</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>Transmission heat flow</td>
<td>$W$</td>
</tr>
<tr>
<td>$l_{hb}$</td>
<td>Distribution of thermal bridge</td>
<td>$m$</td>
</tr>
<tr>
<td>$\chi$</td>
<td>Point thermal transmittance</td>
<td>$W/K$</td>
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Chapter 1

Introduction

In this chapter, the background and aim of this thesis is discussed.

1.1 Background

In recent years, the topic of moisture damage and mould in buildings has become more conspicuous in Iceland. News of sky-high costs due to mould and moisture damage in many buildings could explain this awakening, as well as awareness of the negative health effect of mould exposure on humans [1–3].

The urgency of research on moisture problems which origin in exterior concrete wall structures is immense. The occurrence of mould in buildings in Iceland has increased over and above reasonable limits. The impacts of the mould in buildings has had a drastic effect on the inhabitants living or working in these constructions. The call for building moisture safe constructions is of great importance in Iceland.

The World Health Organization [4] states that people living in buildings with mould problems are at increased risk of precarious health problems. These health problems are e.g. respiratory symptoms such as allergic rhinitis and asthma [4]. Moisture damages are directly associated with adverse effects relating to sickness and bad health caused by poor indoor climate and the sick building syndrome [4]. The sick-building syndrome (SBS) is described as a medical condition when people in a specific building suffer from symptoms of illness or feel unwell for no apparent reason. The symptoms tend to increase in severity with the time people spend in the building, and improve over time or even disappear when people are away from the building [4]. A study
CHAPTER 1. INTRODUCTION

done in U.S.A showed that people spend around 87% of their time indoors, which supports the critical importance for satisfactory indoor air quality in buildings [5].

There have been many conjectures on the cause of the increased moisture problems in Icelandic buildings. A report by the Ministry for the Environment and Natural Resources of Iceland in 2015 included poor design and manufacturing of buildings, dereliction of proper building maintenance and wrong behaviour of the inhabitants as factors contributing predominantly to the increased moisture and mould problems in Icelandic buildings [6]. The report also reaffirms the urgency of further research in this field which could lead to more advanced and improved building design and practice.

1.1.1 Most common exterior wall type

In Iceland, the most common exterior wall structure of buildings has encountered major moisture problems. This wall is a concrete wall insulated on the interior side of the structure and coated on the exterior [7]. Due to difference in vapour pressure between the inside and the outside of the building, the conjecture is that vapour migrates through the walls from the interior towards the exterior, which can cause condensation on the cold concrete interior surface. To allow for the water vapour to dry out, water vapour open exterior surface treatments have commonly been applied [8].

The concrete and the screed serve as the rain control layer of the building envelope while the concrete provides structural support of the building. At both the concrete floor slab connection and the interior wall connection to the outer wall the insulation generally gets disconnected at the joints resulting in thermal bridges and cracks from thermal expansion. Because of this thermal bridge there is a risk of condensation surrounding this junction [7].

This method of insulating on the interior side of the wall is suspected to be the cause of moisture and mould problems in many buildings and experts claim to have seen condensation on the concrete surface which is expected to be due to warm moist air from inside of buildings. Yet, the Icelandic building code Byggingarreglugerð, does not explicitly prohibit this construction method. Section 10.5 in the building code states [9]:

"Buildings should be designed and built so that water and moisture can not cause damage to the building as a whole nor its components, or create circumstances which can cause discomfort, accidents or be dangerous to the health of people, e.g due to mould or dangerous micro-organisms".

"Building components should be designed and constructed so no damage can occur due to accumulated moisture condensation"

These statement can be interpreted in different ways and do not exclude any types of building components. However, with these statements in mind, the most common exterior wall type in Iceland will be studied in this thesis.

1.1.2 Climate and location

Iceland is an island located in the North Atlantic in close proximity to the Arctic circle. Iceland is in the tempered climate zone and thermal weather changes are therefore limited. From Köppen’s classification two climate types exist in Iceland. In the southern and western part there is a temperate rainy climate with cool and short summers, while other parts of Iceland, especially the highlands and the north, have a snow climate [10]. Although Iceland is situated just south of the Arctic Circle, the average air temperature is seldom really low or high. The average temperature fluctuation between the warmest month and the coldest month is on the average around 12 °C, and the mean yearly temperature around 5°C [7]. Iceland lies in the path of extra-tropical cyclones which travel over the Atlantic, meeting with cold polar masses and creating weather fronts resulting in rapid change of weather and strong winds [10]. With the North Atlantic ocean drift passing from the south-east direction, and the East Greenland ocean current passing from the north, this results in a temperature front at the South-east and North-west coasts of Iceland [10]. There is more precipitation on the southern part of the country compared to the northern part since atmospheric clouds precipitate as they cross the high-altitude mountains on the southern coast. In the capital city Reykjavík, precipitation is measured around 200 days per year [7]. The mean yearly precipitation in Iceland the years 1971-2000 can be seen in figure 1.1 and the monthly mean temperature and precipitation in Reykjavík (South-West Iceland) and Akureyri (North-Iceland)
the year 1961-1990 can be seen in figure 1.2.

Figure 1.1: The mean yearly precipitation in Iceland (1971-2000) [11].

Figure 1.2: Monthly mean temperature (°C) and precipitation (mm) the years 1961–1990 at Reykjavík (Southwest-Iceland) and Akureyri (North-Iceland) [12].

In Iceland the length of the day varies greatly by time of the year and the solar altitude is never large due to geographical location. The
length of day in Reykjavík is between 4 hours at winter solstice while on summer solstice it’s about 21 hours [10].

1.1.3 History of concrete structures in Iceland

The first concrete building in Iceland was built in the year 1895. By the year 1950 the concrete had become the main building material for Icelandic buildings [13]. The first attempts to insulate the walls were done by fixing panel on the interior side of the wall and fill the empty space between the panel and concrete wall with hay or pumice [13]. Since then, many variations of insulation have been tried. Some walls were double with insulating material in between but later, most walls were made with insulation fixed on the interior side of the concrete wall [13]. This method is still very common today. Around 1960, EPS was governing insulation material on interior insulated concrete walls. The insulation was fixed to the concrete with mortar and then finished with mortar and paint on the interior surface [13].

Between 1960 and 1990 alkali silica reactions caused large problems in Icelandic concrete structures, especially in residential buildings. Under wet conditions, this reaction creates hygroscopic and hydraulic gel which can cause cracking in the concrete [14]. After an extensive research, the addition of silica fume was initiated to mitigate the damage [14]. Until the year 2012, 5-8% silica fume (as a percentage of cement weight) was added to all cement used in Iceland [15]. After cement production in Iceland ceased, Norwegian cement is used with the possibility of adding silica fume to it [15].

1.2 Aim

In this master thesis moisture problems in the typical Icelandic wall are addressed. The main purpose is to identify factors that contribute to critical moisture conditions in the wall and to estimate the mould growth risk. The project is threefold. In the first part, the aim is to compare the performance of the Icelandic wall with a different wall type to assess if the wall construction impacts the moisture levels and mould risk. In the second part, the focus will be on identifying parameters in the Icelandic wall which impact the moisture conditions in the wall. In the third part, an experiment that was setup during the thesis
work is described which will be aimed at validating the results from the first two parts.

Based on the previously mentioned assumption, i.e. that condensation occurs on the concrete surface due to warm moist air from the interior, the thesis will try to answer the following statements:

- Condensation will occur on the interface of concrete and insulation in the Icelandic wall
- The condensation is due to warm moist air entering from the inside of the building
- Mould will occur on the interior surface of the concrete

### 1.2.1 Limitations

This master thesis is written over a period of 20 weeks, hence the extent of the study is limited to the time at disposal.

Information and data about the hygrothermal properties of the Icelandic concrete are scarce. The main parts of the thesis, the comparative analysis and the parametric study, are based on approximations and assumptions on these properties and therefore exists a large risk of uncertainty and errors in the calculations. Furthermore, little data exists on the relative humidity in buildings in Iceland. To accommodate for this, a standard method for calculating interior relative humidity offered in WUFI is used in this study. Selecting a moisture class in WUFI poses an additional risk of error, as the relative humidity can impact the results.

The comparative analysis is limited to two wall types only, a concrete wall with exterior insulation and a concrete wall with interior insulation. Walls types such as with cladding systems or "smart" insulation systems are left out in the study. The mould risk calculations are dependant on assumptions and simplifications made for the wall, which poses a risk of uncertainty and errors in the results. The parametric study is limited to the internally insulated concrete wall, fixed to variations of few parameters and a certain number of simulation cases. One of the main foci is to investigate the impact of external coating of the wall. The purpose is not to identify the ideal wall, rather to see how different parameters influence the calculations results. Every parameter is altered independently of other parameters. Some parameters of the building materials are interrelated and thus altering only
one parameter at a time might not describe a realistic building material. However, the results might still give an indication of what to expect for materials with specific characteristics.

Some property approximations of the Icelandic concrete will be verified with a laboratory experiment in the near future, but due to time constraints these results will not be reported. However, the experimental set-up will be described in this thesis.
Chapter 2

Methods

This chapter explains and supports the methods chosen to address the research questions. The chapter describes the methods for information and data collection. Furthermore, a laboratory experiment that will be executed to evaluate the calculations and approximations of values will be described, as well as the evaluation methods for assessing the results of the simulations.

2.1 Information and data collection methods

Information and data for this study was collected through literature review, hygrothermal simulations, mould risk simulations and thermal simulations. This section outlines the different data collection methods.

2.1.1 Literature review

The literature review aims to provide general understanding of the topic as well as provide a detailed insight into previous studies, and counts for a big part of this thesis work.

The literature search was carried out via online academic databases and search engines (e.g. KTHB Primo, Google Scholar, Science Direct). Furthermore, reference lists were used to find more literature on certain topics. For information only relevant to Icelandic conditions, technical reports were used to compliment academic literature. The search was mainly conducted in English, but for topics specific for Icelandic conditions, Icelandic was also used.
To ensure quality of information and rule out unreliable papers, the sources were evaluated with respect to their publication-status. Scientific journal publications were evaluated as reliable and preferred over other sources.

### 2.1.2 Hygrothermal calculations

Before the introduction of simulation software for hygrothermal calculations, the Glaser method was traditionally applied for that purpose. This simplified steady-state method assumes non-hygroscopic materials and neglects the effects of radiation, precipitation, orientation etc. The method analyses the vapour diffusion transport in building components, but does not take into consideration capillary forces of building materials, sorption capacity or moisture and thermal storage capacity. Due to these limitations, a more sophisticated tool was chosen to obtain more reliable results.

There is a number of hygrothermal simulation software available for commercial use, including HEAT3, THERM, hygIRC and WUFI®. For the purpose of this study, WUFI® has been chosen over other simulation software for all hygrothermal calculations in this study. This is due to availability and the knowledge of the software by the authors. Furthermore, due to number of factors affecting mould growth and the extensive task of determining the mould risk, WUFI® is considered a feasible software as it offers mould risk calculations via an add-on software.

### 2.1.3 WUFI® - Hygrothermal Simulation Software

In this section, the WUFI® simulation software is described as well as the add-on used for mould risk calculations.

**WUFI® Pro 6.1**

WUFI® Pro 6.1 was developed by the Department of Hygrothermics at Fraunhofer Institute of Building Physics for the purpose of one-dimensional dynamic hygrothermal analysis [16]. WUFI® uses real weather data for the simulations, where the influence of driving rain, solar radiation, temperature, RH, cloud index and pressure is taken into account. The results can be used to evaluate the hygrothermal conditions of the building component, its drying behaviour and the
risk of condensation. An extensive data-base of building materials and climate data for many locations is included in the software. WUFI® has been validated with numerous of comparisons between experiments and simulations [17]. Validations have shown that WUFI® can accurately simulate both laboratory tests and complex processes of actual building parts which are exposed to real weather conditions. However, there are still prevailing risks of error, especially regarding user error.

**WUFI Mould Index VTT**

WUFI® VTT is an add-on developed for WUFI® Pro to predict mould growth on building materials as a function of temperature, relative humidity and the substrate itself, based on the hygrothermal simulation results from WUFI® Pro[18]. The model is based on the Viitanen model [19, 20] and includes various settings to account for different building materials. The model assesses the risk of mould growth but does not simulate the growth process. The VTT software contains mould criteria according to ASHRAE standard 160, which includes four different sensitivity and material specific mould decline classes [18].

### 2.1.4 Thermal bridge calculation

To simulate the thermal bridge of the interior insulated concrete wall-slab section, an inhomogeneous two dimensional building component, the COMSOL Multiphysics, a cross-platform finite element and multiphysics simulation software was used. The temperature changes and total transmission heat flow of the thermal bridge, with heat transfer mechanism consisting of convection, conduction and radiation was obtained from Comsol to calculate the linear thermal bridge transmittance of the structure.

### 2.2 Study design

The study is split into three parts: a comparative analysis, parametric study and a laboratory experiment. This section describes the purpose of each study.
2.2.1 Comparative analysis

The focus of the comparative analysis is to compare the hygrothermal performance of exterior and interior insulated concrete outer walls under different conditions. The purpose of this study is to evaluate and compare the hygrothermal performance of these two wall types and investigate if the hygrothermal performance of these walls is associated with different type of concrete. The analysis will be done by a parametric study including multiple simulation cases for investigating and comparing the performance of the two types of wall structures. In the parametric study, the two wall types will have various concrete types under different exterior climate and interior moisture load. First the interior insulated wall type will be compared to the exterior insulated wall type under same conditions and then it will be investigated if a higher interior moisture load increases the risk of mould growth in the wall. For evaluating the results of the comparative analysis, the relative humidity, temperature, total water content and mould risk is assessed for each simulation case. A more detailed description of the parameters simulated and the simulation cases are provided in chapter 6.

2.2.2 Parametric study

The focus of this study is to investigate the typical Icelandic external wall, which is usually constructed with Icelandic concrete, subject to Icelandic weather conditions. As the Icelandic concrete proves to be different from most concrete used in Europe, and the climate is different from European climate, a sensitivity analysis was used to identify which parameters, when simulating the Icelandic case, are most critical for obtaining reliable results. For evaluating the results of the parametric study, the relative humidity of a constant monitor point is assessed for each parameter variation. A more detailed description of the parameters simulated and the simulation cases are provided in chapter 7.

2.2.3 Laboratory experiment

Since the Icelandic concrete is different from other European concrete, it is important to evaluate whether concrete from the built-in data-base
of WUFI® is suitable for simulations of the Icelandic external wall. Furthermore, the approximations of the Icelandic concrete in WUFI® must be validated.

The objective of the laboratory experiment is to compare the simulation results, both with built-in concrete from the WUFI® data-base and the Icelandic concrete to test their validity. In this thesis the experimental set-up and anticipated results are covered. Due to time constraints no results will be introduced in this thesis. A more detailed description of the experimental set-up, equipment and further steps is provided in chapter 9.
Chapter 3

Theoretical framework

3.1 Moisture Mechanics

In this chapter the properties of moisture and the mechanics of moisture transport in building components is described.

3.1.1 The chemical structure of the water molecule

The chemical structure of the water molecule consists of two negatively charged oxygen atoms and one positively charged hydrogen atom. When water is in its liquid form, the water molecules bundle up together, forming a clump of around 80 water molecules in size. When the temperature rises it disengages these clumps to a smaller size [21]. Water consists therefore of larger clumps in its liquid form compared to its vapour form. The boiling point of water depends largely on the atmospheric air pressure. When the temperature of water cools down

![Chemical structure of water molecule]

Figure 3.1: The chemical structure of the water molecule [21]
it changes from its liquid form to a solid form, ice. When the temperature cools down close to freezing point, 0°C, it results in expansion of water. The cause of this expansion is that when water freezes, its molecules form a six sided crystal, which hold more space than a single molecule would [21]. As the temperature of water cools down, its density will furthermore increase. Moisture in building materials will hereby after denote the physically bound water.

3.1.2 Destructive effects of moisture

When considering building performance and durability of building components, moisture is a crucial influencer, especially in cold climate areas [21].

Destructive effects of excessive moisture can cause serious problems to building components and the occupants in the building. Understanding and controlling moisture within and in the building envelope is necessary to prevent problems related to moisture [21].

Straube [21] mentions four conditions necessary for moisture problems to arise in building components. Firstly, there must be some type of a moisture source present. The types of sources will be discussed in detail in section 3.2. Secondly for the moisture to be able to transfer there must be some means or routes for its displacement. Thirdly there has to exists some type of driving force, facilitating the displacement of the moisture. Lastly the building component must be vulnerable to moisture related damage. If one of these conditions is not fulfilled, the occurrence of moisture damage could in theory be averted [21]. Unfortunately the goal to eliminate all moisture sources would be both impractical and and almost unattainable for real world situations. Therefore the most practical way of diminishing moisture damage has been to control moisture in the best possible way and minimizing risk of failure by appropriate design and selection of efficient and durable building materials [21].

Excessive moisture in buildings makes it feasible for the growth of micro-organisms such as mould and fungus which can have bad influence on the habitants living in that space [22]. Excessive moisture in building components such as insulating materials affect its thermal properties and results in decreased thermal resistance of building components, as water has much higher thermal conductivity than e.g air. This leads to worse insulation properties of the structure which can
result in energy loss of the building envelope [22].

Moisture can also lead to mechanical stresses in materials, as some materials can expand or shrink according to their moisture content, leading to decreased stability of the structure [22]. Phenomena such as efflorescent are caused by liquid transport, when salt remains left in the building component due to the evaporation of the liquid. This phenomena can lead to staining and discolouration and has more aesthetic damage. If the salt however crystallises it can lead to additional mechanical stresses resulting in cracks or removal of surface treatments [22].

### 3.1.3 Vapour properties

Generally, density is defined as \( \rho \) (kg/m\(^3\)). The physical quantity used when dealing with water vapour content is the ratio of water vapour mass \( m \) to volume of gas \( V \), or the absolute humidity \( u \) (kg/m\(^3\)) [22, 23]:

\[
u = \frac{m}{V} \quad (3.1)
\]

Another physical quantity used to for measuring water vapour content is the ratio of ratio of water vapour mass \( m \) (kg) to the mass of dry gas \( m_d \) (kg), humidity ratio \( x \) [22]:

\[
x = \frac{m}{m_d} \quad (3.2)
\]

**Relative Humidity**

Vapour is made up of several gas components, such as nitrogen, oxygen, argon and water. The total pressure of a gas is said to be the total sum of the partial pressures of these gas components. The water vapour pressure at saturation, is the maximum partial pressure of water vapour possible for a given temperature, and lies on the border of the phase change from vapour phase to liquid or solid. It is important to note that these conversions from gas to solid or solid to gas occur in an equilibrium state [22]. The dew-point is defined as the temperature where gas is unable to contain more than a certain amount of vapour content, \( v \), for the vapour content at saturation, \( v_s \). As the saturated
vapour content is always attributable to a certain temperature it has been a custom to note it as $v_s(T)$, where T is the temperature [23]. The Relative Humidity $\phi$ is defined as the ratio between the actual vapour content of the air and the saturated vapour content for the same temperature, denoted as:

$$\phi = \frac{v}{v_s} \quad (3.3)$$

where $\phi$ or RH is measured in %. In other words relative humidity represents the ratio of vapour in the air to the maximum vapour possible of that air at a certain temperature. Air’s potential to hold moisture is determined by its temperature. Air at higher temperature can hold more vapour than at colder temperature. Air is said to be saturated when $RH = 100\%$, so that the air can not hold more water vapour (at that temperature) and condensation occurs. When the $RH < 100\%$ the air is said to be unsaturated and can hold more water vapour [23].

### 3.1.4 Moisture content in materials

Moisture can be regarded as the physical bound water, ($H_2O$) in it’s different phases vapour, liquid or ice [23]. Building component’s moisture properties are directly related to their porosity, pore-size distribution, physical and chemical structure [23].

There is always a certain balance between the moisture level inside of the material to the exterior environment. A material can take in moisture from the environment which is called adsorption and it can give moisture to the environment through desorption. The building component can also be in equilibrium with its environment, absorbing as much moisture as it is drying out [23]. These moisture transport mechanism are discussed in detail in section 3.1.5.

There are several ways a material can absorb water from the environment. Three conditions will be discussed here. The first condition is when a material is in contact with moist air. The hygroscopic properties of the material is the dominant factor in this case. The second condition is when a material is in contact with free water (unbound water). The dominant factor in this case is the capillary and permeability abilities of the material. The third condition is when a material is in contact with another material. In this case both hygroscopic properties, permeability and capillary properties can have an impact [23].

The moisture content of a material can be expressed in several ways.
Firstly the term \textit{mass concentration of water} \(w\) (\(kg/m^3\)) will be used as in [23]:

\[
w = \frac{m_w}{V} \tag{3.4}
\]

where \(m_w\) is the mass of water (kg) which the material contains and \(V\) is the volume \(m^3\) of the material. Equation 3.4 gives directly the moisture content in a material. Another term used is the \textit{moisture ratio} or the \textit{mass ratio of water to dry matter} \(u\) as in [23]:

\[
u = \frac{m_w}{m_0} \tag{3.5}
\]

where \(m_w\) is the mass of water (kg) which the material contains and \(m_0\) is mass of dry matter (kg). There is a relationship between equation 3.4 and equation 3.5 referred as the \textit{bulk density} \(\rho\) (\(kg/m^3\)) as:

\[
\rho = \frac{w}{u} \tag{3.6}
\]

\textbf{Porosity}

The greater part of all building materials are porous in a way that they consist of voids. Concrete, thermal insulation and wood are defined as porous materials while glass and steel are example of non-porous materials [22]. A strong implication can be made on the porosity of a material from the \textit{bulk density} (eq. 3.6) and it is used for conversion between the \textit{moisture ratio} and the \textit{moisture concentration}.

The porosity of a material is generally a dominant factor for moisture transport in materials. The total porosity of a dry material sample can be denoted as the ratio of total air volume inside the material sample to the total volume of the that material sample [21]. The pores can vary in size and they can be closed off or open to the exterior environment. Large open pores advance fast transport of air, vapour and water. Water gets bound more tightly the material with small pores which results in increased hygroscopic moisture balance [23]. The leading factor that facilitates transfer of liquid water in materials is the porosity while the fundamental mechanism is the capillary action [22]. This will be discussed further in section 3.1.5.
The *porosity* $n$ of a material can be defined as [23]:

$$n = 1 - \frac{\rho}{\rho_{\text{particle}}}$$  \hspace{1cm} (3.7)

where $\rho$ [kg/m$^3$] is the mass of dry water to the total volume of the material described in eq. 3.6 and the *packed density* $\rho_{\text{particle}}$ [kg/m$^3$] is denoted as [23]:

$$\rho_{\text{particle}} = \frac{\text{mass}}{(\text{total volume of sample}) - (\text{pore volume})}$$  \hspace{1cm} (3.8)

To measure how much moisture is stored in open pores of materials we use the *degree of saturation*, $S$. It is defined as the percentage of open pores in a building materials that are filled with water [21]. It is defined as [23]:

$$S = \frac{w}{n\rho_w}$$  \hspace{1cm} (3.9)

where $\rho_w$ is the density of water and $w$ is defined in eq. 3.4. When $S=1$ in eq. 3.9 it is said to be saturated. The *capillary saturation ratio*, $S_{\text{cap}}$ describes the ration of how much water the material contains to the the maximum amount of water that the material can absorb through capillary suction. It is defined as [23]:

$$S_{\text{cap}} = \frac{u}{u_{\text{capillary}}}$$  \hspace{1cm} (3.10)

where $u$ is defined in eq. 3.5 and $u_{\text{capillary}}$ is denoted as [23]:

$$u_{\text{capillary}} = \frac{\text{maximum absorbed moisture through capillary suction}}{\text{dry weight of sample}}$$  \hspace{1cm} (3.11)

**Permeability**

*Permeability* is a term used to describe the arrangement of pore connections inside the material. Pores are not always closed off to the environment or to other pores. The pores can be connected to other pores in the material creating a linked network, or they are not connected to any pores, so called dead ends. The pores can be open to the environment or open to a neighbouring material. The permeability of materials affects both air and moisture transport through the material.
and is dependent on the pore connections [24].

### 3.1.5 Moisture transport

It is of importance to cover the fundamental physics of moisture transport in building components. Moisture flow is always denoted as the product of transport coefficient and the potential difference per unit length. Moisture flow calculations in materials can be worked out from four fundamental aspects, namely material properties, initial conditions, boundary conditions and moisture transport theories.

The material properties are in terms of both thermal and moisture mechanics. The initial conditions are established on the moisture content and temperature of the material and the surrounding at the initial moment. The boundary conditions take into account and define the behaviour of the moisture and temperature condition at the boundary of the materials [23].

**Hygroscopic moisture transport**

Condensation has already been discussed in chapter 3.1.3, where air gets saturated and liquid water gets extracted. When the relative humidity is less than 100% a building material is able to absorb water molecules through two different physical phenomena, namely adsorption and capillary condensation. When water molecules are bound to solid material through attraction forces it is called adsorption. The amount of water adsorbed in a material is in close relation to the humidity of the surrounding air [23]. When the relative humidity is low it is mainly adsorption at work while at higher relative humidity the capillary condensation phenomena is more dominant [23]. How capable a material is in attracting and holding water molecules is determined by its hygroscopy [22].

If a material is porous, it will adjust itself in equilibrium to the surrounding air so that the water molecules will adsorb in one or more molecular layer of the pore walls at low humidity. At high humidity fine capillaries get filled in terms of capillary condensation. If a material has a high hygroscopic moisture content it has large porosity [23]. Materials with large porosity get damped by moist air while materials which are non-hygroscopic do not get damped and remain dry. The pore system of hygroscopic materials draws water molecules to the inner surface while in contact with moist air until an equilibrium has
been reached to the humidity level of the air in the surrounding environment [25]. An example of hygroscopic materials are concrete and timber. An example of non-hygroscopic materials are glass and insulators [22].

Capillary condensation

When water rises in a capillary, the water forms a concave meniscus at a lower relative humidity than what would be needed if the surface was flat. The water molecules can get trapped in these menisci at a considerably lower level than 100%RH. This phenomena is denoted as capillary condensation [23].

Capillary force

When building materials are in direct contact with groundwater or when a façade wall is hit with driving rain there are certain capillary forces which are attributed to the moisture transport at play [23]. The attraction forces which contribute to the water molecules binding to the surface of materials are associated with the physical principle of surface tension [23]. Liquid molecules are in a lower state of energy when bound to neighbouring molecule.

This is related to the physical tendency of interior molecules to
reduce the amount of boundary molecules to possess higher energy while the boundary molecules will attempt to loose neighbouring molecules. By reducing the number of bordering molecules, there is an physical minimization of the surface area of the liquid [22]. This physical phenomena is defined as surface tension. This interplay between attraction forces and surface tension gives rise to the capillary forces in materials [23]. These capillary forces contribute greatly to moisture transport. The capillary suction pressure is an important concept in the nature of moisture movement in capillaries. The direction of moisture flow is strictly from low to high capillary pressure. Small pores prompt higher pressure with lower moisture flow rate while larger pores prompt lower pressure with higher moisture flow rate [26].

**Types of moisture transport**

Moisture transport through its vapour phase in the following ways [23]:

1. *Moisture Diffusion*
2. *Moisture Convection*
3. *Effusion*

Driving forces of moisture transport in its liquid phase are [23]:

1. *Gravity*
2. *Capillary suction*
3. *Wind pressure*
4. *Capillary forces*

**Diffusion**

In an inhomogeneous gas mixture the molecules have a tendency to become equally distributed in the mixture. This endeavour of molecules to minimize concentration differences is called diffusion. Moisture diffusion transport of water vapour is a consequence of difference in moisture content and the random movement and collision of molecules with themselves or to another material [23]. The transport of vapour
from its domain of high concentration to a lower concentration is a frequent phenomena in building construction materials.

When a diffusion occurs it is at play movement of particles colliding into each other which advance the moisture transport by contribution of difference in moisture content [23]. If a material has finer pores or capillaries, the collision of molecules and pore walls will be of great influence to the moisture transport. When the the pore size is of a greater magnitude than or equal to the mean free path between collision of molecules the diffuse transport can be described by Fick’s law. If the pore size is smaller than the mean free path of the molecules, the main cause of moisture transport will be the effect of this collision between water molecules and pore walls. This type of transport mode is often called effusion and is governed by Knudsen transport. These two types of diffusion processes are described in figure 3.3 [21, 23].

Moisture convection

Moisture transport through convection occurs when water vapour travels with air flow. This mode of transport is defined as moisture convection. There is a certain condition of total pressure difference for the airflow to happen [23]. The consequence of moisture convection with air flow are dependent on the thermal conditions. If the air flow cools down it reduces its capability to hold water and gives rise to condensation. If the air flow gets warmer it increases the moisture uptake
capability of the air which leads to drying process [23].

**Water absorption coefficient**

Wetting is mainly the result of rain water penetration and adsorption, condensation of vapour by (convection or diffusion), or capillary transport. When liquid water is carried into a dry material it follows a simplified form of Darcy’s equation [21]:

\[ m_w = A \cdot \sqrt{t} \]  \hspace{1cm} (3.12)

where \( m_w \) is the mass of the water absorbed per unit area (kg/m\(^2\)), \( A \) is the water absorption coefficient (kg/m\(^2\) s\(^0.5\)) or kg/m\(^2\) hr\(^0.5\)) and \( t \) is time (seconds or hours) [21].

**Water vapour diffusion resistance**

In porous building materials, diffusion occurs in the air of the pores. Diffusion flow through porous material has to overcome resistance due to tortuous pore routes and cross-sectional changes of the pore structure [27]. Obstruction of vapour diffusion is represented by a *water vapour diffusion resistance factor*, \( \mu \)-value (-), which describes the diffusion resistance of the material as proportion to the vapour resistance of air layer of same thickness. \( \mu \) is the factor by which the vapour diffusion in the material is impeded, as compared to diffusion in air. For very permeable materials the \( \mu \)-value is low and close to 1 but with higher density the \( \mu \)-value increases with increased diffusion resistance [27].

Another value, \( sd \)-value (m), is used to describe the water vapour diffusion resistance. The resistance is dependent on the thickness of the material layer. The relationship between the \( \mu \)-value and the \( sd \)-value is the following:

\[ sd = \mu \times m \]  \hspace{1cm} (3.13)

where \( m \) is the thickness of the material layer.

**3.1.6 Moisture storage function**

When a dry material is located in an environment with a constant temperature and relative humidity, it will by time reach an equilibrium
with the moisture content of the environment. If the situation is repeated with the same constant temperature and material but different relative humidity level, a relationship between the moisture content of the material and the relative humidity of the air can be determined [23]. This relationship can be transformed into a curve denoted as the *Sorption Isotherm Curve* where the equilibrium situation is characterised. If the same procedure is done for a damp material the same relationship can be transformed into a function. The function for the dry material describes dampening by *adsorption* while the function for the damp material describes drying by *desorption* [23]. This sorption isotherm function is divided into two regions: sorption moisture region and capillary water region [27]. In the sorption moisture region, water molecules of the pore air bind with the pore walls due to adsorption, and water accumulates until equilibrium is reached. In this region is the increase of equilibrium moisture content roughly in proportion to the relative humidity. The capillary moisture region takes over when the relative humidity rises above 60-80%. In this region, the material can take up water until reaching capillary saturation. This is due to reduction of the saturation vapour pressure in the smaller capillaries which causes additional condensation of water. In this region, water is both bound by adsorption and unbound liquid water in the pores and the equilibrium moisture content rises sharply. The two regions can be illustrated together on a curve where each air humidity value corresponds to water content in the material (Figure 3.4). The processes behind the functions are complex but the amount of moisture the building material can hold depends on the material properties, including the porosity, pore structure and the types of pores [27].
3.1.7 Liquid transport coefficients

As with the moisture storage, liquid transportation in hygroscopic building materials is divided into the two regions of sorption moisture and capillary water region [27]. The main activity of the sorption moisture region is surface diffusion while capillary action takes place in the capillary water region. However, the capillary liquid transport is the predominant moisture transport mechanism. The liquid transport is regarded as diffusion phenomenon described by the following equation

$$ g_w = -D_w(w) \times \text{grad}(w) $$  \hspace{1cm} (3.14)

where $g_w$ (kg/m$^2$/s) is the liquid transport flux density, $w$ (kg/m$^3$) is the moisture content and $D_w$ (m$^2$/s) is the liquid transport coefficient. $D_w$ is dependent on moisture content of the material. When the material surface is wetted due to rain event, $D_{ws}$ describes capillary uptake of water where the suction is dominated by larger capillaries as they have small flow resistance. After wetting, $D_{ww}$ describes the redistribution of water, i.e. the migration of water in the absence of rain. This pro-
cess is dominated by smaller capillaries as their high capillary tension sucks the water from the larger pores [28]. Measuring of the liquid transport coefficients is hard and therefore data is scarce. However, the coefficients can be estimated by the water absorption coefficient, A-value (kg/m²s⁰.⁵) and the moisture storage function. The A-value is dominated by capillary forces and is more easily measured by observing water uptake of a sample with regard to time.

3.2 Moisture sources

It is of great importance when analysing moisture in buildings to recognize where moisture is originated from. The origin of moisture in buildings will be denoted here as moisture sources. The biggest factor causing damage and degradation to building components of the building envelope is moisture [29]. There can be many moisture sources acting on a building component at once. There can again be a moisture source which is much more dominant than others. There are a number of moisture sources in buildings [23]:

1. Rain, snow and driving rain
2. Air humidity
3. Built-in moisture
4. Groundwater
5. Leakage from installations

There can also be a certain moisture production which origins from human behaviour, such as perspiration (sweating), washing, cooking or cleaning. These types of moisture sources is usually the consequence of various disorderliness and is a more of a sociological aspect.

Built-in moisture

Building materials consist of moisture due to various reasons. Built-in moisture can be defined as the amount of water that must be removed for the material to reach an equilibrium with its environment [23]. When concrete is cast there are certain chemical processes at hand that result in added moisture production which can take some time to
evaporate to its environment. Built-in moisture can be explained by the equation [23]:

$$w_{bm} = w_0 - w_\infty$$

(3.15)

where $w_0$ (kg/m$^3$) is the moisture content of the material when built, $w_\infty$ (kg/m$^3$) is the moisture concentration of the material while in equilibrium with its surrounding and $w_{bm}$ (kg/m$^3$) the built-in moisture.

So the built-in moisture can be denoted as the excess moisture that the material needs to get rid of before it it reaches its equilibrium state in terms of moisture balance. This is directly related to the moisture isotherm curve as previously discussed. Building materials should be contained and protected in dry places in the construction phase in order to protect it from factors such as weather.

**Rain and driving rain**

Moisture in building component emanates from various types of weather sources. It is important to distinguish between the these types of moisture sources in terms of building physics.

*Rain* falls vertically onto the building envelope encountering roof or similar constructions. The roof should be completely watertight and drain off the rain to gutters that drain the rain further from the building envelope. *Driving rain* is another phenomena which is an interplay between rain and wind. When vertical rain, encounters a horizontal wind component, the interaction results in rain falling on vertical building components such as walls and similar vertical constructions [23]. Straube [21], states that driving rain is the biggest contribution of moisture source in terms of water content permeating the building envelope of buildings. Driving rain can support the moisture penetration through the cladding and leakages on the building envelope [21].

**Air humidity**

Moisture in building components is generally associated to the water vapour in the surrounding air. There are two types of air humidity that should be taken into consideration when investigating moisture related to building components. They are namely the *indoor air humidity* and the *outdoor air humidity*. These two situations can be described
by either by vapour content $v$ (kg/m$^3$), or by its relative humidity $\phi$ (%) described in equation 3.3. The outdoor air humidity, is related to the climate conditions of the location being considered. Obtaining data for the outdoor air humidity is possible through weather stations close to the desirable location being investigated. Outdoor air humidity data is usually in terms of relative humidity, but can be converted to vapour content from the RH and the outdoor air temperature.

The indoor air humidity of a building is generally expressed in terms of vapour content $v$ (kg/m$^3$). The humidity level of the indoor air can be derived from the outdoor humidity conditions, indoor moisture production and the ventilation capacity in terms of air change rate (h$^{-1}$). Moisture production indoors is usually the result of human and plant evaporation, cleaning, washing, cooking and humidification [23]. The moisture production from theses factors should be removed by proper ventilation to the outside. To determine the moisture concentration of the indoor air, the following equation can be used [23]:

$$v_i = v_e + \frac{G}{nV} \cdot (1 - e^{-nt})$$  \hspace{1cm} (3.16)

where $v_i$ (kg/m$^3$) is vapour concentration indoors, $v_e$ (kg/m$^3$) is the vapour concentration outdoors, $n$ (s$^{-1}$) is the air changes per second, $V$ (m$^3$) is the ventilated room volume, $t$ is time (s), $G$ (kg/s) is the moisture production and $R_L$ (m$^3$/s) is the airflow.

After a certain time period $t$, the $v_i$ can be approximated as:

$$v_i = v_e + \frac{G}{nV} = v_e + v_{ms}$$  \hspace{1cm} (3.17)

where $v_{ms}$ is the moisture supply and is regarded as the difference between the indoor and outdoor vapour content. To reduce the added moisture, the ventilation rate should be increased and indoor moisture production sources reduces as well.

The relative humidity indoors is also of an importance. In the wintertime in cold climate, the vapour content outdoors is low. When the cold outdoor air streams inside, it results in low relative humidity indoors [23]. In the summertime there is a smaller temperature difference between the indoor air and outdoor air which results in higher relative humidity indoors in the summertime than in the wintertime.
The relative humidity indoors can be found through the following equation [23]:

$$\phi_i = \frac{v_e + v_{ms}}{v_s(T_i)} \cdot 100(\%)$$

(3.18)

where $v_s(T_i)$ is the saturated vapour content (kg/m$^3$) at indoor temperature $T_i$. The indoor relative humidity varies by geographical location and season. As previously discussed, the relative humidity is associated with the vapour content of the air (kg/m$^3$) and the air temperature (°C). It is of high importance to control the humidity level indoors as it can affect indoor air quality, energy performance and contribute to deterioration of building components of the building envelope. If the indoor relative humidity is too low it can have health impact on the occupants in the space as well if the indoor relative humidity is too high [30].

**Psychrometrics**

When considering the physical and thermodynamic properties of gas-vapour mixtures, the field of psychrometrics is used in engineering. In previous sections the moisture content has been discussed, but the humid air energy is also of interest. When analysing the energy of the humid air, the specific enthalpy, is determined as the ratio of enthalpy to mass of dry air. Enthalpy is an attribute of a system, which accounts for both the system’s internal energy and the energy needed to make space for that system [22]. Psychrometric charts such as the Mollier diagram, in figure 3.5, present many psychrometrics quantities in the same chart. As it is considered more difficult to measure the energy of air, the diagram brings forth a way to connect energy to properties which are more easily measured such as temperature and relative humidity. The Mollier diagram shows at a certain atmospheric pressure, usually at 101.3kPa, the specific enthalpy $h$, water vapour mass ratio $x$, relative humidity $\phi$, density $\rho$ and temperature $\theta$. The Mollier chart provides a way of looking up values if two of psychrometric quantities are known and it also provides understanding of phase changes of the humid air.
Leakages

Leakages can be the result of many occurrences. Nevander & Elmars-
son[23] names leakages from installation as on of the most common
cause of moisture problems in buildings. Rain can enter the building
ever due to cracks, bad design, poor material quality or incorrect
installation of building parts. Roofs and windows can be leaky due to
weather load, poor maintenance or defects. Plumbing inside walls or
under slabs can crack and cause water leakage which can have severe
consequences and cause water damage.

**Groundwater**

As discussed in section 3.1.5, if a building component is in contact with groundwater, there is an interplay between attraction forces and surface tension between the material and the liquid which can result in *capillary forces* in the building component [23]. This capillary action is denoted as *rising damp*. When building parts are in contact with soil which is soaked, there is a risk of this phenomena occurring. Most building components are hydrophilic and porous and the capillary structure is interconnected with the pores [22]. When the building component is in contact with the soaked groundwater, it enables a transport way of water into the capillary structure of the material. Due to the capillary effect, the groundwater will rise upwards in the building material, higher than the groundwater level and can evaporate through the wall and leave salt behind. When the water has evaporated, it enables more groundwater to rise upwards in the building component, creating a continuous cycle of rising damp [22].
Chapter 4

Literature review

In this chapter, the study of existing literature on concrete properties, moisture behaviour of external walls and mould in buildings is introduced. The aim of the literature review is to understand the properties of concrete that are special for Icelandic concrete and might influence the moisture behaviour of the wall, discuss studies on moisture behaviour of coated walls and interior insulated walls and introduce mould growth criteria and mould growth models.

4.1 Concrete properties

4.1.1 Aggregates

Concrete is largely constituted of aggregates, which typically account for 60-80% of the total concrete volume. Due to the high percentage of aggregates in the total concrete volume, they influence the thermal characteristics of concrete such as thermal conductivity, specific heat and coefficient of thermal expansion as well as vapour permeability [31].

Icelandic aggregates differ from aggregates from other European countries, as they are mainly derived from basalt rock. The porosity of basalt varies from low to very high. On the other hand, aggregates from other European countries all have a very low porosity in common [32]. Aggregates can carry water in the pore system, which can impact the overall properties of the concrete. The saturated water content of typical Icelandic aggregates is on the range of 50-70 l/m$^3$ compared to saturated water content of 10-20 l/m$^3$ for aggregates from the other
Nordic countries [33]. This indicates that Icelandic concrete contains more porous aggregates, resulting in higher total porosity of the concrete.

In most studies which focus on the pore system of concrete, the pore structures of the aggregates is ignored. However, most aggregates have a pore system to some extent and some even have substantial content of pores [34], which is the case of the typical Icelandic aggregates. Therefore, the pore system of aggregates can have a significant impact on the transportation of fluids in the concrete.

4.1.2 Silica fume

The smelting process in the silicon and ferrosilicon industry produces a by-product, silica fume. The silica fume consists of very fine particles with high surface area ranging from 13,000-30,000 m$^2$/kg [35]. Over 95% of all silica fume particles are finer than 1 μm [36], which is around 100 times smaller than cement particles [35]. Silica fume is added to cement to improve some properties of concrete, including reduction in permeability.

Studies on water permeability of concrete containing silica fume have shown a reduction in permeability compared to concrete without silica fume [36–40]. Hooton [37] reported a large difference in permeability between a reference concrete and a concrete mix with 10% silica fume, where the permeability fell from $1.8 \times 10^{-14}$ m/s to such a low value it could not be measured (lower than $1 \times 10^{-17}$ m/s). Song et al. [39] reported a dramatic reduction in permeability in concrete with silica fume over 8%, but above 12% the reduction in permeability becomes insignificant or even increased in some cases. Byfors [40] showed a reduction in diffusion rate of cement paste with addition of silica fume where addition of 10-20% of silica fume reduced the diffusion constant by a factor of 11.

Silica fume has also been shown to have an impact on the porosity of concrete [41–44]. Khan [42] studied the potential benefits of adding silica fume to cement. He observed that partial replacement of cement with silica fume resulted in reduction of porosity. Incorporation of 8-12% silica fume instead of cement gave optimum performance and resulted in the lowest porosity. However, after that the reduction was marginal or reversed. Igarashi et al. [41] studied the characteristics of capillary pores and pore size in high-strength concrete at early ages.
They studied the impact of adding 10% silica fume to cement mix and found that silica fume reduced the number of coarse pores compared to ordinary concrete, even at early ages of 12 and 24 hours. Cwirzen and Pettala [44] investigated the porosity of eight non-air-entrained concretes with water-to-binder (w/b) ratios of 0.3, 0.35 and 0.42. The dosages of silica fume added to the mix were 3% and 7% of the cement weight. The results did not show significant variations in porosity of the different mixes. Only the concrete with w/b ratio of 0.3 showed a reduction in capillary porosity with added silica fume, approximately 2%. However, concretes with w/b ratios of 0.3 and 0.42 had similar capillary and total porosity with and without silica fume. Poon et al [43] studied the effect of 5% and 10% replacement of cement with silica fume on the porosity of concrete mixtures. They reported a reduction in porosity with age in concretes with added silica fume.

Addition of silica fume has also showed a reduction in pH values of cement paste [40]. Addition of 10% and 20% of silica fume reduced the pH value of the cement paste by 0.4 and 0.7 units, respectively.

4.2 Moisture performance of exterior walls

Little research has been done on concrete walls insulated on the interior side. However, the performance of internally insulated walls are of interest for this thesis. Therefore, a study on brick walls comparing internally and externally insulation is reviewed in this section, to evaluate the impact of the insulation position. Furthermore, two studies on exterior coatings are presented, thereof one that specifically looks at coating on interior insulated concrete walls.

4.2.1 Effect of interior and exterior insulation on the hygrothermal behaviour of exposed walls

Künzel [45] made a numerical study on a 40 cm thick un-rendered brick wall, comparing interior and exterior plaster insulation with the computer program WUFI. The calculations were done over several years with the same weather reference year of Holzkirchen in Germany, until an equilibrium had been reached. The high driving rain load in Holzkirchen was divided by two as the monolithic type of wall is not used in areas with such high driving rain loads. In figure 4.1,
mean distribution, shown as a solid line and the hatched annual vari-
ation range of the transient profile of the the un-insulated brick wall is
shown with 50% and 75% of the driving rain.

Due to rain load in both cases, the moisture variation range is high-
est at the surface of the brick façade with the moisture range declining
to a more or less steady state conditions on the interior side of the
wall. It is to be noted that the highest average moisture content lies
not on the surface but a few centimetres inside the brick wall in both
cases. This can be explained by a strong non-linearity of the moisture
transport equations, caused mainly by the moisture dependence of the
liquid diffusivity.

Applying exterior insulation system on walls with non-hygroscopic
insulation material provides excellent rain protection which also pro-
motes the drying of the wall [45]. In figure 4.2 the brick wall has been
upgraded with exterior insulation and the drying process for 5 years
is shown for two different types of materials, mineral wool and EPS
insulation, of thickness 60mm and 100mm. The rain load was 50% of
the Holzkirchen rain.
Figure 4.2: Drying of the brick wall \( [\text{kg/m}^2] \) is presented here with two types of exterior insulating materials, mineral wool and EPS. The EPS has synthetic resin rendering and the mineral wool has mineral rendering. [45].

As can be seen on figure 4.2, the drying of the exterior insulated brick wall is faster with mineral wool and takes about two years while the drying takes about four years for the EPS insulation. As can be seen the insulating thickness has almost no influence on the drying rate of the two types of exterior insulation systems. This could be a connection between a higher mean temperature of the brick layer with thicker exterior insulation and a higher diffusion rate of the thicker insulation[45].

When interior insulation is applied on the brick wall instead of an exterior insulation system the temperature of the brick layer is reduced. This also lowers the drying capacity of the wall which results in higher average moisture content of the brick wall. In figure 4.3 the yearly average moisture profile (solid lines) and yearly moisture variation in the brick layer is shown with three types of 60mm insulating materials, EPS, mineral wool and insulating plaster. The insulating plaster consisted of premixed expanded polystyrene particles and lime-cement mortar.
In figure 4.3, the effect of having interior insulation leads to higher average moisture content in the brick masonry in all three insulating materials. To reduce this high moisture content of the interior insulating wall systems, the walls were impregnated with a water-repellent surface treatment. To calculate the drying process of the walls, the effect of the surface treatment was assumed to eliminate the rain water absorption while affecting on a small scale the diffusion resistance of the exterior façade. The results are shown in figure 4.4.

In figure 4.4 it can be seen that the brick with no insulation has the fastest drying rate. The effect of having interior insulation reduces the drying capability of the impregnated masonry wall. The wall systems are impregnated in July and the initial moisture content of the wall was determined by the moisture situation at that time. It takes less than two years for the uninsulated wall to dry out the precipitation
moisture while it takes more than five years for the interior insulated walls [45].

![Figure 4.4: The drying rate of the interior insulated brick systems with no render after surface treatment on the exterior side in terms of masonry moisture. The initial water content correspond the condition of the walls in July without surface treatment [45].](image)

Due to a high vapour diffusion resistance factor of the Expanded polystyrene ($\mu$=30) it performs worse than the mineral wool and the insulating plaster in terms of drying time but as the main moisture flux is to the outside of the wall, the difference can be seen as insignificant [45]. The results from the study show that exterior insulated masonry wall systems perform better and result in drying of the wall, with the drying rate depending on the vapour permeability of the insulation system. Using exterior mineral wool insulation results in faster drying rate of the brick wall but could also have a potential frost damage risk if the insulation is applied on a wet surface during winter [45]. As the vapour diffusion resistance of the mineral wool ($\mu$=1.3) is lower than of the EPS, there is a risk of moisture accumulating behind exterior render with a higher diffusion resistance. The interior insulated wall leads to higher moisture content of the wall and results in lower temperature of the masonry and has a high frost damage risk. It is important for the façade of the interior insulated masonry wall systems to be surface treated with rain protection before installing the interior insulation material in order to decrease the drying time. By this frost
damage to the wall and decreased thermal resistance of the masonry can be avoided [45].

### 4.3 Rain protection characteristics

Künzel et al. [46] performed large-scale field tests on the driving rain protection of coated walls in order to connect the water absorption and diffusion resistance characteristics of coatings with moisture behaviour of external walls. The aim was to find out the characteristics that provide appropriate rain protection on external walls.

The moisture transport on the exterior surface is mainly controlled by water absorption due to capillary action (A-value) and water vapour diffusion (sd-value) [46]. The transportation of rain into the wall that hits the façade is governed by the A-value, whereas the drying out after a rain event is controlled by the sd-value.

Künzel et al. derived a driving rain protection coefficient, \( C_{RP} \) which lumps together the A-value and the sd-value according to:

\[
A \times sd < C_{RP} \quad (4.1)
\]

The suggested limit for the \( C_{RP} \) is \( 0.1 \) (kg/mh\(^{0.5}\)) (or 0.00166 kg/ms\(^{0.5}\)). The purpose of this coefficient is to prevent moisture accumulation in an external wall by making sure that the amount of water drying out is always larger than the amount of water absorbed by the wall due to rain. Furthermore, Künzel et al. suggests that the sd-value is set to maximum of 2 m and the A-value to 0.00833 (kg/m\(^2\)s\(^{0.5}\)).

#### 4.3.1 Vapour permeability of exterior surface treatment

A research project conducted by the Icelandic Building research institute [8] studied the effect of exterior coatings on moisture content in concrete walls. The aim was to determine whether it is safe to use strong, relatively thick, water-impermeable coatings on the exterior wall which can serve as elastomeric bridges over cracks.

In the study the moisture content of the typical exterior wall in 18 houses in south-west Iceland was investigated. The external walls consisted of 180-200mm reinforced concrete with interior insulation. The interior insulation was 50-100mm thick slabs of expanded polystyrene
fixed to the inner concrete surface with cement mortar. On the exterior
side of the concrete, the façade consisted of cement-based rendering in
the range of 5-20mm thick. The interior side of the EPS was usually
treated with cement based rendering, 20 to 40mm thick, reinforced by
wired mesh and painted. The interior paint was mostly of water re-
ducible plastic dispersion but no vapour barriers were installed. The
were various exterior finishes, most common being paint coatings with
or without water repellents as priming impregnation. The construc-
tion type can be seen in figure 4.5. The exterior paints were normally
made of thermoplastic polymers, usually not elastomeric and in many
cases they were brittle.

Figure 4.5: The typical interior insulated concrete wall from the case
study and a drilled sample [8].

Samples were drilled out from the concrete core during winter time
and moisture measurements performed. Four samples were taken
from each house, two from a south facing wall and two from a north
facing wall.
The samples represented a cross section of the types of walls in Icelandic buildings. The relative humidity in the walls was on average high, or 82%. It was observed that the relative humidity of the walls did not depend on their orientation. This was considered to be the result of drying due to solar radiation falling on the south facing walls, which mitigated for the heavy rain falling on them.

The results indicated that the relative humidity in the walls is however dependant on the surface treatment. For thick coatings and/or with high water vapour diffusion resistance, the relative humidity was observed to be lower than for walls with either no coating, only water repellent impregnations or very thin coatings with high water vapour diffusion resistance. From the results it was concluded that the water repellents did not contribute in lowering the moisture content in the walls. Furthermore, surface treatment with low water vapour diffusion resistance showed similar performance as water repellents and no surface treatment did. Permeability measurements on similar coating materials with the cup method supported these results.

The author concludes that the high relative humidity of walls in Iceland is caused by the wet climate and comes from the exterior of the building, not the interior. Therefore, the author suggests a good vapour barrier on the outside of the wall. Since relative humidity was considerably lower for walls painted with coatings with high water vapour diffusions resistance, such a coating is proposed as a good vapour barrier for the exterior. However, as little barrier as possible is recommended on the interior side of the wall to allow for drying-out to the interior of the building.

### 4.4 Mould

Mould is a type of fungi which consists of many species and is often found in damp buildings. It produces airborne spores and is widely spread in the environment. Under favourable conditions, the spores will germinate and hypha will form. Under continuous favourable conditions the hyphae will form a mycelium, a hyphae colony. When the mould grows on building materials it produces numbers of compounds, such as mycotoxins that can have negative effect on human health. Furthermore, some type of mould can cause allergic reactions in people. The material, temperature, moisture conditions and co-
habitation with other mould species can influence which substances a mould specie produces [47, 48].

In this chapter, the conditions for mould growth are presented, mould species commonly found in concrete as well as mould prediction models for estimating mould growth in buildings.

4.4.1 Mould species

A wide variety of mould species have been found in damp buildings, counting in hundreds [49]. Studies have been conducted to investigate the most common mould species in concrete materials. In a large study by Andersen et al. [50], which was based on more than 5300 surfaces and 23 building materials, concrete showed the highest quantitative frequency. The study also identified 45 mould species incident on various building materials. The most common being Penicillium and Aspergillus versicolor. The study indicates that mould species have different associations with building materials and different materials attract different species of mould. For concrete, a high association was found with the Chaetomium family, Penicillium family and the Aspergillus family as those species may tolerate the alkaline conditions in concrete. On the other hand, a low association was found with Cladosporium sphaerospermum.

Hyvärinen et al. [51] studied the concentration of mould species on building materials. 25 mould species were identified and the study indicated the highest concentration of mould in wooden materials. Although the mould concentration was higher in wooden materials, 12% of the wooden samples were under the detection limits, whereas only 15% of samples for ceramic products (including concrete). The most frequently observed mould species for ceramic materials were found to be of the Penicillium family, Aspergillus family and Acremonium.

4.4.2 Critical factors for mould growth

The most critical factors determining the development of growth of mould and time needed for the beginning of mould growth is the interaction of humidity, temperature and exposure time [52]. Furthermore, the surface quality of the material plays an important part in determining mould growth [20, 49, 52], but other influencing factors include pH value and oxygen content [49].
Temperature, relative humidity and exposure time

Mould growth may occur in temperatures between 0 and 50°C [20, 49, 52]. Keeping in mind a normal temperature range inside buildings, it is unlikely that temperature is a limiting factor for mould growth. On the other hand, humidity conditions in walls and on the interior can better be controlled and thus the RH is more dominant for determining mould growth.

Water activity, $a_w$, describes the available humidity for the mould fungus. The $a_w$ can be obtained from both air and a building material in the form of liquid water or vapour [49]. RH and $a_w$ are directly linked according to equation 4.2:

$$RH = 0.01 \times a_w$$  \hspace{1cm} (4.2)

The term critical moisture conditions describes the lowest RH that risk degradation due to microbial contamination [53]. The critical levels of RH required for mould growth are dependent on the temperature and exposure time [52]. Furthermore, critical conditions for mould growth vary between different building materials as the potential for nutrient supply for the mould depends on the material type [54].

Nielsen et al. [55] reported mould growth on concrete to occur at 86% RH of and 25°C but when the temperature was decreased to 20°C the critical RH increased to 90%. Giannantonio et al. [56] observed mould growth on concrete at 95%-100% RH at 25°C. The Swedish National Testing and Research Institute, SP, estimates critical moisture levels to be 90-95% RH at 20°C during long term exposure at the concrete surface layer [53]. For lower temperatures the critical RH increases. The critical conditions are typically higher for pure or clean materials than for soiled or contaminated, due to different growth performance characteristics [20, 57]. Table 4.1 shows suggested values for critical relative humidity of concrete, insulation materials and soiled building materials.
Table 4.1: Examples of critical relative humidity of concrete, insulation materials and contaminated building materials

<table>
<thead>
<tr>
<th>Building Material</th>
<th>Critical Moisture Level [%RH]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>90-95</td>
<td>[53, 55]</td>
</tr>
<tr>
<td>Insulation Materials</td>
<td>90-95</td>
<td>[58, 59]</td>
</tr>
<tr>
<td>Contaminated or Soiled</td>
<td>75-80</td>
<td>[53]</td>
</tr>
</tbody>
</table>

The exposure time required to initiate mould growth depends on the material type [49] as well as the RH and temperature. Since RH and temperature fluctuate, knowledge of exposure time under favourable conditions is necessary in order to estimate the mould growth, as well as knowledge of the nutrient base [60]. The more time the humidity of a building material is over the critical RH the higher the risk of mould growth [61]. Viitanen and Ojanen [20] studied the effect of fluctuating temperature and relative humidity conditions on building materials. They observed that under fluctuating conditions, the exposure time required for initiating mould growth is controlled by RH, temperature and the periods of high and low humidity conditions. Viitanen and Bjurman (as cited in [61]) showed that a fungal growth will not occur under short periods of high humidity conditions if the preventing periods of low humidity conditions last long enough. Furthermore, periods of low humidity do not only hinder the growth of mould but have an effect on the total exposure time that is required for the occurrence of mould growth [61].

Different studies have shown different critical moisture levels. This can be explained by variations in the sensitivity to mould of individual materials, experimental setup, fungi type, duration, analytical method, frequency of analysis or the evaluation [62]. Furthermore, different studies may have different interpretation of when growth is considered critical [62]. There are several methods existing for the quantification of mould attack on materials [53]. One method identifies the level of mould by a microscope or a naked eye, other methods use the CO₂ diameter of colony or the total number of spores to decide on the the level of mould growth [53].
Substrate and surface quality

Building materials have different tolerance to moisture, but when critical moisture level and exposure time is exceeded, it may subsequently lead to the growth of harmful organisms, such as mould [20].

As a cement based material, concrete contains pores which may contain organic dust and give a potential of colonisation.

Factors impacting the concrete surface, such as aging, treatment, and accumulation of organic dust stimulate mould growth [20]. In dense concrete assemblies with critical humidity levels of air in the pores above 80%-90% RH, the most susceptible point for mould growth is a layer which contains an organic material [20]. However, Viitanen (cited in Viitanen & Ojanen [20]), shows that the limit rises to 97%-98% RH for growth in dense layers of new clean concrete.

Mineral composition, roughness and porosity are all substrate characteristics that influence the establishment of microorganisms [56, 63–67]. Roughness causes higher water retention and eases the adhesion of microorganisms and organic materials and consequently supports the growth of microorganisms [63]. The total porosity and the distribution of pore size within the material are influencing factors for absorption and retention of water and for the capillary rise where wall and soil are in contact [68, 69] and increased porosity is associated with higher risk of microorganism growth [70, 71]. Consequently, it has been suggested that the use of dense mortar can slow down microorganism growth [70].

Cheng et al. [65] studied the effect of moisture variation, including surface moisture and moisture content, and the microstructure (porosity) on the mould growth on cement based materials. Concrete with w/c of 0.4 and 0.6, as well as brick and tile were studied. The brick contained the highest total porosity, followed by cement mortar w/c=0.6, cement mortar w/c=0.4 and the tile, respectively. The results showed a corresponding relationship between high surface moisture and large pore size and number of pores. The higher the porosity, the more susceptible is the material to environmental humidity leading to larger fluctuations in the surface moisture [65].

According to the results, surface moisture, which is affected by the environmental humidity, was showed to influence mould growth [65]. Highly porous material, which has higher surface water ratio, enables mould spores to adhere to the material surface [65]. The results did
not indicate a significant correlation between the moisture content of
the material and mould growth, but showed that environmental tem-
perature and relative humidity affect surface water ratio which signif-
icantly contributes to mould growth [65].

Giannantonio et al. [56] studied the effect of concrete properties
on mould colonisation. In the study, the effect of water-to-cement ra-
tio (w/c) was examined. The results from the research agreed with
aforementioned study, i.e. it identified a strong relationship between
w/c ratio and mould growth, with higher ratio making concrete more
susceptible to mould.

**pH value**

Most fungi species grow within the pH range of 3 and 9 [49]. However,
despite the high pH value of concrete, which can be above 12, mould
growth may still occur as the pH value of the available nutrition is the
determining factor [49]. Due to weathering, the initial high alkaline
of concrete falls, enabling microorganisms to colonise on cement and
renderings [72].

### 4.4.3 Mould growth models

In order to provide healthy indoor environment it is important to to
make a reliable mould risk prediction in building components. There
are several prediction models existing that aim at evaluating mould
risk in building envelopes, including biohygrothermal model, temper-
ature ratio, isopleth systems, empirical VTT-model etc. [73]. Despite
extensive research, no model can feature a completely accurate and re-
liable prediction of the mould growth process [73]. All models differ
in assumptions and simplification of the mould process and conse-
quently, different models give rise to different conclusions in the anal-
ysis [73]. These variations lie in large differences in germination time,
mould intensity and the risk of mould growth [73].

**WUFI** offers two extensions to it’s hygrothermal software for cal-
culating the risk of mould growth in building components, **WUFI** Bio
and **WUFI** Mould Index VTT.
The VTT model

The VTT model, which is an empirical model, was developed by Hukka and Viitanen [19] for the prediction of mould growth on wooden materials. It is based on a visual inspection and is used for the quantification of mould growth [19]. The mould index classification is found in Table 4.2 where the mould index (MI) ranges between 0 (no mould growth) to 6 (visually detected 100% coverage and heavy mould growth). The mould growth rate is described by differential equations under fluctuating conditions. The VTT model includes temperature, RH, exposure time and dry periods [19]. The model is based on regression analysis of a set of experimental data for mould growth of different mould species on pine and spruce [19].

<table>
<thead>
<tr>
<th>Index</th>
<th>Description of Growth Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No growth</td>
</tr>
<tr>
<td>1</td>
<td>Small amount of growth detected with microscope, initial stages of local growth</td>
</tr>
<tr>
<td>2</td>
<td>Moderate growth detected with microscope, several local colonies</td>
</tr>
<tr>
<td>3</td>
<td>Some growth detected visually, &lt;10% coverage or &lt;50% coverage of mould (microscope)</td>
</tr>
<tr>
<td>4</td>
<td>Visually detected coverage, 10% - 50% coverage, or &gt;50% coverage of mould (microscope)</td>
</tr>
<tr>
<td>5</td>
<td>Visually detected coverage more than 50%, plenty of growth</td>
</tr>
<tr>
<td>6</td>
<td>Visually detected coverage 100%, heavy and tight growth</td>
</tr>
</tbody>
</table>

The critical relative humidity RH\(_{\text{crit}}\), is the lowest RH required to initiate mould growth if the material is exposed for a long enough time. RH\(_{\text{crit}}\) is a function of temperature and for the temperature range of 5-40°C RH\(_{\text{crit}}\) is described by a polynomial function:

\[
RH_{\text{crit}} = \begin{cases} 
-0.00267T^3 + 0.160T^2 - 3.137T + 100, & \text{when } T \leq 20^\circ C \\
RH_{\text{min}} & \text{when } T > 20^\circ C 
\end{cases}
\]

(4.3)

where RH\(_{\text{min}}\) is 80%. The complete mould index model which calculates incremental changes in the mould index under favourable conditions for pine and spruce is given by:
\[
\frac{dM}{dt} = \frac{k_1 k_1}{7 \times t_{M=1}} 
\]

The factor \(k_1\) defines the mould growth rate, which is presumed to be constant, under continually constant favourable conditions. The factor is given by:

\[
k_1 = \begin{cases} 
1 & \text{when } M < 1 \\
\frac{2}{t_v/t_m-1} & \text{when } M > 1
\end{cases}
\]

where \(t_m\) and \(t_v\) are regression equations for the time response (weeks) required to reach \(M=1\) (initiation of mould growth) and \(M=3\) (first visual appearance of mould growth), respectively. Under constant temperature and humidity conditions the time response for wood is given by the following equations:

\[
t_m = \exp(-0.68 \ln(T) - 13.9 \ln(RH) + 0.14W - 0.33SQ + 66.02) \tag{4.6}
\]

\[
t_v = \exp(-0.74 \ln(T) - 12.72 \ln(RH) + 0.06W + 61.50) \tag{4.7}
\]

where \(SQ\) stands for surface quality corresponding to original kiln-dried (1) and re-sawn (0) timber and \(W\) for wood species (pine=0, spruce=1) [19]. The upper limit for mould growth as described by equation 4.3 for \(RH_{crit}\), is implemented by the factor \(k_2\):

\[
k_2 = 1 - \exp[2, 3(M - M_{\text{max}})] \tag{4.8}
\]

The largest mould index value possible, \(M_{\text{max}}\) is the limiting value that the mould index does not rise above, regardless of exposure time under favourable conditions. This value lies on the range of 1 to 6 and assumes a parabolic form [19]:

\[
M_{\text{max}} = 1 + 7 \frac{RH_{\text{crit}} - RH}{RH_{\text{crit}} - 100} - 2 \left( \frac{RH_{\text{crit}} - RH}{RH_{\text{crit}} - 100} \right)^2 \tag{4.9}
\]

Finally, the model takes into account the declination of the mould growth index when conditions are unfavourable, such as fluctuating humidity conditions. The mould can therefore decline under dry periods. Although the visual appearance of the mould does not change during dry periods, the growth is delayed [19]. The delay is given by:
\[
\frac{dM}{dt} = \begin{cases} 
-0.032 & \text{when } t - t_1 \leqslant 6h \\
0 & \text{when } 6h \leqslant t - t_1 \leqslant 24h \\
-0.016 & \text{when } t - t_1 > 24h 
\end{cases} 
\] (4.10)

Where \( t - t_1 \) (h) represents the dry period. It must be noted that the mathematical description of the delay is based on limited number of observations where the period does not exceed 14 days and the temperature does not fall below 0°C.

**Improved VTT model - WUFI® Mould Index VTT**

The biggest draw-back of the original mould growth model are due to shortcomings in the simulation of long seasonal cycle under too dry or cold conditions and the limitation to spruce and pine [20]. Large sets of experiments on common building materials (spruce board, concrete, aerated concrete, cellular concrete, polyurethane thermal insulation, glass wool, polyester wool, EPS) in a climate chamber and in real climate conditions were conducted in order to improve the model. The main improvement of the VTT model is that it takes into account different mould growth types that occur on various material surfaces. For some materials, the mould growth coverage could already be high without being visible to the naked eye, such as in pores of concrete [74]. The mould index was updated accordingly and is emphasised in bold letters in table 4.2. The model was expanded as well, to include values for factors in equations 4.5, 4.9 and 4.10 for different building materials. Furthermore, the mould growth threshold value, \( RH_{\text{min}} \) in equation 4.3, was set to 85% for more resistant materials, \( SQ = 0 \) is used and times steps are reduced from days to hours [74].

In the improved VTT model, building materials are separated into four mould sensitivity classes: very sensitive, sensitive, medium resistant and resistant [74] (Table 4.4). The factor \( k_1 \) is calculated for each sensitivity class with pine sapwood as reference according to:

\[
k_1 = \begin{cases} 
\frac{t_{M=1,\text{pine}}}{t_{M=1}} & \text{when } M < 1 \\
2 \times \frac{t_{M=3,\text{pine}} - t_{M=1,\text{pine}}}{t_{M=3} - t_{M=1}} & \text{when } M > 1 
\end{cases} 
\] (4.11)
The factor $k_2$, according to equation 4.8 is determined for each sensitivity class through the equation of maximum mould index [74]:

$$M_{\text{max}} = A + B \times \frac{RH_{\text{crit}} - RH}{RH_{\text{crit}} - 100} - C \times \left(\frac{RH_{\text{crit}} - RH}{RH_{\text{crit}} - 100}\right)^2$$ (4.12)

with values for $A$, $B$ and $C$ depending on the material sensitivity classes. Values for $k_1$, $k_2$, $A$, $B$, $C$, and $RH_{\text{min}}$ are found in table 4.3.

Table 4.3: Parameters for the different mould sensitivity classes in the Improved VTT mould model [74].

<table>
<thead>
<tr>
<th>Sensitivity Class</th>
<th>$k_1$</th>
<th>$k_2$ ($M_{\text{max}}$)</th>
<th>$RH_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M &lt;1</td>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Very Sensitive</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Sensitive</td>
<td>0,578</td>
<td>0,386</td>
<td>0,3</td>
</tr>
<tr>
<td>Medium Resistant</td>
<td>0,072</td>
<td>0,097</td>
<td>0</td>
</tr>
<tr>
<td>Resistant</td>
<td>0,033</td>
<td>0,014</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.4: Sensitivity classes of building materials in the improved VTT mould model.

<table>
<thead>
<tr>
<th>Sensitivity Class</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Sensitive</td>
<td>Pine Sapwood</td>
</tr>
<tr>
<td>Sensitive</td>
<td>Glued wooden boards, PUR with paper surfaces, spruce</td>
</tr>
<tr>
<td>Medium Resistant</td>
<td>Concrete, aerated and cellular concrete, glass wool, polyester wool</td>
</tr>
<tr>
<td>Resistant</td>
<td>PUR with polished surfaces</td>
</tr>
</tbody>
</table>

The declination of the mould index for the improved model is estimated with a constant, relative coefficient $C_{\text{mat}}$ (Figure 4.6, Table 4.5), defined for the different types of materials in the study [74]. With this factor, the original declination model is improved:

$$\frac{dM}{dt_{\text{mat}}} = C_{\text{mat}} \times \frac{dM}{dt_0}$$ (4.13)
where \( \frac{dM}{dt}_{\text{mat}} \) is the mould decline intensity for the improved VTT model and \( \frac{dM}{dt}_{0} \) the mould decline intensity for pine in the original model [74].

![Figure 4.6: The relative decline intensity of mould (C_{mat}). Comparison of different building materials to pine in the original model [74].](image)

Table 4.5: Classification of mould index decline [74].

<table>
<thead>
<tr>
<th>C_{mat}</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pine in original model, short periods</td>
</tr>
<tr>
<td>0.5</td>
<td>Significant relevant decline</td>
</tr>
<tr>
<td>0.25</td>
<td>Relatively low decline</td>
</tr>
<tr>
<td>0.1</td>
<td>Almost no decline</td>
</tr>
</tbody>
</table>

**WUFI® Bio**

WUFI® Bio is based on two models, an isopleth model and a transient biohygrothermal model [49].

**Isopleth systems**

The water content of mould spores changes with ambient temperature and humidity. The water content that is required for the initiation of biological activity is called critical moisture content. The time needed
for germination of mould spores and mycelium growth under different combinations of temperature and RH is showed in temperature-humidity diagrams. In such diagrams, isopleths are the curves of equal germination time [49]. The isopleth model predicts the germination time of mould spores with regard to the substrate, temperature and humidity conditions and exposure time. The Lowest Isopleth for Mould (LIM) is the line under which no mould growth will occur. WUFI® Bio assumes occurrence of germination if ambient conditions exceed LIM of at least one mould specie which poses a health risk.

The substrate quality, i.e. the quality of the building material, has an influence on the critical moisture content as well. In order to account for that, the model uses three isopleth systems designed for three different categories of substrates. The substrate classes are the following [75, 76]:

0 Optimal culture media.
I Bio-utilizable building materials - e.g. wall paper, plaster, card board.
   Less bio-utilizable building materials - i.e. renderings,
II mineral building materials, certain wood,
   insulation materials not covered by I.

Some mould species are more critical to human health than others. The class K, hazardous class, is used to assess the growth risks of such species [76, 77]. Class K includes species such as Aspergillus flavus, Aspergillus fumigatus and Stachybotrys chartarum which are defined in literature as dangerous to human health [76, 77]. The isopleth systems for this class assume growth on optimal substrate (Class 0). Figure 4.7 illustrates the isopleth systems for all substrate classes as well as class K.
Figure 4.7: Left, 0-II, Sedlbauer’s isopleth systems for spore germination and mycelium growth for three substrate classes, as cited in [76]. Right, class K, the isopleth systems for the mould species critical to health [76].

**Biohygrothermal model**

The isopleth system can model the spore germination time or mycelium growth under transient boundary conditions of temperature and relative humidity. However, the disadvantage is that drying out of the spores cannot be taken into account [49, 76, 77]. Therefore, the isopleth systems will predict spore germination more often than is realistic. The biohygrothermal model calculates the moisture balance of a spore, which can absorb water from transient ambient boundary conditions [49]. This includes calculating the balance when the spore is drying out. The spore germinates when the moisture content has reached the critical value, according to the relevant LIM-curve on the isopleth systems, but no metabolic processes occur before that. Therefore, the influence of substrate is taken into account. The critical moisture content is calculated with help from the moisture storage function which is assigned to the spores [49]. The model calculates the transient water content of the spore, based on climate conditions and material data. For every time step a comparison is made with the temperature-dependant critical water content determined from the respective LIM. After germination has occurred, the model uses the mycelium growth
isopleth systems to estimate expected growth in millimetres. Once the moisture content falls below the critical water content of the spore the mycelium growth stops but resumes when the water content rises again[49].

The mould growth of WUFI® Bio [mm/day] can also be interpreted by the VTT mould index (Table 4.2) [75].

**Comparison between WUFI® Bio and WUFI® Mould Index VTT**

The difference between WUFI® Bio and WUFI® Mould Index VTT is the approach of the construction of the two models. The VTT model is a purely empirical mathematical model based on mould growth rates observed in laboratory experiments while. On the other hand, the biohygrothermal model simulates the moisture content of the mould spores depending on the temperature and relative humidity of the environment and compares it with the critical water content for spore germination. The VTT model calculates a decay in mould growth under unfavourable conditions whereas the biohygrothermal model assumes stagnant growth [75].

Due to the difference in the nature of these two models it can be assumed that different results may be obtained depending on which model is used. In a study by Vereecken & Roels [73], the VTT model always predicted less mould growth and in some cases it assumed no risk where WUFI Bio predicted mould risks.
Chapter 5

Moisture calculation configuration

5.1 Background

In this chapter, the moisture calculation configuration of the studies in Chapters 6 and 7 are described. In Chapter 6, the Icelandic wall is compared to another type of wall, which will also be described in this chapter.
5.2 Constructions

Icelandic wall type

The Icelandic wall type has a 180mm C25 concrete layer with 100mm interior EPS insulation. On the exterior side of the concrete is a 25mm surface coated screed which along with the concrete serves the purpose of the weather barrier. On the interior side of the insulation is a 25mm painted screed. The interior insulation is cut apart at the concrete slab [7]. The Icelandic wall construction and dimensions can be seen in figure 5.1.

Figure 5.1: The Icelandic wall type construction.
German wall type

The comparison wall for the study in Chapter 6 is exterior insulated as a contrast to the Icelandic wall. This exterior insulated concrete wall type will be hereafter be referred as the German wall type, as its design is influenced by this common wall structure in Germany. The German wall type has a 180mm concrete layer with 100mm exterior EPS insulation. On the exterior side of the insulation is a 25mm surface coated screed which serves the purpose of the weather barrier. On the interior side of the concrete is a 25mm painted screed. The German wall construction and dimensions can be seen in figure 5.2

Figure 5.2: The German wall type construction.
5.3 Data input in WUFI

Surface transfer coefficients

The surface transfer coefficients describe how conditions in the surrounding impact the building. They are largely dependent on the façade properties, such as the colour, as well as on solar radiation, wind and terrain. The surface transfer coefficients chosen are from the international standard ISO 6946 (2007) [78]. The surface transfer coefficients chosen for the studies are shown in Appendix A.2.

Calculation period

For achieving quasi steady state condition of a wall structure the dynamic simulation performed should consist of a period long enough for the wall to attain the same seasonal changes from year to year [79]. The simulation period was chosen as 6 years in all the simulation cases of this study as it resulted in a conclusive quasi state condition of the wall structure. The simulation starts at January 2018 and ends at December 2023. However, it must be noted that the years of calculation chosen will not impact the results, as the climate files used in WUFI represent a typical climate year at each location and therefore the same year is run throughout the calculation period.

Initial conditions

The ASHRAE standards [80] describes guidelines for determining the initial moisture content of the material layers and states a standard value corresponding to a 80% equilibrium moisture content in the material layers. There are some exceptions that suggest applying a higher value such as 90% initial initial moisture content of the material layers. That value should be used if the construction is known to have a higher moisture content due to e.g. driving rain on a unprotected façade or if a concrete layer is known to have a high initial moisture content. One reason for applying a higher initial moisture content can also be when the drying potential of the façade is to be studied [79]. For the simulation cases the initial temperature in the component was set at 20°C while the initial moisture content of the layers were set as 80% RH.
Orientation

The dominant direction of the driving rain was observed to be from the south-east direction in both Bergen and Reykavík. To study the hygrothermal properties and mould risk of the wall, it was decided to place the wall facing to the south-east in direction of the highest driving rain load. This was done to take into account the worst situation in terms of weather load on the wall.

Monitor position

The monitor position location was chosen to be on the interior surface of the concrete in both wall constructions. This point is known to be critical regarding condensation in the Icelandic wall structure. The monitor position in the Icelandic Wall structure is on the boundary between the concrete and interior insulation as illustrated in figure 5.3.

5.3.1 Material data

Due to the difference between Icelandic concrete and most concrete used in Europe as described in chapter 4, it was important to define a new material in WUFI® which would resemble the characteristics of the Icelandic concrete as much as possible. The material properties that are required for moisture calculations of concrete in WUFI® are:

- Bulk density
- Porosity
• Specific Heat Capacity
• Thermal Conductivity
• Water Vapour Diffusion Resistance Factor
• Moisture Storage Function
• Liquid Transport Coefficients for Suction and Redistribution

The Icelandic concrete used in the simulations as well as the experiment is characterised and named after the quarry of the aggregates, Vatnsskard. The data on bulk density already exists for the Vatnsskard concrete [7]. The moisture storage function of the Vatnsskard concrete has been measured[7] and can be found in Table B.1 (named Base Case) in Appendix B. Data on the porosity was not found. Therefore, the minimum porosity of the concrete was estimated by the moisture storage function where the porosity can not be less than the water content of the concrete at a 100% RH. Additionally, no information exists on the specific heat capacity so the value of a German concrete (w/c=0,5) from the Fraunhofer-IBP database in WUFI® was used. Values for the water vapour diffusion resistance factor and the thermal conductivity are approximations that have been used in previous studies of the Icelandic wall with the Glaser method [7]. The liquid transport coefficients have not been measured for the Vatnsskard concrete but as discussed in section 3.1.6 these coefficients can be generated with the A-value and the moisture storage function. The A-value of the Vatnsskard concrete has been measured [7] and therefore the liquid transport coefficients can be generated. Table 5.1 lists the parameters of the concrete used to approximate the Icelandic concrete.

Table 5.1: Material Properties of the Icelandic concrete.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density [kg/m³]</td>
<td>2113,9[7]</td>
</tr>
<tr>
<td>Porosity [m³/m³]</td>
<td>216</td>
</tr>
<tr>
<td>Specific Heat Capacity [J/kgK]</td>
<td>850</td>
</tr>
<tr>
<td>Thermal Conductivity [W/mK]</td>
<td>1,95[7]</td>
</tr>
<tr>
<td>Water Vapour Diffusion Resistance Factor [-]</td>
<td>80[7]</td>
</tr>
<tr>
<td>A-value [kg/m²s0,5]</td>
<td>0,032[7]</td>
</tr>
</tbody>
</table>
The screed commonly used in Iceland is also approximated for the simulations. Data on the bulk density and the moisture storage function exists (Table B.2 in Appendix B) [81] and the minimum porosity is again estimated from the moisture storage function. The value for specific heat capacity is from the Fraunhofer-IBP database in WUFI®. Values for the water vapour diffusion resistance factor and the thermal conductivity are approximations that have been used in previous studies of the Icelandic wall with the Glaser method [7]. The liquid transport coefficients are calculated from the A-value as is done for the concrete. The properties of the screed are listed in Table 5.2.

Table 5.2: Material Properties of the Icelandic screed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density [kg/m³]</td>
<td>1435 [81]</td>
</tr>
<tr>
<td>Porosity [m³/m³]</td>
<td>188</td>
</tr>
<tr>
<td>Specific Heat Capacity [J/kgK]</td>
<td>850</td>
</tr>
<tr>
<td>Thermal Conductivity [W/mK]</td>
<td>1.4 [7]</td>
</tr>
<tr>
<td>Water Vapour Diffusion Resistance Factor [-]</td>
<td>50/80 [7]</td>
</tr>
<tr>
<td>A-value [kg/m²s⁰.⁵]</td>
<td>0.02 [81]</td>
</tr>
</tbody>
</table>

For this study, EPS insulation density of 30kg/m³ was chosen for both walls from the WUFI database. Material properties can be found in Appendix A.

The material properties of the German wall are taken from the WUFI database and can be found in Appendix A.

5.3.2 Boundary conditions of the wall

The goal for determining the hygrothermal behaviour and performance of the simulation cases depends on a true realistic presentation of the boundary conditions on either side of the wall. For assessing plausible risks related to moisture damage it is recommended to simulate the worst possible situation that the wall is exposed to both on the interior side and on the exterior side. The wall construction should perform well both in terms of durability and relating to indoor air quality and thermal comfort [79].
Exterior climate

The weather file for Reykjavík is not built in to the WUFI software and therefore, the it was to be obtained from the meteorological weather station Veðurstofan, situated in Reykjavík. The weather data was obtained in ASCII format and was transferred with a WUFI weather climate file converter to .WAC file. This .WAC file is imported in WUFI when the weather in Reykjavík is to be simulated.

From weather data consisting of more than 10 years, the reference year was found to be the year 2015 which is a year with high precipitation. The weather reference year for Reykjavík was calculated using ÍST EN-15026 [82]. The comparison climate location chosen was the city of Bergen in Norway. The coastal climate of Bergen was chosen due to the fact that the driving rain load is also coming from the south-east direction, and the driving rain sum [mm/annum] is almost two times higher in Bergen. The climate data of Bergen in the WUFI database is based on the Moisture Design Reference Year (MDRY) [83]. In table 5.3 the exterior climate of Bergen and Reykjavík are compared. The climate analysis, outdoor relative humidity and air temperature for the reference year of Reykjavík and Bergen is shown in appendix A.

Table 5.3: Comparison of the weather year of Reykjavík and Bergen.

<table>
<thead>
<tr>
<th>Location</th>
<th>Temperature [°C]</th>
<th>Relative humidity [%]</th>
<th>Normal rain [mm/a]</th>
<th>Counterradiation [kwh/m²a]</th>
<th>Mean Cloud index [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reykjavík</td>
<td>4.6</td>
<td>20.2</td>
<td>-9.8</td>
<td>75.4</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>Max. 20.2</td>
<td>Min. -9.8</td>
<td>Mean 75.4</td>
<td>Max. 97</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sum 959.3</td>
<td></td>
<td>2618</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td>Bergen</td>
<td>8.1</td>
<td>28</td>
<td>-9.7</td>
<td>79.2</td>
<td>99</td>
</tr>
<tr>
<td></td>
<td>Max. 28</td>
<td>Min. -9.7</td>
<td>Mean 79.2</td>
<td>Max. 99</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sum 2421</td>
<td></td>
<td>2758</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.71</td>
</tr>
</tbody>
</table>

Interior climate

The interior climate has to be configured as the boundary condition on the interior side of the wall component. Indoor humidity level is directly related to the outdoor relative humidity level and the indoor moisture load. With higher air temperature it can be seen from the saturated water content, that the relative humidity increases for the same water content in air. The indoor air is indeed originated from the inflow of outdoor air inside the building and therefore has the same water content as the outdoor air with the addition of the indoor air moisture production.
In wintertime in a cold climate, the vapour content outdoors is low. When the cold outdoor air streams inside, it results in low relative humidity indoors [23]. In summertime there is a smaller temperature difference between indoor air and outdoor air which results in high relative humidity indoors in the summertime. The indoor relative humidity varies by geographical location and season.

As previously discussed the RH is associated with the vapour content of the air (kg/m\(^3\)) and the air temperature (°C). Ventilation rate is dependent on the type of facility and occupant behaviour. In bedrooms the air humidity can rise if not properly ventilated, and both bathrooms and laundry rooms usually have high moisture load.

There are few possible standards to determine the interior climate in WUFI. These are EN-15026/WTA 6-2, ISO 13788 or ASHRAE 160. Interior climate standard based on ISO 13788 was chosen for this study. It has five humidity classes. Two moisture load functions will be studied, level 2 and 4. The moisture load of humidity classes 1-4 of ISO 13788 can be seen in figure 5.4. The temperature was chosen to be constant 22°C throughout the year. The ISO moisture load functions describe the interior climate in terms of various moisture load and air change rate. This is described further in equation 3.18 where the air changes per second (n), and the moisture production (G), determine the slopes of the functions in figure 5.4.
Modelling water-repellent treatment of a façade

Without adding a water repellent treatment to the exterior screed of the concrete exterior walls in WUFI, the screed has a very low rain protection. The wetting and drying of the concrete in the exterior walls is highly dependent on the moisture behaviour of the exterior stucco. Therefore, the exterior boundary of the screed must be defined according to the water repellent treatment.

The water repellent surface treatment in the study cases is paint, and Fraunhofer [84] recommends adding a thin layer, corresponding to the penetration depth of the surface treatment. Fraunhofer [84] also suggests adjusting the A-value, the water absorption coefficient (kg/m²√h), for modelling the water-repellent treatment of the façade. This is a German recommendation according to the WTA-Merkblatt 3-17 [84].

For sufficient water vapour diffusion capability in order to allow the drying out of water due to imperfections, the $\mu$, diffusion resistance factor must not be increased by more than 50%. According to the recommendation, values of $A < 0,1$ kg/m²√h should be achieved i.e.
A<0,001667 kg/m$^2\sqrt{s}$ for a German standard.

Marteinsson et al. [85] studied the water absorption of of Icelandic screed. The results showed that an Icelandic screed with surface treatment (Monosilan 40) had a four times lower A-value than an Icelandic screed without surface treatment. Therefore, a new A-value for the surface treatment, four times lower than the exterior Icelandic screed (A=0.02 kg/m$^2\, s^{0.5}$) was chosen for the simulations. The A-value for the surface treatment was accordingly set as 0.005 kg/m$^2\, s^{0.5}$. Additionally to the A-value, the vapour diffusion resistance was chosen to be 50% higher than of the screed. Since the surface treatment is modelled with a thin layer, the sd-value of the exterior was set to 0.
Chapter 6

Comparison Study

6.1 Aim

In this chapter, dynamic numerical simulations of the transport of heat and moisture are used to determine the risk of high moisture content and mould using the hygrothermal simulation program WUFI® Pro. The aim of this study is comparing the hygrothermal performance of two different concrete outer wall structures with interior- and exterior insulation by performing a parametric study. The focus of the parametric study is to simulate the two wall types with different concrete properties and external conditions. The results of the simulations are used to evaluate the moisture conditions of each case with a comparative study in terms of relative humidity, temperature and total water content. The risk of mould growth at the monitor point is post-processed by the WUFI® Mould Index VTT add-on. The purpose of performing this parametric study is to clarify the hygrothermal performance and mould risk criteria of these two wall types under various conditions.
6.1.1 Hygrothermal and mould risk evaluation

The two wall constructions were studied by an investigation of the influence of parameter variation. The hygrothermal performance of the two wall constructions over the simulation period was compared in terms of relative humidity, temperature and mould risk at the monitor point. The total water content in each case was also simulated. The moisture calculation configuration is described in chapter 5. A post-processing analysis was used to determine the mould risk at the monitor point derived from the hygrothermal simulation results. This was done by evaluating the mould growth index and the traffic light classification using the improved VTT model described in section 4.4.3. As the monitor point is located on the interior surface of the concrete in both wall types, the mould sensitivity class was chosen to be medium resistant from table 4.4. Figure 4.6 shows that concrete is $c_{\text{mat}} = 0.2-0.4$ and therefore it is categorized as relatively low decline according to table 4.5. The soiling of the surface in terms of dust, nutrients and spores at the interior surface of the concrete can effect biological growth at the monitor point. In VTT there are two option for determining the surface quality, either cleaned or soiled. If a material surface has been in contact with surrounding air spaces (outdoor or indoor) for long periods which have accumulated nutrients and spores, VTT recommends the use of very sensitive material class. As there is a certain uncertainty in the two wall constructions whether the surface of the concrete is cleaned or contaminated with nutrients and spores, the material class is chosen as medium resistant but with the surface quality set to soiled. The interior screed should be air tight along with the paint layer which serves the purpose of vapour barrier. As the monitor point is located in an unventilated structure having practically no air leakages this results in very limited contact to air with nutrients for mould growth. This as a result should make the mould criteria more tolerant. The occupant exposition class was therefore defined as inside constructions without direct contact to interior air.

Traffic light classification

In addition to the mould growth index ranging from 0 to 6 seen in table 4.2, the WUFI® VTT provides a graphical representation of the mould risk by a traffic light classification consisting of green light, yellow light and red. This classification is only a guideline according to
the experience of VTT and IBP [86]. For interfaces and surfaces which are not in direct contact with the interior air such as the monitor points in the simulation cases there is only negligible risk of invisible starting mould growth with a mould index up to 2 and the traffic light remains green. The mould growth index range from 2 to 3 represents mould growth risk still invisible to the naked eye and gives a yellow light. This implies a mould risk that the user has to decide if he is prepared to accept for each case. When the Mould growth index reaches above 3 the mould growth starts to be visible and the traffic light give a red light. The red light indicates a high mould risk and should not be accepted [86]. In table 6.1 the traffic light classification risk evaluation is shown.

Table 6.1: The mould risk traffic light classification based on the mould growth index [MI] [86].

<table>
<thead>
<tr>
<th>Traffic light</th>
<th>Interior surface / Direct contact to the indoor air</th>
<th>Surfaces inside the assembly / No contact to the indoor air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>MI &lt; 1</td>
<td>MI &lt; 2</td>
</tr>
<tr>
<td></td>
<td>(i)</td>
<td>(i)</td>
</tr>
<tr>
<td>Yellow</td>
<td>1 ≤ MI ≤ 2</td>
<td>2 ≤ MI ≤ 3</td>
</tr>
<tr>
<td></td>
<td>(ii)</td>
<td>(iii)</td>
</tr>
<tr>
<td>Red</td>
<td>2 ≤ MI</td>
<td>3 ≤ MI</td>
</tr>
<tr>
<td></td>
<td>(iv)</td>
<td>(iv)</td>
</tr>
</tbody>
</table>

(i) No mould growth or only invisible growth (recognizable only by microscope, acceptable in indoor spaces)

(ii) Invisible growth, recognizable only by microscope

(iii) Growth starts to become visible to the naked eye

(iv) Mould growth is visible to the naked eye and starts covering the surface
6.2 Simulation cases and parameter variation

This study consists of two parts. In part I the focus will is on the effect of different type of wall structure, concrete, external climate and interior humidity load. In part II of this study the focus is on the effect of higher initial moisture, different orientation and different simulation start. Some background variables are held constant while other variables, are varied and studied if it affects the target variable, i.e. hygrothermal conditions and mould risk at the monitor position of each case.

6.2.1 Part I

In table 6.2 the simulation cases and the parameter variation of part I are shown. The moisture configuration is explained further in chapter 5.

<table>
<thead>
<tr>
<th>Variable</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Icelandic wall type</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>German wall type</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td></td>
</tr>
<tr>
<td>Concrete type</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Icelandic</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
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<td>German</td>
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<td></td>
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<td>x</td>
<td>x</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exterior Climate</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>x</td>
<td>x</td>
<td>x</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Interior moisture load</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<td>Humidity class 2</td>
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<td>x</td>
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6.2.2 Part II

In table 6.3 the simulation cases and the parameter variation of part II is shown.

Table 6.3: Simulation cases and parameter variation of part II.

<table>
<thead>
<tr>
<th>Variable</th>
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<th>21</th>
<th>22</th>
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<td>German wall type</td>
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<td>Concrete type</td>
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<td>Icelandic</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>German</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
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<td>Exterior climate</td>
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<td></td>
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<td>Reykjavík-Iceland</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>x</td>
</tr>
<tr>
<td>Interior moisture load</td>
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</tr>
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<td>Humidity class 2</td>
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<td>x</td>
<td>x</td>
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<td>90%</td>
<td>x</td>
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<td>Orientation</td>
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<td>Simulation start</td>
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<td></td>
</tr>
<tr>
<td>1. January</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1. May</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

6.2.3 Monitor points

In figure 6.1 the monitor point of the wall structures is shown.

![Figure 6.1: The monitor points of the two wall structures.](image-url)
6.3 Results and discussion

The maximum mould growth index and the traffic light classification results from part I and II are shown in table 6.4.

Table 6.4: Maximum mould growth index and the corresponding traffic light classification color.

<table>
<thead>
<tr>
<th>Case</th>
<th>Maximum Mould Growth Index</th>
<th>Traffic Light Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.117</td>
<td>Green</td>
</tr>
<tr>
<td>2</td>
<td>2.542</td>
<td>Yellow</td>
</tr>
<tr>
<td>3</td>
<td>0.366</td>
<td>Green</td>
</tr>
<tr>
<td>4</td>
<td>2.583</td>
<td>Yellow</td>
</tr>
<tr>
<td>5</td>
<td>0.000</td>
<td>Green</td>
</tr>
<tr>
<td>6</td>
<td>0.000</td>
<td>Green</td>
</tr>
<tr>
<td>7</td>
<td>0.000</td>
<td>Green</td>
</tr>
<tr>
<td>8</td>
<td>0.000</td>
<td>Green</td>
</tr>
<tr>
<td>9</td>
<td>0.133</td>
<td>Yellow</td>
</tr>
<tr>
<td>10</td>
<td>2.559</td>
<td>Green</td>
</tr>
<tr>
<td>11</td>
<td>0.760</td>
<td>Green</td>
</tr>
<tr>
<td>12</td>
<td>2.618</td>
<td>Yellow</td>
</tr>
<tr>
<td>13</td>
<td>0.000</td>
<td>Green</td>
</tr>
<tr>
<td>14</td>
<td>0.000</td>
<td>Green</td>
</tr>
<tr>
<td>15</td>
<td>0.000</td>
<td>Green</td>
</tr>
<tr>
<td>16</td>
<td>0.000</td>
<td>Green</td>
</tr>
<tr>
<td>17</td>
<td>0.185</td>
<td>Green</td>
</tr>
<tr>
<td>18</td>
<td>0.234</td>
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<td>19</td>
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<tr>
<td>20</td>
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<td>Green</td>
</tr>
<tr>
<td>21</td>
<td>0.117</td>
<td>Green</td>
</tr>
<tr>
<td>22</td>
<td>0.000</td>
<td>Green</td>
</tr>
</tbody>
</table>
6.3.1 Part I

Reykjavík climate

In this section the results from the simulations of Icelandic and German wall types located in the Reykjavík climate with Icelandic and German concrete are analysed and compared.

Effect of different wall types with Icelandic concrete

In figure 6.2 the temperature is shown at the monitor point for cases 1 and 5. The temperature was much more stable at the monitor point for the German wall (5), ranging from 20°C in the wintertime to 22°C in the summertime and oscillated with the indoor temperature variation. The Icelandic wall (1) had extreme variations in temperature, ranging from -7°C in the wintertime to 25°C in the summertime. This is due to the fact that the concrete has no thermal protection and its material layer oscillates with the outdoor temperature.

Figure 6.2: The temperature [°C] at the monitor point of the Icelandic concrete, Icelandic wall (1) and German wall (5).
In figure 6.3 the RH is shown at the monitor point for Icelandic cases 1 and 5. The RH of the Icelandic wall (1), rose quickly from the initial RH and reached slightly below 90% RH after 4 months. The RH then decreased again to 80% RH, entering its periodic seasonal equilibrium state ranging from 80% RH to 91%RH. The RH of the German wall (5) decreased linearly by 10% every year until it reached its equilibrium state at 50%RH.

Figure 6.3: The relative humidity [%] at the monitor point of the Icelandic concrete, Icelandic wall (1) and German wall (5).
In figure 6.4 the total water content is shown for cases 1 and 5. Similar to the RH, the water content quickly rose in the Icelandic wall (1) and reached its seasonal equilibrium state ranging from its maximum 32 kg/m$^2$ in May and drying to its minimum 28 kg/m$^2$ in August. The German wall decreased linearly from its initial water content until year 4 when it reached its seasonal equilibrium state ranging from 20 kg/m$^2$ to 22 kg/m$^2$.

Figure 6.4: The total water content [kg/m$^2$] of the Icelandic wall (1) and the German wall (5) with Icelandic concrete.
In figure 6.5 the mould growth index [-] is shown for cases 1 and 5. In the Icelandic wall (1) the mould growth index increased a bit the first year and then reached slightly above 0.11 the second year and then follows the seasonal moisture variation of the wall reaching 0.117 every year. There was no mould growth at the monitor point of the German wall (5).

Figure 6.5: The mould growth index [-] of the Icelandic concrete, Icelandic wall (1) and German wall (5).
Effect of different wall types with German concrete

For the German concrete (case 3 and 7) the temperature in the monitor point of the walls was analogous to figure 6.2. The temperature was stable for the German wall (3), ranging from 20°C in the wintertime to 22°C in the summertime. The Icelandic wall (3) had similar extreme variations in temperature, ranging from -7°C in the wintertime to 25°C in the summertime.

In figure 6.6 the relative humidity [%] is shown at the monitor point for cases 3 and 7. The RH of the Icelandic wall (3) increased directly, until its equilibrium state of 90% RH after 2 years and the seasonal oscillation was much lower compared to the Icelandic wall with Icelandic concrete (1). The RH increased and declined slightly above 90% every year. The RH of the German wall (7) decreased rapidly from its initial condition until it reached its 50% RH equilibrium steady state in the fourth year.

Figure 6.6: The relative humidity at the monitor point of the German concrete, Icelandic wall (3) and German wall (7).
In figure 6.7 the total water content [kg/m²] is shown for cases 3 and 7. The water content of the Icelandic wall (3) quickly reached its equilibrium seasonal state after the first year, fluctuating between 19 and 22 kg/m². The RH of the German wall (7) decreased linearly to its steady state after the fifth year varied between 11.5 and 13 kg/m² in its equilibrium state.

Figure 6.7: The total water content [kg/m²] of the Icelandic wall (3) and the German wall (7) with German concrete.
In figure 6.8 the mould growth index [-] is shown for cases 3 and 7. The Icelandic wall (3) had almost no mould growth the first year but the mould growth index jumped suddenly to 0.22 in the second year. The mould growth index then decreased quickly down to zero in the end of the second year. This continuous cycle continued in the next years reaching a new maximum crest every year until the sixth year when it reached its maximum crest value, 0.366. As with the German wall with Icelandic concrete (1) the German wall with German concrete (7) had no mould growth at the monitor point.

Figure 6.8: The mould growth index for the German concrete, Icelandic wall (3) and German wall (7).
**Bergen climate**

In this section the results from the simulations of Icelandic and German wall types located in the Bergen climate with Icelandic and German concrete are analysed and compared.

**Effect of different wall types with Icelandic concrete**

In figure 6.9 the temperature is shown at the monitor point for cases 2 and 6. Similarly to the Reykjavík climate the temperature was much more stable for the German wall type (6), ranging from $20^\circ C$ to $22^\circ C$. The Icelandic wall (2) in the Bergen climate had more extreme variations in temperature than in the Reykjavík climate. The temperature varied between $-6.9^\circ C$ in the wintertime to $29.9^\circ C$ in the summertime.

![Temperature Graph](image)

*Figure 6.9: The temperature [°C] at the monitor point of the Icelandic concrete, Icelandic wall (2) and German wall (6).*
In figure 6.10 the relative humidity [%] is shown at the monitor point for cases 2 and 6. For the Icelandic wall (2) the relative humidity increased rapidly the first year into the yearly periodic equilibrium state, ranging from 88% RH in the summertime to 95.3% RH in the wintertime. The RH at the monitor point was really close to 100% RH, in January every year, but did not reach condensation throughout the years. Table 4.1 proposes critical moisture levels at 20°C during long term exposure at the concrete surface layer to be 90-95% RH. The temperature at the monitor point was 20°C or higher for over four months every year, with 90% RH or higher every year. This implies a high mould growth risk. The German wall conversely decline rapidly about 10% every year until it reached its equilibrium state of 55% RH, 5% higher than in the Reykjavík climate.

Figure 6.10: The relative humidity [%] at the monitor point of the Icelandic concrete, Icelandic wall (2) and German wall (6).
In figure 6.11 the total water content [kg/m\(^2\)] is shown for cases 2 and 6. The German wall (6) dried out similarly as in the Reykjavík climate and the water content was around 24 kg/m\(^2\) in the equilibrium state. The water content of the Icelandic wall (2) increased rapidly the first year until it entered its periodic equilibrium state fluctuating between 32 and 35 kg/m\(^2\) which was higher than in the Reykjavík climate.

Figure 6.11: The total water content [kg/m\(^2\)] of the Icelandic wall (2) and the German wall (6) with Icelandic concrete.
In figure 6.12 the mould growth index [ - ] is shown for cases 2 and 6. For the Icelandic wall (2) the mould growth increased rapidly every year reaching its maximum at 2.54 in year 6. This results in a yellow mould light classification indicating mould risk. There was no mould growth in the German wall (6).

Figure 6.12: The mould growth index for the Icelandic concrete, Icelandic wall (2) and German wall (6).
**Effect of different wall types with German concrete**

For the German concrete (case 4 and 8) the temperature in the monitor point of the walls was analogous to figure 6.9. The temperature was stable for the German wall (3), ranging from 20°C to 22°C. The Icelandic wall (3) had similarly extreme variations in temperature, ranging from -6.9°C in the wintertime to 29.6°C in the summertime. In figure 6.13 the relative humidity [%] is shown at the monitor point for cases 4 and 8. The German wall (8) dried rapidly the first two years and then slowly reached its equilibrium state around 55 % RH in the fifth year. The RH of the Icelandic wall increased the first year until it reached its equilibrium state ranging from 92% to 95% RH. As in the Icelandic concrete this does not indicate a condensation at the monitor point but does likewise indicate a high mould growth risk according to table 4.1 when the temperature is 20°C or higher which is over 4 months every year.

![Figure 6.13: The relative humidity [%] at the monitor point of German concrete, Icelandic wall (4) and German wall (8).](image-url)
In figure 6.14 the total water content [kg/m$^2$] is shown for cases 4 and 8. The German wall (8) dried out slowly the first years until it reached its seasonal equilibrium state in the fourth year, fluctuating between 13.5 and 15.6 kg/m$^2$. The water content of the Icelandic wall (4) increased the first year until it reached its equilibrium state, fluctuating between 23 and 26 kg/m$^2$ throughout the simulation period. Compared to the Icelandic concrete (case 2 and 6) the German concrete had a relatively similar hygrothermal behaviour apart from a lower water content in its equilibrium state.

Figure 6.14: The total water content [kg/m$^2$] of the Icelandic wall (4) and the German wall (8) with German concrete.
In figure 6.15 the mould growth index \([-\] is shown for cases 4 and 8. For the Icelandic wall (4) the mould growth increased rapidly the first three years until it reached its equilibrium state with its maximum mould growth at 2.58 at year 6. This result gives a yellow light classification from table 6.1 indicating mould risk. There was no mould growth in the German wall (8).

Figure 6.15: The mould growth index for cases 4 and 8.
Effect of higher indoor moisture load

In this section the simulation cases 1-8 are compared to simulation cases 9-16 which in the same order are identical apart from a higher indoor moisture load. Increasing the indoor moisture load did not affect the temperature at the monitor point.

Reykjavík climate

Icelandic wall with Icelandic and German concrete

In figure 6.16 the RH [%] is shown at the monitor point for cases 1, 9, 3 and 11. Increasing the indoor moisture load for the Icelandic concrete wall (1) resulted in almost no effect on the RH of the identical wall (9). Increasing the indoor moisture load for the German concrete wall (3) resulted in higher RH at the monitor point for the identical wall (11), fluctuating between 89 and 91 % RH in its seasonal equilibrium state. Table 4.1 proposes $RH_{crit}$ at 20°C at the concrete surface layer to be 90-95% RH. The temperature at the monitor point of cases 1, 9 and 3 never reached 20°C when the RH was 90% or higher. Case 11 did nevertheless have around 11 days when $RH_{crit}$ applies and that does imply a high mould growth risk.

Figure 6.16: The relative humidity [%] of the Icelandic wall with Icelandic concrete (1 and 9) and German concrete (3 and 11).
The total water content of the Icelandic wall (9 and 11) did not change significantly with a higher interior load. It did increase the water content slightly in both walls but their behaviour was identical to Case 1 and 3 seen in figure 6.4 and 6.7 respectively. The wall did not dry out and the water content increased from its initial water content. In figure 6.17 the mould growth index [-] is shown for cases 1, 9, 3 and 11. It is clear that as the RH increased in the German concrete wall (11), this directly affects the mould growth at the monitor point. The mould growth increased periodically every year for the German concrete (11) and the maximum mould growth during the simulation period was 0.76. Increasing the moisture load did slightly affect the mould growth of the Icelandic concrete (1 and 9) with the maximum mould growth increasing from 0.11 to 0.13.

Figure 6.17: The mould growth index of the Icelandic wall with Icelandic concrete (1 and 9) and German concrete (3 and 11).
German wall with Icelandic and German concrete

In figure 6.18 the relative humidity [%] is shown at the monitor point for cases 5, 13, 7 and 15. Increasing the indoor moisture load for the German wall with German concrete (7) resulted in a higher RH for the identical wall (15). The RH decreased directly in the German wall (15), eventually reaching its equilibrium state in the sixth year, with 57% RH at the monitor point. Increasing the indoor moisture load for the German wall with Icelandic concrete (5) also resulted in a higher RH in the identical wall (13), reaching its equilibrium state in the sixth year, 60% RH. The RH of the German wall with German concrete decreased faster compared to the Icelandic concrete but both walls ultimately reached a very similar RH in the equilibrium state.

![Figure 6.18: The relative humidity [%] of the German wall with Icelandic concrete (5 and 13) and German concrete (7 and 15).](image)
The total water content of the German wall did not change significantly with the higher interior load. It did increase the water content slightly in both walls but their behaviour was identical to Case 1 and 3 seen in figure 6.4 and 6.7 respectively. The German wall dried out again for both concrete types with the water content around 10 kg/m² higher in the German wall with Icelandic concrete compared to the German concrete. There was no mould growth at the monitor point in cases 5 and 7 as previously shown. Increasing the interior moisture load did not affect the mould growth index in the German wall (cases 13 and 15) and both cases showed no signs of mould growth.

Bergen climate

Icelandic wall with Icelandic and German concrete

In figure 6.19 the relative humidity [%] is shown at the monitor point for cases 2, 10, 4 and 12. Increasing the interior humidity load did not affect the RH substantially in the Icelandic wall for both concrete types (10 and 12).

![Figure 6.19: The relative humidity [%] of the Icelandic wall with Icelandic concrete (2 and 10) and German concrete (4 and 12).](image)
The total water content of the Icelandic wall (2 and 4) did not change significantly with a higher interior load. It did increase the water content slightly in both cases but the behaviour was identical to cases 2 and 4 seen in figure 6.11 and 6.14 respectively. The wall did not dry out and the water content increased from its initial water content. Increasing the interior moisture load did not affect the mould growth substantially in the Icelandic wall. The traffic light classification remained yellow and the maximum mould growth for the Icelandic wall with Icelandic concrete (10) was 2.559 and slightly higher for the German concrete (12), 2.618.

**German wall with Icelandic and German concrete**

In figure 6.20 the relative humidity [%] is shown at the monitor point for cases 6, 14, 8 and 16. Increasing the indoor moisture load for the German wall with German concrete (8) resulted in a higher RH for the identical wall. The RH decreased every year and eventually the German concrete (16) reached its equilibrium state in the sixth year, with 60.6% RH at the monitor point. Increasing the indoor moisture load for the German wall with Icelandic concrete (6) also resulted in a higher RH in the identical wall (14), reaching its equilibrium state in the sixth year, with 63.6% RH at the monitor point. The RH of the German wall with German concrete (8 and 16) decreased faster compared to the Icelandic concrete (6 ad 14) but ultimately reached a very similar RH in the equilibrium state.
The total water content of the German wall did not change significantly with the higher interior load. It did increase the water content slightly in both walls but their behaviour was identical to Case 6 and 8 seen in figure 6.11 and 6.14 respectively. The German wall dried out again for both concrete types with the water content around 10 kg/m² higher in the German wall with Icelandic concrete compared to the German concrete. There was no mould growth at the monitor point in cases 6 and 8 as previously shown. Increasing the interior moisture load did not affect the mould growth in cases 14 and 16 and both cases showed no signs of mould growth.
6.3.2 Part II

In this section, the hygrothermal performance of the two wall types are investigated in terms of higher initial moisture content, different orientation and different simulation start. The Icelandic wall with Icelandic concrete (case 1) and the German wall with Icelandic concrete (case 5) were chosen for comparison in the Reykjavík climate. The simulation cases and parameter variation is shown in table 6.3.

Effect of higher initial moisture condition in wall

Here, the effect of increasing the initial moisture content of the wall structure from 80% to 90% was investigated.

In figure 6.21 the RH is shown at the monitor point for the Icelandic wall (1, 17) and the German wall (5, 18). The RH of the Icelandic wall (17) increased directly from its initial condition, 90% RH. The RH then starts dropping down at 92.3% RH in May and reaches its equilibrium state later that year, the same as in case 1, fluctuating between 80% and 91%RH every year. The RH of the German wall (17) decreased directly linearly until it reached a very similar equilibrium state as case 1, around 50% RH.
Figure 6.21: The relative humidity [%] at the monitor point for the Icelandic wall with 80% and 90% initial RH (case 1 and 17) and the German wall with 80% and 90% initial RH (case 5 and 18).

The total water content behaviour of the walls were similar to the RH. The Icelandic wall (17) dried out the first year until reaching the same equilibrium state as case 1. The total water content of the Icelandic wall fluctuated between 28 and 33 kg/m² in its equilibrium state. The German walls both dried out until reaching the same equilibrium state in the sixth year, fluctuating between 21 and 23 kg/m².

In figure 6.22 the mould growth index [-] is shown at the monitor point for the Icelandic wall (1, 17) and the German wall (5, 18). The mould growth index in the Icelandic wall (17) increased substantially higher in the first year compared to case 1. In the second year the Icelandic walls (1, 17) reached the same steady state mould growth cycles every year, increased in the summertime to 0.11 and decreased to zero in the wintertime. The German wall (18) had an interesting increase of mould growth index the first year due to higher initial moisture content. The temperature was always 20°C or higher at the monitor point of the German wall which results in positive conditions for mould growth if the RH is 90-95%. The German wall (17) dried out
during the simulation period and there is no mould growth after the first year.

Figure 6.22: The mould growth index at the monitor point for the Icelandic wall with 80% and 90% initial RH (Cases 1 and 17) and the German wall with 80% and 90% initial RH (Cases 5 and 18).
Effect of different orientation

To study the effects of different wall orientation the orientation of the two wall types were shifted to the north.

In figure 6.23 the temperature [°C] is shown at the monitor point for the Icelandic wall, south-east (1), north (19) and the German wall, south-east (5) and north (20). There was no change in temperature of the German wall. The temperature in the Icelandic wall shifted to the north was lower than the south-east oriented wall. The wall oriented to the north (19) had a maximum temperature 17.4°C in its seasonal cycle while in the wall oriented to the south-east (1) it was 24.6°C. This can be explained by the fact that the wall oriented to the north gains much less solar radiation.

![Figure 6.23](image-url)

Figure 6.23: The temperature [°C] at the monitor point of the Icelandic wall, south-east (1), north (19) and the German wall, south-east (5) and north (20).

In figure 6.24 the RH [%] is shown at the monitor point of the Icelandic wall (1,19) and the German wall (5,20) with orientation to the north and south-east. The RH fluctuation of the Icelandic wall was much higher when orientated to the south-east due to more solar radiation. The Icelandic wall (19) never reached the RH_{crit} during its simulation period. The RH of the German wall (5,20) did not change sub-
stantially by shifting the orientation and the RH decreased the whole simulation period until its equilibrium state in the sixth year.

![Figure 6.24: The relative humidity [%] at the monitor point of the Icelandic wall, south-east (1), north (19) and the German wall, south-east (5) and north (20).](image)

The total water content of the wall had similar behaviour as the RH. The German wall dried out and the Icelandic wall had lower fluctuations of water content in its equilibrium state while orientated to the north. Shifting the orientation of the German wall type did not result in change of mould growth index for the German wall and the mould growth index remained zero. The mould growth index of the Icelandic wall (1) orientated to the south-east can be seen in figure 6.5, where the maximum mould growth index was 0.117. Shifting the Icelandic wall to the north resulted in zero mould growth index throughout the years. This can be explained by a lower temperature for the north orientated wall (19) and that it has a lower RH, reaching a maximum 83% RH every year.

**Effect of different simulation start**

Here the simulation period started in January and May respectively, and its effect was compared. In figure 6.25 the total water content is
shown at the monitor point the first two years for the Icelandic wall (cases 1 and 21) and the German wall (cases 5 and 22). The Icelandic wall starting in May (21) directly began to dry out but rapidly entered the same seasonal equilibrium state amplitude of the Icelandic wall starting in January with the water content fluctuating between 28 and 32 kg/m$^2$. The water content of the German walls (5,22) showed similar behaviour pattern with both walls drying out.

Figure 6.25: The total water content [kg/m$^2$] for for the Icelandic wall (cases 1 and 21) and the German wall (cases 5 and 22).

Shifting the simulation start did not affect the mould growth index in the German wall (5,22). Shifting the simulation start did not affect the amplitude of the mould growth index of Icelandic wall, but did result in an earlier mould growth index equilibrium state for the wall starting in May.
6.3.3 Summary

The German wall showed no risk of mould growth in neither Icelandic or Norwegian climate conditions according to VTT mould growth model. The German wall has a stable temperature variation at the interior surface of the concrete fluctuating between 20 and 22°C. The total water content of the German wall dries out throughout the six years reaching an equilibrium water content between 21 and 25 kg/m² with a Icelandic concrete and 12 to 15 kg/m² with a German concrete in the equilibrium state. The RH at the interior surface of the concrete walls decreases in each case from its initial RH reaching an equilibrium state between 50 and 55% RH. No German wall had a mould risk at the concrete surface, All of the German wall types dried out constantly with the relative humidity decreasing almost the whole period until reaching its seasonal steady state equilibrium in the fifth or the sixth year. The Icelandic wall showed a risk of mould growth at the interior surface of the concrete in the Bergen climate with a yellow light mould risk classification at the monitor point which implies a mould growth visible to the naked eye. The yellow light and the mould growth index implies a mould risk that the user has to decide if he is prepared to accept. The risk of mould growth in the Reykjavík climate was lower and did not imply a mould growth risk. The Icelandic wall has extreme variations in temperature ranging between -7°C in the winter time up to 29°C in the summertime. The total water content of the Icelandic wall does not dry out and is between 28 and 36 kg/m² with Icelandic concrete and 19 and 26 kg/m² with German concrete in its equilibrium state. The RH at the interior surface of the walls increased in every case from its initial RH reaching an equilibrium state between 80 and 95% RH with Icelandic concrete and 90 to 95% RH with German concrete. Table 4.1 from the Swedish National Testing and Research Institute estimates critical moisture levels for mould growth to be 90-95% RH at 20°C during long term exposure at the concrete surface layer. The high temperature variation in the Icelandic wall with Icelandic concrete in Reykjavík, has an negative effect on the mould growth due the low temperature in the wintertime when the RH is highest. Due to the high RH fluctuation/variation at the monitor point of the Icelandic wall with Icelandic concrete (case 1), the temperature at the monitor point was between -3-16°C when the RH humidity is at its maximum seasonal RH value, 91%. The RH at the surface
starts decreasing from the maximum RH when the temperature starts increasing. When the temperature at the monitor point reaches 20°C the relative humidity has dropped to down to 80%. This cycle continues throughout the simulating period for the Icelandic wall (case 1).

The maximum mould growth index results and the traffic light classification estimating the mould risk can be seen in table 6.4. The Icelandic wall type in Bergen with Icelandic and German concrete (cases 2, 4 10 and 12) resulted in a yellow light mould risk classification at the monitor point. This implies a mould growth visible to the naked eye. The mould growth index was around 2.6 for these cases which implies a mould risk that the user has to decide if he is prepared to accept. This clearly shows the sensitivity of the Icelandic wall type to driving rain, taking into account that the driving rain load in Bergen is almost double the driving rain load in Reykjavík. The results also showed that the Icelandic wall with German concrete resulted in higher relative humidity at the interior surface, higher mould growth index and a lower total water content of the wall compared to an Icelandic wall with Icelandic concrete. The effect of increasing the interior moisture load had almost no effect on the RH at the monitor point of the Icelandic walls. Increasing the interior moisture load did affect the German walls more but they still managed to dry out. The effect of increasing the initial moisture content of the wall from 80 to 90%RH had no effect on equilibrium RH state of the the Icelandic wall. The effect of increasing the initial moisture content of the German wall did result in a higher RH the first five years during its drying, but ultimately it reached its equilibrium state in the sixth year with similar RH as the wall with 80% initial moisture content. The effect of shifting the orientation of the Icelandic wall to the north had an effect on the RH resulting in lower variation in RH due to less driving rain load. The temperature was substantially lower due to less solar radiation. The effect of shifting the orientation of the German wall had no effect on the temperature and low effect on the RH, apart from lower fluctuation of total water content. The effect of different simulation start had little effect on the temperature and moisture condition performance of both wall types. From the results of the study it is clear that the interior insulated concrete Icelandic wall performs worse than the exterior insulated concrete German wall when comparing the moisture content and mould risk of the two wall types. Placing the insulation on the interior side of the concrete clearly has an large effect on the moisture content in
the wall and does increase the mould growth risk on the interior sur-
face of the concrete. There is an uncertainty in many parameters used
for the materials in the simulation cases and some are approximated
from known factors. The material properties and important param-
ters affecting the hygrothermal behaviour of the wall structures will
be evaluated through an sensitivity analysis in chapter 7.
Chapter 7

Parametric study

7.1 Purpose

Computational simulations on hygrothermal performance of building assemblies have not yet become a standard procedure in the design process of buildings in Iceland. There is a lack of experience with computational simulations, e.g. with WUFI, estimating hygrothermal performance of the Icelandic external concrete wall. Furthermore, the lack of knowledge of many important parameters in Icelandic material data causes a large uncertainty in simulations.

The simulations from the comparative study are to a large extent based on estimations of various parameters related to Icelandic building materials. In order to evaluate the influence of these parameters on the simulation results, a sensitivity analysis is conducted in this chapter. The purpose is to investigate the impact of the estimated parameters on the simulations results.

7.2 Simulation cases and parameter variations

In this parametric study, the impact of different parameters on the relative humidity conditions in the Icelandic wall is evaluated. The Icelandic wall is the same as described before (Chapter 5), insulated on the interior side of the wall and constructed from Icelandic building materials. In this chapter, this configuration will hereafter be referred to as the Base Case.
As results from chapter 6 have indicated, the impact of wind driven rain on the Icelandic wall is large. Therefore, the starting point of the parametric study is to investigate the impact of different external coating on the moisture behaviour of the wall. Based on the results from this study, two additional types of coating will be chosen to undergo a further parametric analysis. The aim is then to compare the impacts of parameter variations on the three different types of coatings and compare the moisture behaviour of the wall.

The choice of simulation cases in the study was based on number of simulations that were performed to test the sensitivity of the wall to different parameters. In this study, the performance of the wall is evaluated based on the levels of relative humidity at the interface of the concrete and insulation, as this has been shown to be the critical point in the Icelandic wall. Additional to the surface coating, the following parameters are studied for the Icelandic wall with three different coatings:

- Interior finish
- A-value of concrete
- Moisture storage function of concrete
- Penetration depth of coating
- Moisture storage function of external screed

**Surface coating on the exterior surface**

The exterior surface coating, i.e. in this case the paint, is simulated by adding a thin layer on the exterior surface, which mainly has two properties: water vapour diffusion resistance factor and water absorption coefficient. By adjusting these two parameters of the layer, different types of coating can be achieved. When the the \( \mu \)-value is changed, only the diffusion resistance is affected and not the rain-permeability of the coating. To model a coating that includes the rain-permeability, the liquid transport coefficients of the outermost surface are altered by changing the A-value (Water absorption coefficient).

In the parametric study, the water absorption and the vapour diffusion resistance are varied around the base case, as can be seen in table 7.1. The table also gives the driving rain protection coefficient \((C_{RP})\) (as
Table 7.1: A and $\mu$-values tested in the parametric study. The grey numbers represent values above the driving rain protection coefficient $C_{RP}$.

<table>
<thead>
<tr>
<th>$A / \mu$</th>
<th>1</th>
<th>15</th>
<th>45</th>
<th>75</th>
<th>160</th>
<th>240</th>
<th>320</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0003</td>
<td>0.0001</td>
<td>0.0015</td>
<td>0.0045</td>
<td>0.0075</td>
<td>0.0160</td>
<td>0.0240</td>
<td>0.0320</td>
</tr>
<tr>
<td>0.001</td>
<td>0.0003</td>
<td>0.0045</td>
<td>0.0135</td>
<td>0.0225</td>
<td>0.0480</td>
<td>0.0720</td>
<td>0.0960</td>
</tr>
<tr>
<td>0.0015</td>
<td>0.0005</td>
<td>0.0068</td>
<td>0.0203</td>
<td>0.0338</td>
<td>0.0720</td>
<td>1.0800</td>
<td>1.4400</td>
</tr>
<tr>
<td>0.002</td>
<td>0.0006</td>
<td>0.0090</td>
<td>0.0270</td>
<td>0.0450</td>
<td>0.0960</td>
<td>0.1440</td>
<td>0.1920</td>
</tr>
<tr>
<td>0.003</td>
<td>0.0009</td>
<td>0.0135</td>
<td>0.0405</td>
<td>0.0675</td>
<td>0.1440</td>
<td>0.2160</td>
<td>0.2880</td>
</tr>
<tr>
<td>0.005</td>
<td>0.0015</td>
<td>0.0225</td>
<td>0.0675</td>
<td>0.1125</td>
<td>0.2400</td>
<td>0.3600</td>
<td>0.4800</td>
</tr>
<tr>
<td>0.0085</td>
<td>0.0026</td>
<td>0.0383</td>
<td>0.1148</td>
<td>0.1913</td>
<td>0.4080</td>
<td>0.6120</td>
<td>0.8160</td>
</tr>
<tr>
<td>0.0224</td>
<td>0.0067</td>
<td>0.1008</td>
<td>0.3024</td>
<td>0.5040</td>
<td>1.0752</td>
<td>1.6128</td>
<td>2.1504</td>
</tr>
</tbody>
</table>

described in section 4.3) of a 5 mm coating, for the different $A$-values and $\mu$-values.

In this parametric analysis the importance of coating for the relative humidity conditions in the wall is evaluated.

**Interior finish**

In the parametric study, the term ‘interior finish’ covers the screed and painting on the internal side of the wall. As mentioned in section 1.2, experts have suspected that the reason for condensation inside the wall is due to warm, moist air entering the wall from the inside of a building and meeting the cold concrete. Therefore, the properties of the interior finish are varied to study the impact of different materials applied as interior finish on the moisture behaviour at the monitor point. The two parameters studied are the sd-value of the coating and the moisture storage function of the screed. Both parameters are subjected to two different humidity classes, 1 and 4. The sd-values tested are 0.4, 2.5 and 5. The moisture storage function is illustrated in figure 7.1. The functions can be found in tableB.2 in Appendix B.

The aim of this sensitivity analysis is to observe if interior conditions impact the relative humidity in the monitor point.

**Different types of concrete**

In this sensitivity analysis the impact of different types of concrete will be evaluated through two parameters: the water absorption coefficient
Figure 7.1: Moisture storage functions of the interior screed tested in the parametric study [87, 88].

Table 7.2: Simulation cases of the interior finish.

<table>
<thead>
<tr>
<th>RH</th>
<th>MSF</th>
<th>RH</th>
<th>sd</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Class 1</td>
<td>C1</td>
<td>Class 1</td>
</tr>
<tr>
<td>S2</td>
<td>Class 1</td>
<td>C2</td>
<td>Class 1</td>
</tr>
<tr>
<td>S3</td>
<td>Class 1</td>
<td>C3</td>
<td>Class 1</td>
</tr>
<tr>
<td>S4</td>
<td>Class 4</td>
<td>C4</td>
<td>Class 4</td>
</tr>
<tr>
<td>S5</td>
<td>Class 4</td>
<td>C5</td>
<td>Class 4</td>
</tr>
<tr>
<td>S6</td>
<td>Class 4</td>
<td>C6</td>
<td>Class 4</td>
</tr>
</tbody>
</table>

(A-value) and the moisture storage function. The aim is to observe whether moisture performance depends on the pore characteristics of the concrete, i.e. whether less or more porous materials perform better.

**A-value of concrete**

Only one source exists that has estimated the A-value of the Icelandic concrete used in the comparative study [87]. The A-value describes the
water uptake in the concrete and errors in the choice of the value in the Base Case could impact the moisture conditions in the wall. Therefore, the A-value of the concrete is subjected to a sensitivity analysis. The A-value tested is varied over a range of $0.003 < A < 0.061$. The highest and the lowest values are from concrete in the WUFI database but other values are for different types of Icelandic concrete [87].

**Moisture storage function of concrete**

As with the A-value, there is only one source for the moisture storage function of the Icelandic concrete [87]. The moisture storage function depends largely on the pore system of the material, where higher porosity leads to higher moisture content in the material. Figure 7.2 illustrates the three moisture storage functions compared in the parametric study, the Base Case and two others. MSF1 is taken from the WUI data base, whereas MSF2 is created to show the impact of higher moisture storage function than of the Base Case. The moisture storage functions are illustrated in Appendix B in tabulated form.

![Figure 7.2: Moisture storage functions of the concrete tested in the parametric study [87].](image-url)
Penetration depth of coating

The Base Case assumes a 5mm thick layer of external coating on the wall. The penetration depth depends on the type of screed it is applied to (such as the porosity) and the value used in the Base Case is the upper limit (J. Bjarnason, personal communication, May 7, 2018). Therefore, the study tests less penetration depth of the coating than the Base Case assumes, in order to evaluate the importance of selecting the correct penetration depth.

The aim of this parametric analysis is to observe if the thickness and penetration depth of the exterior coating influence the moisture behaviour of the wall in the monitor point.

Moisture storage function of external screed

In the Base Case, a typical Icelandic exterior screed is used. This screed has a high moisture storage function and therefore it is of interest to test the impact of a lower moisture storage function on the behaviour of the wall. For that purpose, a moisture storage function from the WUFI database was chosen as a reference. The reference moisture storage function lies much below the Icelandic one, as illustrated in figure 7.3. The functions can be found in table B.2 in Appendix B.

7.3 Results and discussion

In this chapter, the results from the parametric study are presented along with a short discussion on each parameter.

7.3.1 Surface coating of the exterior surface

Altering the values of the vapour diffusion resistance factor and the rain permeability effects the moisture behaviour of the wall. The A-value (water absorption coefficient) controls the water uptake of the coating, where higher A-value means more liquid absorption of the coating. On the other hand, the $\mu$-value (diffusions resistance factor) controls the drying out through the coating, where low $\mu$-value is vapour open and high $\mu$-value hinders the water vapour diffusion. This behaviour is illustrated in figures 7.4 and 7.5.

From the figures, it can be seen that the type of exterior coating plays a vital role in the performance of the Icelandic exterior wall. Wa-
parametric study results in high relative humidity conditions on the interface of the concrete and the insulation whereas low permeable coatings result in drying of the wall.

Figure 7.4 shows 8 graphs, each representing one A-value of the coating. For every A-value, six different μ-values are plotted. When a coating has a low A-value, μ becomes the controlling factor for moisture conditions within the wall. With increasing A-value the impact of μ decreases until the rain completely dominates the moisture behaviour. Based on these results, the wall shows high sensitivity to rain exposure.

Figure 7.5 shows 6 graphs, each representing one μ-value of the coating. For every μ-value, eight different A-values are plotted. As can be seen, the Base Case (A=0.005) lies on the higher end of the graph, indicating a poor performance of the coating. Due to that, two other coatings are additionally selected to the Base Case to undertake a further parametric study, in order to evaluate the effect of parameter variations on differently performing coatings.

The coatings were selected with two criterion in mind: their C_{RP} and the relative humidity profile in the monitor point. Table 7.3 shows the values of A and μ for each of the coatings chosen and the respec-
tive $C_{RP}$ values. The Base Case has a $C_{RP}$ slightly higher than the adequate performance limit proposed by Künzel et al. [46] and C-II has a value that is slightly lower. C-I has a value that is much lower than the performance limit. This type of coating could represent a high performance coating such as StoColor Lotusan®[89]. Additionally, all coatings are below the recommended limits of $A$ and $\mu$-value proposed by Künzel et al. [46] (see section 7.2).

Figure 7.6 illustrates the relative humidity profiles of the three coatings. As can be seen, all three coatings have a different behavioural pattern, which impacted the selection of these three coatings. The Base Case fluctuates around RH of 85% and reaches above 90% during the winter months. For case C-I, the relative humidity decreases with time and reaches below 70% after three years. C-II also decreases, but with much less slope than C-I and mainly fluctuates between RH of 75%-80%.

Table 7.3: $A$, $\mu$ and $C_{RP}$ values of coatings in parametric study.

<table>
<thead>
<tr>
<th>Coating</th>
<th>$A$-value [$kg/m^2s^{0.5}$]</th>
<th>$\mu$ [-]</th>
<th>$C_{RP}$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-I</td>
<td>0.001</td>
<td>45</td>
<td>0.0135</td>
</tr>
<tr>
<td>Case-II</td>
<td>0.002</td>
<td>160</td>
<td>0.096</td>
</tr>
<tr>
<td>Case-III</td>
<td>0.005</td>
<td>75</td>
<td>0.1125</td>
</tr>
</tbody>
</table>
Figure 7.4: Results of exterior coatings with different $A$-values. For each $A$-value, various $\mu$-values are plotted.
Figure 7.5: Results of exterior coatings with different $\mu$-values. For each $\mu$-value, various A-values are plotted.
Figure 7.6: The three external coatings selected for a further parametric study.
7.3.2 Interior finish

The results from the sensitivity analysis on the interior finish are illustrated in figures 7.7 and 7.8. As can be seen, the sd value of the interior coating doesn’t have a large impact on the results, independent from both the relative humidity load on the interior side and the exterior coating of the wall. This indicates that the wall is not affected by the drying-out potential on the interior side and therefore can it be concluded that the sd-value of the interior coating is not critical for the Icelandic wall. The same applies for the moisture storage function of the interior screed, in fact the two parameters show similar graphs. The conclusion is that the interior conditions, be it relative humidity or material properties of the screed and coating, do not play a significant role for the Icelandic wall. This conflicts with the current believe that the Icelandic wall is largely affected by the interior relative humidity condensing on the concrete surface.

Figure 7.7: RH in the monitor point for different moisture storage functions of the interior screed.
7.3.3 A-value of concrete

The impact of different A-value of the concrete is illustrated in figure 7.9. From the results it is observed that the A-value of the concrete has an impact on the RH in the observation point for all three cases. In Case-I, where the rain has negligible impact on the wall, the general trend of all the RH profiles is decreasing. For that case, the lowest A-value of the concrete (A=0.003) shows the highest RH profile whereas the highest value (A=0.061) shows the lowest RH profile. Except during the first year of A=0.003, the relative humidity does not go above 85% for any of the A-values. In Case-II, the difference between the results decreases at the same time the relative humidity at the monitor point barely goes below 75% for all A-values. Higher A-values of concrete still show slightly better results than lower A-values. For Case-III, where rain has much more impact, the effect is turned around. The three higher A-values show much larger fluctuations and reach above RH of 90% during winter.

With a rain permeable coating, rain has more impact on the wall
and less permeable concrete performs better. However, with high performance coating such as in Case-I, a water permeable concrete shows the best performance regarding relative humidity in the monitor point. Therefore, the Icelandic wall would show the best performance with Icelandic concrete and high performance coating.

After silica fume was introduced to cement in Iceland, it can be concluded that the concrete got more dense and less permeable (see Section 4.1.2). It can be concluded from the results of this parametric study that the performance of the Icelandic wall might have changed to better or worse with added silica fume, depending on the type of coatings applied.

![Graphs of RH as a function of concrete A-value for Case-I, Case-II, and Case-III](image)

Figure 7.9: Impact on the RH of the monitor point as a function of the concrete A-value.

### 7.3.4 Moisture storage function of the concrete

The results of the simulations for the different moisture storage function is illustrated in 7.10. As can be seen, moisture behaviour in the observation point is impacted by the moisture storage function of the concrete.
MSF1 has the lowest moisture storage function and when rain is reduced as in Case-I, it gives by far the worst results. MSF2 has a slightly higher moisture storage function than the Base Case and gives the best performance in Case-I.

For Case-II however, the difference in performance of the moisture storage functions is reduced. Base Case and MSF2 show similar peak values of relative humidity, 80%, but MSF2 has larger fluctuations. MSF1 shows still the worst performance of all, both regarding peak values and stability.

In Case-III all moisture storage functions show similar results as they fluctuate around RH of about 85%. Figure 7.11 shows the behaviour of walls with various coating for each moisture storage function. From these graphs, it is observed that the coating does not effect the RH in the observation point for MSF1. For the other two moisture storage function, the type of coating has a large impact on the performance of the wall.

The concrete with the lowest moisture storage function, MSF1, shows the highest RH for the two coatings with lower A-values (A=0,001 and A=0,002). For A=0,005, MSF1 shows a slightly lower RH profile than the other two moisture storage functions. This behaviour resonates with the results from the A-value of the concrete. MSF1 has a lower moisture storage function, which indicates higher density of that concrete whereas the porous Icelandic concrete has a higher moisture storage function. With a rain permeable coating, rain has more impact on the wall and a concrete with low moisture storage function performs a bit better. However, with high performance coating such as in Case-I, a concrete with higher moisture storage function shows the best performance regarding relative humidity in the monitor point.
Figure 7.10: Results from the sensitivity analysis of the moisture storage function of concrete. Here, each graph represents one coating type plotted as a function of different moisture storage function.
7.3.5 Penetration depth of coating

The impact of the penetration depth of the exterior coating is illustrated in figure 7.12. The Base Case assumes 5 mm thickness of coating, which, as stated earlier (Section 7.2), is the upper limit of the penetration depth. This results in the best performance of all cases. The penetration depth of the coating plays a role for the two better coatings, $A=0.001$ and $A=0.002$. However, the impact is little when the coating is more open for rain water as in the case for $A=0.005$. 
7.3.6 Exterior screed

In figure 7.13 the comparison of the two exterior screed moisture storage functions is illustrated. As can be noticed, the results of the moisture storage function of the Icelandic screed are very sensitive to the type of exterior coating whereas the screed from the database gives the same results independently of the coating. As with the moisture storage function of the concrete, the less dense material gives better results for a high performance coating (A=0.001) but when the rain has larger impact on the wall, the more open moisture storage function performs much worse. The A-value of the screed was also tested, but showed negligible results and will therefore not be discussed.
7.3.7 Discussion

In the previous sections, the results of the parametric study have been presented. The results indicate that the Icelandic wall is not showing condensation at the interface of the insulation and concrete under any circumstances for Icelandic climate.

From the parametric study, the wind-driven rain seems to be the dominating factor regarding the moisture behaviour of the wall. Yet, the relative humidity at the point of interest never reaches 100% no matter how poor the exterior coating of the wall is. This agrees with the observations made by Gíslason [8] discussed in section 4.3.1, that is, the high moisture conditions in the wall are due to the exterior climate but not interior conditions. However, the parametric study does not reflect the observations made by Gíslason that high water vapour diffusion resistance has a more impact acquiring lower relative humidity in the wall than the water absorption. The results from the parametric study showed that the water absorption plays a large role in determining the relative humidity conditions in the wall and that the
combination of low water absorption and low water vapour resistivity give the best hygrothermal performance of the wall.

Gislason suggests no vapour barrier on the interior of the wall to ensure that the wall has the possibility to emit vapour to the interior of the building. However, this could possibly lead to problems in case the moisture from the interior migrates through the wall and gets blocked behind the surface treatment. From the parametric study on the interior finish of the wall, it seems that the material properties do not affect the moisture conditions in the wall, i.e. the more vapour open materials do not support a rise in the relative humidity in the monitor point. A possible explanation to this is that the insulation has a very low moisture storage function, resembling a vapour barrier and is therefore treated almost as such in WUFI. The insulation then prevents the vapour from the interior to migrate in the wall. Due to this, it is possible that the water vapour diffusion resistance factor on the surface treatment is less critical and therefore shows lower impact in the results.

The results show that a lower A-value of the coating can largely improve the performance of the wall. This is reasonable as it supports the observation that the rain is a dominating factor for the Icelandic wall. With high performance coating the wall has the possibility of drying out, which has been suspected that the wall does not do. The interplay between the porosity of concrete and coating are interesting to look at. In case a less water permeable coating is applied to the wall, a more open concrete (higher A-value, higher moisture storage function) will perform better than a denser concrete. The reason could be that with high performing coating, very little rain gets through and the wall has a chance to dry out. A more open concrete, such as the Icelandic one, will under these circumstances dry out faster than a more dense concrete and therefore show better performance. However, if the coating applied to the wall is very water open the matters turn around. Less dense coating will transport the water faster and show higher relative humidity inside the structure, whereas a more dense concrete will dampen the effect of rain as the moisture transportation is slower. The exterior screed behaves in a similar way. However, a less water permeable coating will always perform better than a water open coating according to the results.
Chapter 8

Thermal bridge simulation

8.1 Thermal mechanics

Heat transport of building envelopes consist of convection, conduction and radiation. When considering heat transport in building components there are two types to consider. These are homogeneous and inhomogeneous building components. Homogeneous building components are one dimensional and heat flows perpendicular to the its dimension while inhomogeneous building components are two dimensional with heat flowing in various directions. The thermal conductivity, $\lambda$ [W/mK] is a property of a material to conduct heat. The thermal resistance, $R$ [m$^2$K/W] depends on the thermal conductivity and the thickness of the material layer and describes the material’s ability to resist conductive heat flow. The $U$-value [W/m$^2$K], the inverse of $R$, is often used to describe how well a building component (or a house) conducts heat or in rate of heat transfer through a square meter of the building component divided by the temperature difference on either side of the building component [22].

8.1.1 Comsol simulation

When an irregularity exists in a component or an area of a building envelope, thermal transmittance and direction of density of heat flow rate change considerably, contributing to a critically higher heat transfer compared to the surrounding components or areas. This irregularity is denoted by a linear thermal bridge value, $\Psi$ [W/mK]. The $\Psi$-value is used to analyse the overall heat transfer ability of the ele-
ment.

Both the surface temperature and the total normal heat flux were calculated to determine the thermal loss. The external wall - slab connection of the Icelandic wall structure was studied. The construction is shown in figure 5.2 and the material properties of the concrete, insulation and screed are shown in section 5.3.1. The internal temperature was set to 293.15K and the exterior temperature was set to 263.15K resulting in 30K temperature difference. The inward heat flux was determined by the formula for convective heat flux of the surfaces:

\[ q_0 = h \cdot (T_{\text{ext}} - T) \]  

where \( h \) [W/m\(^2\)K] is the inverse of the surface resistance coefficients seen in table 8.1, \( T_{\text{ext}} \) [°C] is the external temperature and \( T \) is the ambient temperature. Graphics of Conductive heat flux magnitude in 2D and Line Integration of the total normal heat flux [W/m] was obtained from the COMSOL simulation. For the line integration the internal lines of the construction were set as boundaries as is the convention in Sweden.

### 8.1.2 Boundary conditions

In table 8.1 the surface resistance which were used for the thermal bridge simulation of the construction are shown. These values are from the international standard ISO 6946 (2007) [78]. The boundary conditions at the border edges of the construction were considered as perfect thermal insulation i.e. under adiabatic boundary conditions.

<table>
<thead>
<tr>
<th>Surface Resistance (m2K/W)</th>
<th>Direction of Heat Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upward</td>
</tr>
<tr>
<td><strong>Inner Surface Resistance</strong></td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Outer Surface Resistance</strong></td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 8.1: The surface resistance according to ISO 6946 (2007).
8.1.3 Results from thermal simulation

In figure 8.1, the temperature distribution in the cross section of the Icelandic wall is shown in Kelvin:

Figure 8.1: The temperature distribution [K] of the cross section of the Icelandic wall type. The corresponding cross-section is shown in Figure 5.1.
The Transmission heat flow through homogeneous wall surfaces is denoted by [90]:

\[ \Phi_T = \Delta T \sum A \cdot U \]  

(8.2)

where \( \Phi_T \) [W] is the transmission heat flow, \( A \) [m\(^2\)] is the surface area of the elements, length of the element times the distribution of the thermal bridge. \( U \) [W/m\(^2\)K] is the thermal transmittance of the element. The Transmission heat flow through thermal bridges is [90]:

\[ \Phi_{TB} = \Delta T \left( \sum \Psi \cdot l_{tb} + \sum \chi \right) \]  

(8.3)

where \( \Phi_{TB} \) [W] is the transmission heat flow, \( \Psi \) [W/mK] is the linear thermal transmittance of a thermal bridge and \( \chi \) [W/K] is the point thermal transmittance. The point thermal transmittance is used for a point where such or a corner where the heat in the thermal bridge flows in three dimensions so it is not needed in the following calculation. The \( l_{tb} \) [m] is the distribution of the thermal bridge, set as 1m.

The total transmission heat flow is[90]:

\[ \Phi_{tot} = \Phi_T + \Phi_{TB} \]  

(8.4)

or

\[ \Phi_{tot} = (\Delta T \sum A \cdot U) + (\Delta T \sum \Psi \cdot l + \sum \chi) \]  

(8.5)

where \( A \) [m\(^2\)] is the interior surface area of a building component such as a wall, a roof or a window. The Normal total heat flux was found to be 62.07 W/m. The linear thermal bridge value \( \Psi \) can be obtained by equation 8.5:

\[ 62.07 \frac{W}{m} \cdot l_{tb} = \Delta T \cdot (A_{wall} \cdot U_{wall}) + \Delta T \cdot (\Psi \cdot l_{tb}) \]

so that

\[ 62.07 \frac{W}{m} \cdot 1m = 30K \cdot U_{wall} \cdot (l_{tb}L_1 + l_{tb}L_2) + 30K \cdot (\Psi \cdot l_{tb}) \]

where \( l_{tb} \) is set to 1m, \( U_{wall}=0.363 \frac{W}{m^2K} \) and \( U_{slab}=4.33 \frac{W}{m^2K} \),

\[ \frac{62.07 \frac{W}{m} \cdot 1m}{30K} = 0.363 \frac{W}{m^2K} \cdot (1m \cdot 0.998m + 1m \cdot 0.998m) + (\Psi \cdot 1m) \]

which gives

\[ 2.07 \frac{W}{K} = 0.72 \frac{W}{K} + \Psi \cdot 1m \]
so the linear thermal bridge transmittance value is

\[ \Psi = 1.35 \frac{W}{mK} \]

This high value represents the thermal loss per meter and 1.31 W/mK is almost ten times more than what to expect per square meter in a well insulated outer wall.

In figure 8.2, the surface temperature of the interior ceiling, under the concrete slab is shown. When the surface temperature has reached an equilibrium its temperature is 285.17K which is equal to 12°C. If the interior temperature is 20°C and the interior moisture load is high such as in laundry rooms etc. it can lead to condensation if the moisture load (g/m3) is high enough. For 12°C the vapour content at saturation for 60%RH is 11°C which is really close to the surface temperature of the ceiling [90].

Figure 8.2: The surface temperature of the interior ceiling in the Icelandic wall construction.
Chapter 9

Laboratory experiment

9.1 Purpose

The results of the studies in chapters 6 and 7 indicate that the main influence on the RH at the monitor point is the wind driven rain, not the relative humidity inside the building. As results have illustrated, no condensation is expected between the concrete and the insulation. This conflicts with statements made by experts, who claim to have seen condensation occur at this position in walls in Iceland. The Glaser method however, which does not take into consideration the impact of rain, predicts condensation at the interface.

To investigate whether condensation actually occurs at the interface of the concrete and the insulation, a laboratory experiment was set up. Furthermore, the experiment was also intended to validate the parameter approximations of the building materials made in WUFI. This will be achieved by comparing the experiment results with results from WUFI.

Due to the time constraints of this thesis work, only the experimental set-up was performed. The study will be continued after the end of this thesis work. In this chapter, the experimental set-up will be described as well as WUFI simulations of the experimental wall.
9.2 Experimental set-up

Description

The experiment consists of a concrete T-beam, representing an external wall-to-floor section, with interior insulation disconnected at the slab. The interior is finished with interior screed, but the exterior side is untreated. The experiment is conducted inside a laboratory. To simulate cold climate, a freezer was placed on the exterior side of the wall to imitate constant cold conditions. The effect of driving rain will be excluded, as there will is no moisture load at the exterior surface of the concrete.

The T-beam was cast with reinforced concrete. Nine temperature sensors were cast in the concrete. Humidity sensors were placed between the insulation and concrete in three places. Figure 9.1 shows the placement of all the sensor and table 9.1 shows the placement coordinates of the sensors. The measurements will be logged by data loggers with a sample rate of one hour to match the results from WUFI. Furthermore, temperature and humidity data loggers will be placed both inside the freezer and and in the lab to monitor ambient conditions.
Figure 9.1: The T-beam with placement of all sensors. Red dots represent the temperature sensors, the blue represent the relative humidity sensors and the purple represent temperature and humidity sensors.

<table>
<thead>
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<td>A</td>
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<td>88</td>
<td>-30</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>-10</td>
<td>88</td>
<td>-30</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>49</td>
<td>88</td>
<td>-30</td>
</tr>
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<td>0</td>
<td>31</td>
<td>-30</td>
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<td>-30</td>
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</tr>
<tr>
<td>Temp/RH</td>
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<td>Arbitrary</td>
<td>Arbitrary</td>
<td>Arbitrary</td>
</tr>
<tr>
<td></td>
<td>Exterior</td>
<td>Arbitrary</td>
<td>Arbitrary</td>
<td>Arbitrary</td>
</tr>
</tbody>
</table>
Materials

The concrete used for the T-beam is the aforementioned Vatnsskard concrete. The moisture properties of the concrete are assumed to be similar to the one used for the previous studies. The moisture properties are described in section 5.3.1. Other material properties and further information are found in Appendix C.

The concrete was reinforced with ø8mm hot rolled steel, cold stretched. The reinforcement drawing of the T-beam and the inspection certificate for the reinforcement steel can be seen in Appendix C.

EPS insulation with density of 16 kg/m$^3$ was placed on what represented the interior part of the concrete T-beam. Technical data regarding the insulation can be found in Appendix C.

The interior screed used for the experiment is a standard product applied in many residential building projects.

Moisture measurements

Moisture measurements were carried on the T-beam 44 days after casting. Holes were drilled at various locations with 50-70mm depth. The sensor were put inside the holes at the corresponding depth and sealed from the ambient air. In the third day an equilibrium state was obtained. Measurements gave a 84.7% RH and 22.7°C inside the T-beam. The ambient air was on average 23.3°C and 31.4% RH. The results from the humidity measurements can be seen in table C.1.
Final setup

In figure 9.2 pictures from the experimental set-up are shown.

Figure 9.2: Pictures from the experiment setup.
In figure 9.3 the final setup of the experiment is shown (without insulation on the sides for the thermal boundary conditions).

Figure 9.3: The T-beam with the freezer on top.
Climate

Experiment
The side representing the exterior part of the wall is subjected to temperature conditions fluctuating approximately between -6°C and -20°C and RH of 14-99%. This condition is achieved with the freezer. The impact of precipitation is not taken into consideration. The side representing the interior of the wall is subjected to the interior climate of the laboratory, with conditions fluctuating around 23°C and RH of 30%.

Simulations
For simulating the experiment, the aim was to imitate the experimental climate when choosing the weather conditions in WUFI. To simulate the indoor climate, sinus curves were defined according to the laboratory conditions (23°C and 30% RH) with amplitude of 2°C and 10% RH. The outdoor conditions, i.e. the freezer, was simulated by using measurement values for temperature and RH retrieved from data loggers that were positioned in the freezer for a few days.

9.3 Results from WUFI simulations and discussion

The experimental has two purposes: to investigate whether condensation will occur on the interface of the concrete and insulation and to verify if WUFI shows similar results as the experiment. In this thesis, only the results from the WUFI simulations will be presented and discussed with the purposes of the experiment in mind.

Two simulations, which aimed at mimicking the experiment, were run with the monitor position on the interface of the concrete and the insulation. In the first simulation a concrete from the WUFI database was used (see material data in Appendix C) and in the second simulation the Icelandic concrete described in section 5.3.1 was used.

Figure 9.4 illustrate the first 12 weeks of the results. As can be seen from the figure, the RH profile varied for different types of concrete. The Icelandic concrete showed a steady decrease in RH at the monitor point throughout the simulation period while the WUFI concrete showed steady increase in RH at the monitor point. The difference in behaviour between those two concrete types could be explained by
higher density of the WUFI concrete which could slow down the drying out process of the wall. The results showed there was no condensation at the monitor point in both cases.

During the conduction of the experiment, the RH on the interface will carefully be monitored and compared to this results. From that data, the behaviour of the RH can be analysed and conclusions drawn depending on whether the experiment is showing behaviour that resembles better the Icelandic concrete or the WUFI database concrete. Furthermore, any sign of condensation will be carefully tracked.

Figure 9.4: WUFI simulation results of the experiment. Short period of time.
Chapter 10

Discussion and conclusion

10.1 Discussion

In previous chapters, results have shown that condensation does not occur in the Icelandic wall under Icelandic climate conditions. The results also indicate that the interior conditions, i.e. the relative humidity levels do not influence the relative humidity conditions in the wall. These two outcomes are inconsistent with what has previously been assumed, that the interior moisture migrates into the wall and causes condensation when in contact with the concrete. The Glaser method assumes that vapour only moves through the wall from the inside to the outside, which for an internally insulated wall often results in calculated condensation. Additionally, it ignores the features of wind-driven rain. However, WUFI performs more detailed calculations that take into account the dynamic behaviour of the structure, accounting for the adsorption and desorption of moisture as well as the storage of heat while using representative data for the climatic variations. According to the results from chapters 6 and 7 the wind-driven rain seem to be the dominating factor regarding the moisture behaviour of the interior insulated concrete outer wall. Furthermore, as the insulation is very vapour tight, WUFI might treat it as a vapour barrier, which Glaser does not. This could partially explain why the two methods give different results. However, since claims have been made that condensation has been observed in external walls in buildings in Iceland, the question rises what could be causing that. Possible explanations could be some other factors than the construction type of the wall, such as budget and time constraints that could lead to less
meticulous work, or simply lack of know-how.

From the results it can be seen that the interior insulated Icelandic outer concrete wall has a substantially higher moisture content and worse hygrothermal performance compared to the exterior insulated concrete wall.

The extreme variation in temperature at the interior surface of the concrete in the Icelandic wall type, develops a high risk for freeze-thawing damage which can result in cracks in the wall. There is a need for ventilation at the concrete surface of the Icelandic wall type due to this accumulation of moisture. The Icelandic wall is sensitive to driving rain and when the driving rain load is extremely high such as in Bergen the relative humidity at the concrete surface remained over 90% throughout the simulation period. This high relative humidity in the Icelandic wall resulted in mould growth risk at the concrete surface which the user has to decide if he is ready to accept. In the Reykjavík climate the Icelandic wall has a lower RH with higher variation at the interior surface of the concrete and the risk of mould growth is low according VTT mould growth model and the presumptions that are made there. Because of the high uncertainty in defining the mould classification in the interior surface of the concrete, it remains an factor of error. Presumptions were though made that the surface was medium resistant and that the surface had no contact to interior air.

In the literature review, studies about the link between porosity of concrete and mould growth were introduced. The studies indicated that higher porosity of concrete results in more susceptibility to mould growth as water and organic particles could more easily be retained on the surface. Therefore, for cases with the Icelandic concrete, it could be realistic to assume that the interior surface class of the concrete changes from medium resistant to sensitive for mould calculations due to the possibility of higher levels of organic particles on Icelandic concrete.

In the simulation cases the presumption was also made that there were no leakages through the exterior screed, the interior screed or the surface treatment of the wall. Inserting a water leakage behind the exterior screed could result in a higher RH and higher mould growth index at the interior surface of the concrete.

Because of the high moisture content in the Icelandic wall the possibility of moisture damage is high. Two quotes from the Icelandic Building Code regarding moisture safety in buildings were mentioned
in section 1.1.1. There it is stated that "buildings should be designed and built so that water and moisture can not cause damage to the building as a whole nor its component." The results from this study indicate a high risk of condensation at the wall-slab section of the Icelandic wall-type from the thermal bridge calculation. The result from the WUFI simulation did not show condensation at the interior surface of the concrete in the Icelandic wall type in contrast to earlier studies such based the Glaser method. It is hard to interpret the Icelandic building code in order to assert if the Icelandic wall type fulfils the requirement or not. Its hygrothermal behaviour is though poor and there is a risk of condensation at the thermal bridge.

From presumptions made in WUFI, the simulation results showed no condensation on the interior side of the concrete in the Icelandic wall type under the conditions it was subject to in the hygrothermal simulations. Despite this fact, it must be noted that the relative humidity came dangerously close to 100% RH (condensation) as the RH was fluctuating between 80 and 95% at the interior surface. This high RH of the Icelandic wall exceeded over and over again the critical humidity level recommended by various experts and institutions shown in table 4.1.

Boverket, the Swedish building regulation code implies that "for materials where mould and micro-organisms can grow, a critical moisture condition should be used which is well researched and documented... if the critical moisture level is not researched and documented a limit of 75% RH should be used as the critical humidity level." (BFS 2014:3). There is no critical humidity level or a maximum moisture content requirements for specific materials stated in Boverket but it refers to critical humidity levels recommendations of materials to be found in Sveriges Tekniska Forskningsinstitut, which estimates the critical relative humidity of concrete to be 90-95% at 20°C.

It must be kept in mind that the material properties in chapter 6 are to a large extent based on approximations and collection of data from different origins. From the parametric study in chapter 7, it can be seen that changes in various parameters can have a large impact on the results of the simulations. Therefore, the risk of errors in the results are high. The first attempt to validate the results will be through the experiment that will be carried out after this thesis work.
10.2 Conclusion

This study investigated moisture problems in the typical Icelandic exterior wall regarding the risk of condensation and mould growth on the interface of the concrete and insulation. The following conclusions were drawn according to the assumptions made throughout this work.

Simulation results indicate that there is no condensation at the interior surface of the concrete in the Icelandic wall. Increasing the interior moisture load in WUFI did not affect the RH or mould growth at the interior surface of the concrete in the Icelandic wall.

The Icelandic exterior wall is very sensitive to wind-driven rain and consequently the quality of the exterior coating on the wall. Coatings with low A-value show better performance regarding relative humidity on the interface of concrete and insulation than coatings with high A-values.

From the results of the comparative study in chapter 6, it is clear that the interior insulated concrete wall (Icelandic wall) performs worse than the exterior insulated concrete outer wall (German wall) when comparing the moisture content and mould risk.

The exterior insulated concrete outer wall (German wall) showed no risk of mould growth in neither Icelandic or Norwegian climate conditions according to VTT mould growth model and presumptions made in terms of sensitivity class and occupation class. The German wall had a stable temperature around 21°C. The total water content of the German wall dries out throughout the simulation period. The RH at the interior surface of the concrete walls decreases in every case reaching an equilibrium state between 50 and 55% RH.

The interior insulated concrete outer wall (Icelandic wall) showed a higher mould growth risk at the interior surface of the concrete in the Bergen climate due to higher driving rain load.

The risk of mould growth in the Reykjavík climate was lower and did not imply a high mould growth risk. The Icelandic wall had extreme variations in temperature ranging between -7°C in the winter time up to 29°C in the summertime.

The total water content of the Icelandic wall does not dry out and is between 28 and 36 kg/m² with Icelandic concrete and 19 and 26 kg/m² with German concrete in its equilibrium state. The RH at the interior surface of the concrete in the Icelandic walls increased in each case reaching an equilibrium state between 80 and 95% RH with Icelandic
concrete and 90 to 95% RH with German concrete.

The results also showed that using German concrete in the Icelandic wall resulted in higher relative humidity at the interior surface but a lower total water content of the wall. This reflects the results from the sensitivity analysis on the A-value and moisture storage function of the concrete in chapter 7.

Results from the sensitivity analysis of different concrete types implied that the interplay between the type of coating and the density of concrete impacts the moisture behaviour of the wall. Less dense concrete shows a better performance than a high dense concrete when the exterior coating is low water permeable, but when the coating has a higher permeability the high dense concrete shows better performance than the low dense concrete.

10.3 Future work

This study has been largely based on assumptions about the material properties of the Icelandic concrete. The parametric study has shown that the results of the simulations are sensitive to the type of concrete, exterior screed and coating. If WUFI is going to be used for design of concrete structures in Iceland, it is important that the moisture parameters of the building materials are well known. Therefore, the authors propose that comprehensive measurements on various Icelandic building materials should be conducted to gain a better understanding of their properties and to provide a more reliable simulation results in the future.

Hardly any, to the knowledge of the authors, long-term research on moisture content have been done on concrete wall structures under realistic weather conditions in Iceland. Such research could provide valuable information on the moisture behaviour, i.e. moisture content and drying-out processes etc. It could also provide a better general understanding of the Icelandic wall. Therefore, it is suggested that a full-scale experiment exposed to Icelandic climate with built in temperature and RH sensors should be set up.
Bibliography


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Appendix A

Input data

A.1 Climate data

A.1.1 Exterior Climate

The thin curves show the data read from the climate file, the bold curves represent the centered moving monthly means for easier visual accessibility. (Fraunhofer) The climate analysis of Reykjavik and Bergen can be seen in figure A.1 and A.2. WUFI shows the energy transported by the atmospheric counterradiation onto a horizontal surface (such as a flat roof) during the year. The directional distribution of solar radiation, represented by a radiation rose. The radiation rose shows the yearly sums of global radiation, as incident on receiving surfaces with different orientations and inclinations. For multi-year data sets, the mean yearly energy sums are shown.
Reykjavík

Figure A.1: The exterior climate analysis for Reykjavík.
Figure A.2: The exterior climate analysis for Bergen.
A.2 Data input

Wall assembly

The wall construction is modelled in WUFI as a one dimensional component. Layers are added with corresponding thickness and material properties.

Grid

The computational grid divides the one dimensional wall assembly into smaller elements. For every element in the grid the corresponding hygrothermal conditions are calculated. WUFI offers two grid options, Automatic 1 and Automatic 2 but additionally the grid can be user-defined. Both types of grids were tested but Automatic grid 1 resulted in fewer convergence failures and less difference in balance, which are two ways to determine the calculation performance and accuracy. The numerical grid was set to fine.

Driving rain coefficients

There are two rain coefficients to estimate the driving rain load on the surface of the assembly, R1 and R2. These rain coefficients are derived from data on normal rain, wind velocity and the mean wind direction from the weather file. The rain coefficients are dependent on the specific location on the façade. R1 is set to zero for vertical surfaces and R2 it set to defaults which is 0.07 s/m which is the default setting for building up to 10 m high. This configuration represents the centre of the façade.

Surface transfer coefficients

The exterior surface transfer coefficients define the impact of the surrounding on the wall assembly. The heat resistance represents the heat exchange with the surroundings. The value is set to 0.04 m²K/W, which is the standard value used in previous hygrothermal calculations, according to ÍST EN ISO 6946:1996 [91].

As the surface treatment was modelled with a thin layer on the exterior surface, the diffusions resistance of the component, the sd-value, is set to zero.
The short-wave radiation absorptivity, which is the fraction of the total short-wave radiation absorbed by the wall assembly was set as 0,8 according to ASHRAE Fundamentals [92].

The long-wave radiations emissivity represents emitted heat loss of the wall assembly surface. It was set to 0,9 according to ASHRAE Fundamentals [92].

The explicit radiation balance is activated for the simulations. It allows for simulating the night time overcooling.

The ground short-wave reflectivity is the reflectance of the short-wave global radiation from the ground. The standard value is chosen, 0,2.

The adhering fraction of rain is depends in the inclination of the wall. The wall is vertical, resulting in the adhering fraction of rain of 0,7.

The heat resistance of the interior surface was set to 0,13 m\(^2\)K/W according to ÍST EN ISO 6946:1996 [91].

An alkyd painting is chosen on the interior surface with sd-value of 2,5 m according to NBI:573.430 [93].

**Numerics**

To further improve the results of the calculations the adaptive time step control was activated, with 3 steps and 5 maximum stages.
A.2.1 Data input study 1

In tables A.1 the data input for the simulation cases in chapter 6 are shown.

**Table A.1: Data input overview**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>Grid Automatic 1 - Fine</td>
</tr>
<tr>
<td>Orientation</td>
<td>South East</td>
</tr>
<tr>
<td>Inclination of wall</td>
<td>90°</td>
</tr>
<tr>
<td>Building Height/Driving Rain Coefficients</td>
<td>R1=0 and R2=0.07 (Short building up to 10m)</td>
</tr>
<tr>
<td>Heat Resistance Exterior Surface</td>
<td>0.04 [m2K/W] (EQUAL EN ISO 6946:1996)</td>
</tr>
<tr>
<td>Includes long wave radiation parts</td>
<td>6.5 W/m2K (See explicit radiation balance)</td>
</tr>
<tr>
<td>Sd-value External Wall</td>
<td>No coating (Simulated as a thin layer)</td>
</tr>
<tr>
<td>Short-Wave Radiation Absorptivity</td>
<td>0.8 (ASHRAE Fundamentals 1989)</td>
</tr>
<tr>
<td>Long-Wave Radiation Emissitivity</td>
<td>0.9 (ASHRAE Fundamentals 1989)</td>
</tr>
<tr>
<td>Explicit Radiation Balance</td>
<td>Yes (Takes radiative cooling due to long wave emission into account)</td>
</tr>
<tr>
<td>Ground Short-Wave Reflectivity</td>
<td>0.2 (Standard value)</td>
</tr>
<tr>
<td>Adhering Fraction of Rain</td>
<td>0.7 (Dependent of inclination of wall)</td>
</tr>
<tr>
<td>Heat Resistance Interior Surface</td>
<td>0.13 m2K/W</td>
</tr>
<tr>
<td>Sd-value Interior Surface</td>
<td>2.5 (Alkyd paint: NBI 573.430)</td>
</tr>
<tr>
<td>Initial Temperature in component</td>
<td>20°C (Constant through component)</td>
</tr>
<tr>
<td>Initial Relative Humidity in component</td>
<td>80%</td>
</tr>
<tr>
<td>Calculation Period</td>
<td>1st Jan 2018 - 31. Dec 2023</td>
</tr>
<tr>
<td>Climate</td>
<td>Reykjavik/Bergen</td>
</tr>
<tr>
<td>Indoor Climate</td>
<td>23°C at Level 2 and 4 (ISO 13788:2013-05)</td>
</tr>
</tbody>
</table>
A.2.2 Data input study 2

In table A.2 the data input for the simulation cases in chapter 7 are shown.

Table A.2: Data input overview of study 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>Grid Automatic 1 - Fine</td>
</tr>
<tr>
<td>Orientation</td>
<td>South East</td>
</tr>
<tr>
<td>Inclination of wall</td>
<td>90°</td>
</tr>
<tr>
<td>Building Height/Driving Rain Coefficients</td>
<td>R1=0 and R2=0.07 (Short building up to 10m)</td>
</tr>
<tr>
<td>Heat Resistance Exterior Surface</td>
<td>0.04 [m²K/W] (FST EN ISO 6946:1996)</td>
</tr>
<tr>
<td>Includes long wave radiation parts</td>
<td>6.5 W/m²K (See explicit radiation balance)</td>
</tr>
<tr>
<td>Sd-value External Wall</td>
<td>No coating (Simulated as a thin layer)</td>
</tr>
<tr>
<td>Short-Wave Radiation Absorptivity</td>
<td>0.8 (ASHRAE Fundamentals 1989)</td>
</tr>
<tr>
<td>Long-Wave Radiation Emissivity</td>
<td>0.9 (ASHRAE Fundamentals 1989)</td>
</tr>
<tr>
<td>Explicit Radiation Balance</td>
<td>Yes (Takes radiative cooling due to long wave emission into account)</td>
</tr>
<tr>
<td>Ground Short-Wave Reflectivity</td>
<td>0.2 (Standard value)</td>
</tr>
<tr>
<td>Adhering Fraction of Rain</td>
<td>0.7 (Dependent of inclination of wall)</td>
</tr>
<tr>
<td>Heat Resistance Interior Surface</td>
<td>0.13 m²K/W</td>
</tr>
<tr>
<td>Sd-value Interior Surface</td>
<td>2.5 (Alkyd paint: NBI 573.430)</td>
</tr>
<tr>
<td>Initial Temperature in component</td>
<td>20°C (Constant through component)</td>
</tr>
<tr>
<td>Initial Relative Humidity in component</td>
<td>80%</td>
</tr>
<tr>
<td>Calculation Period</td>
<td>1st Jan 2018 - 31 Dec 2023</td>
</tr>
<tr>
<td>Climate</td>
<td>Reykjavik</td>
</tr>
<tr>
<td>Indoor Climate</td>
<td>23°C at Level 1 (ISO 13788:2013-05)</td>
</tr>
</tbody>
</table>
Figure A.3: The moisture storage function of the German concrete.

Figure A.4: Material parameters of the German concrete.
Figure A.5: The moisture storage function of the insulation used in all simulations.

<table>
<thead>
<tr>
<th>No.</th>
<th>RH [-]</th>
<th>Water Cont. [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>0.461</td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
<td>0.687</td>
</tr>
<tr>
<td>4</td>
<td>0.7</td>
<td>1.06</td>
</tr>
<tr>
<td>5</td>
<td>0.8</td>
<td>1.79</td>
</tr>
<tr>
<td>6</td>
<td>0.85</td>
<td>2.49</td>
</tr>
<tr>
<td>7</td>
<td>0.9</td>
<td>3.83</td>
</tr>
<tr>
<td>8</td>
<td>0.91</td>
<td>4.26</td>
</tr>
<tr>
<td>9</td>
<td>0.92</td>
<td>4.76</td>
</tr>
<tr>
<td>10</td>
<td>0.93</td>
<td>5.43</td>
</tr>
<tr>
<td>11</td>
<td>0.94</td>
<td>6.27</td>
</tr>
<tr>
<td>12</td>
<td>0.95</td>
<td>7.38</td>
</tr>
<tr>
<td>13</td>
<td>0.96</td>
<td>8.94</td>
</tr>
<tr>
<td>14</td>
<td>0.97</td>
<td>11.3</td>
</tr>
<tr>
<td>15</td>
<td>0.98</td>
<td>15.1</td>
</tr>
<tr>
<td>16</td>
<td>0.99</td>
<td>22.7</td>
</tr>
<tr>
<td>17</td>
<td>0.995</td>
<td>30.2</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>44.8</td>
</tr>
</tbody>
</table>

Figure A.6: Material parameters of the insulation used in all simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density [kg/m³]</td>
<td>30</td>
</tr>
<tr>
<td>Porosity [m³/m²]</td>
<td>0.95</td>
</tr>
<tr>
<td>Spec. Heat Capacity [J/(kg·K)]</td>
<td>1500</td>
</tr>
<tr>
<td>Thermal Conductivity [W/mK]</td>
<td>0.04</td>
</tr>
<tr>
<td>Water Vapour Diffusion Resistance Factor [-]</td>
<td>50</td>
</tr>
</tbody>
</table>
A.3 Quality control of the simulations

In table A.3 the quality control of the simulations are shown from the comparative study. Balance 1 and Balance 2 should preferably be the same value, otherwise as close as possible. The number of convergence errors should be kept as low as possible. Slight error is acceptable. The convergence errors and both balance show that the quality of the simulations are sufficient. Numerical parameter setting: Increased accuracy and adaptive convergence Adaptive time step control: enabled: steps 3 : max stages 5. Not excluding any hygrothermal options

Table A.3: Quality control of parametric study 1

<table>
<thead>
<tr>
<th>Case</th>
<th>Convergence Errors</th>
<th>Balance 1</th>
<th>Balance 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>2.18</td>
<td>2.18</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>6.22</td>
<td>6.22</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>2.9</td>
<td>2.9</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>7.74</td>
<td>7.74</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>-6.9</td>
<td>-6.9</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>-5.2</td>
<td>-5.21</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>-5.25</td>
<td>-5.25</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>-3.19</td>
<td>-3.2</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>2.59</td>
<td>2.59</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>6.48</td>
<td>6.48</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>3.53</td>
<td>3.53</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>8.03</td>
<td>8.03</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>-5.42</td>
<td>-5.42</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>-3.93</td>
<td>-3.94</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>-3.29</td>
<td>-3.29</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>-1.67</td>
<td>-1.68</td>
</tr>
</tbody>
</table>
Appendix B

Parametric study

B.1 Moisture storage functions in parametric study

Table B.1: Moisture storage functions of concrete evaluated in the parametric study [87].

<table>
<thead>
<tr>
<th>RH [%]</th>
<th>MSF1</th>
<th>Base case</th>
<th>MSF2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>23</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>20</td>
<td>25,2</td>
<td>60</td>
<td>75</td>
</tr>
<tr>
<td>30</td>
<td>27,6</td>
<td>80</td>
<td>95</td>
</tr>
<tr>
<td>40</td>
<td>30,7</td>
<td>90</td>
<td>110</td>
</tr>
<tr>
<td>50</td>
<td>36,2</td>
<td>100</td>
<td>120</td>
</tr>
<tr>
<td>60</td>
<td>42,5</td>
<td>107</td>
<td>130</td>
</tr>
<tr>
<td>63</td>
<td></td>
<td>110</td>
<td>133</td>
</tr>
<tr>
<td>70</td>
<td>51,2</td>
<td>119</td>
<td>137</td>
</tr>
<tr>
<td>76</td>
<td></td>
<td>128</td>
<td>140</td>
</tr>
<tr>
<td>80</td>
<td>63</td>
<td>136</td>
<td>145</td>
</tr>
<tr>
<td>85</td>
<td></td>
<td>146</td>
<td>149</td>
</tr>
<tr>
<td>90</td>
<td>79,5</td>
<td>156</td>
<td>156</td>
</tr>
<tr>
<td>95</td>
<td></td>
<td>166</td>
<td>163</td>
</tr>
<tr>
<td>97</td>
<td>111</td>
<td></td>
<td></td>
</tr>
<tr>
<td>98</td>
<td>113,4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>216</td>
<td></td>
<td>188</td>
</tr>
</tbody>
</table>
Table B.2: Moisture storage functions of the Icelandic screed (Base Case) and screed tested in the parametric study.

<table>
<thead>
<tr>
<th>Base Case [^{[87]}]</th>
<th>MSF I / MSF I [^{\text{WUFI database}}]</th>
<th>MSF II</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>4,3</td>
</tr>
<tr>
<td>20</td>
<td>35</td>
<td>52,5</td>
</tr>
<tr>
<td>30</td>
<td>50</td>
<td>5,2</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
<td>6,1</td>
</tr>
<tr>
<td>50</td>
<td>70</td>
<td>7,2</td>
</tr>
<tr>
<td>60</td>
<td>80,4</td>
<td>8,6</td>
</tr>
<tr>
<td>70</td>
<td>86,1</td>
<td>10,5</td>
</tr>
<tr>
<td>80</td>
<td>99</td>
<td>13,9</td>
</tr>
<tr>
<td>90</td>
<td>116,2</td>
<td>18,2</td>
</tr>
<tr>
<td>95</td>
<td></td>
<td>46,6</td>
</tr>
<tr>
<td>97</td>
<td>185</td>
<td></td>
</tr>
<tr>
<td>98</td>
<td>186,5</td>
<td>279,75</td>
</tr>
<tr>
<td>99,5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>99,9</td>
<td>83,5</td>
<td></td>
</tr>
<tr>
<td>99,95</td>
<td>105</td>
<td></td>
</tr>
<tr>
<td>99,99</td>
<td>167</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>188</td>
<td>405</td>
</tr>
<tr>
<td></td>
<td></td>
<td>282</td>
</tr>
</tbody>
</table>
Appendix C

Experiment

C.1 Moisture measurement in concrete

Holes were drilled at various locations and depth into the concrete T-beam 44 days after casting. The holes were 50-70mm deep into the concrete. The humidity measurement sensors were placed inside the holes at the corresponding depth and sealed from the ambient air. They stayed in that position for 72 hours and a measurement logger was used to log the temperature 1 day after the sensor had been installed, as well as 2 days and 3 days after. The measurement equipment gave relative humidity values (%) and temperature (°C) at the time of measurement. In position 1, a test slab, which was cast with the same concrete as in the experiment, was tested. Its measurements were 150mm x 600mm x 465mm and the moisture position was in the middle of that test slab. In position 2-4, the experiment concrete slab-wall was tested for relative humidity and the thickness of that slab was 180mm. In table C.1 the measurement results are shown.
Table C.1: Results from humidity measurements of concrete in experiment

<table>
<thead>
<tr>
<th>Position</th>
<th>Days after casting</th>
<th>Depth (mm)</th>
<th>RH(%)</th>
<th>Temperature (°C)</th>
<th>Description</th>
<th>Thickness of slab (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>44</td>
<td>50</td>
<td>81,7</td>
<td>22,8</td>
<td>Test Slab</td>
<td>150</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>50</td>
<td>81,1</td>
<td>22,7</td>
<td>Test Slab</td>
<td>150</td>
</tr>
<tr>
<td>1</td>
<td>46</td>
<td>50</td>
<td>80,9</td>
<td>22,6</td>
<td>Test Slab</td>
<td>150</td>
</tr>
<tr>
<td>2</td>
<td>44</td>
<td>50</td>
<td>85,9</td>
<td>22,8</td>
<td>Wall</td>
<td>180</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>50</td>
<td>85,0</td>
<td>22,8</td>
<td>Wall</td>
<td>180</td>
</tr>
<tr>
<td>2</td>
<td>46</td>
<td>50</td>
<td>84,8</td>
<td>22,9</td>
<td>Wall</td>
<td>180</td>
</tr>
<tr>
<td>3</td>
<td>44</td>
<td>50</td>
<td>85,7</td>
<td>22,8</td>
<td>Slab</td>
<td>180</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>50</td>
<td>85,1</td>
<td>22,8</td>
<td>Slab</td>
<td>180</td>
</tr>
<tr>
<td>3</td>
<td>46</td>
<td>50</td>
<td>85,2</td>
<td>22,8</td>
<td>Slab</td>
<td>180</td>
</tr>
<tr>
<td>4</td>
<td>44</td>
<td>70</td>
<td>88,0</td>
<td>22,5</td>
<td>Slab</td>
<td>180</td>
</tr>
<tr>
<td>4</td>
<td>45</td>
<td>70</td>
<td>86,9</td>
<td>22,4</td>
<td>Slab</td>
<td>180</td>
</tr>
<tr>
<td>4</td>
<td>46</td>
<td>70</td>
<td>86,9</td>
<td>22,5</td>
<td>Slab</td>
<td>180</td>
</tr>
</tbody>
</table>

Average: 84,76 22,7
Measurement error 3 1

Table C.2: Measurements of ambient temperature in the laboratory.
During measurement:

<table>
<thead>
<tr>
<th>Ambient air:</th>
<th>Max</th>
<th>Min</th>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>24,9</td>
<td>22,38</td>
<td>23,3</td>
<td>0,6</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>35,6</td>
<td>28,9</td>
<td>31,4</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure C.1: Temperature and Relative humidity measurement of the ambient air during moisture measurements in concrete setup.
C.2 Concrete cylinder strength test

The concrete used in the T-beam of the experiment was tested by forming three small 200mm height and 100mm wide concrete cylinders. The formwork of the cylinders was removed one day after casting and they were put in a closed off 100% RH room for 28 days. The compressive strength of the cylinders used was found by breaking the cylinders in a compression-testing machine. The compressive strength was calculated from the failure load (kg) divided by the cross-sectional area resisting the load and reported in units of MPa. The rate of loading for the test samples was according to IST EN12390-3-2009. The rate on the compressive device was 12-10 while the loading rate was 0.6 ± 0.2 MPa/s. The test results are primarily used to determine that the concrete mixture as delivered meets the strength requirements. The strength test results can be seen in table C.3

<table>
<thead>
<tr>
<th>Test sample</th>
<th>Diameter (mm)</th>
<th>Height (mm)</th>
<th>Mass (kg)</th>
<th>Load (kg)</th>
<th>Load (N)</th>
<th>Strength (N/m²)</th>
<th>Strength (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100.3</td>
<td>200</td>
<td>3.83</td>
<td>3600</td>
<td>35280</td>
<td>4467422.772</td>
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<td>99.4</td>
<td>200.5</td>
<td>3.74</td>
<td>3496</td>
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<td>4417281.477</td>
<td>4.417281477</td>
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<tr>
<td>3</td>
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<td>200</td>
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<td>3240</td>
<td>31752</td>
<td>4044840.764</td>
<td>4.044840764</td>
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</tbody>
</table>

C.2.1 Water content of cylinders

Big cylinder: casted 13. march. In a 100% RH 21°C for 40 days. Weighed 12.43kg. Small cylinder casted 13. march. In a 100% RH 21°C closet for 43 days 25. april. Weighed 3.77kg. Was put into 50% RH 22°C closet 25. april. Small cylinder 2, casted 13. march. In a 100% RH 21°C closet for 56 days, wighed 3.9kg 8.may. Put into water for 2 days, weighed 3.92kg. Put into 50%RH closet 11. may. The concrete report in appendix showed a cube sample of the same concrete showed that the water cement ration was equal to 0.47. The cube volume was 0.00102m³. It’s unit weight was 2377kg/m³. When the cube was wet it weighed 2,180kg. When the cube was dry it weighed 1952kg.
### Figure C.2: The research note from the concrete producer.

<table>
<thead>
<tr>
<th>Stöð</th>
<th>Kuni</th>
<th>Verkefnin</th>
<th>Hlutur</th>
<th>Prófunarskjörla-Nr.</th>
<th>Póntunarúmer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reykjavík</td>
<td>Nýskópunarmiðstöð Islands</td>
<td>Ársteinsir 2 Keldnaholt</td>
<td>1</td>
<td>2018-300</td>
<td>1-2018-300</td>
</tr>
</tbody>
</table>

#### Steypuskilgreiningar

- **Tegund-Nr**: 05252613
- **Saldurferil**: S3
- **Kornast.**: 22
- **Egilileik**: með bendistál, Últ. Ecm >26 GPa
- **Sement / lauka**: 0, XC2, XF2
- **Framleiðandi**: Aalborg Portland ehf
- **Bjöðunarefn**: MapoPlast P
- **Magn**: 0,55%, Reacon Mapei
- **Frámleiðandi**: Adva Flow 455
- **Iðbjöðunarefn**: Grace Construction Products
- **Magn**: 0,35%
- **SikaAer Loftblendi**: 0,05%, Sika
- **Hlutaflinnhu**: 6

#### Fersksteypurfrfr

<table>
<thead>
<tr>
<th>Sýni</th>
<th>Aðfrarg.-Nr.</th>
<th>Sýnatökutnili</th>
<th>Sýnatökustaður</th>
<th>Hlutasfl. (°C)</th>
<th>Steypa</th>
<th>Þjálini</th>
<th>Þjöppun</th>
<th>Rúmbynd (kg/m³)</th>
<th>Loftinnhalð (%)</th>
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<tr>
<td>300 / 1</td>
<td>115629</td>
<td>12.3.2018 14:55</td>
<td>Steypustöð</td>
<td>13,0</td>
<td>s=75</td>
<td>Vibroð</td>
<td>2306</td>
<td>6,9</td>
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<td>Steypustöð</td>
<td>13,0</td>
<td>s=75</td>
<td>Vibroð</td>
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<td>6,9</td>
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<td>12.3.2018 14:55</td>
<td>Steypustöð</td>
<td>13,0</td>
<td>s=75</td>
<td>Vibroð</td>
<td>2306</td>
<td>6,9</td>
<td></td>
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#### Samsetning

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<th>Affehndingarseðla-Nr.</th>
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<th>115629</th>
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<td>Magn (m³)</td>
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<td>Hólaþríðurandur CDE 0-</td>
<td>1.210,96</td>
<td>1.210,96</td>
<td>1.210,96</td>
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<td>Vatnskkarð 0/8 mm</td>
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<td>578,97</td>
<td>578,97</td>
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<td>VM 8/22 mm</td>
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<td>837,79</td>
<td>837,79</td>
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<tr>
<td>CEM I 52,5 N Rapid</td>
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<td>517,03</td>
<td>517,03</td>
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<td>Vatn kalt</td>
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<td>Endurvínsluvatn</td>
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<td>1,95</td>
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<tr>
<td>Vatn heit</td>
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<td>33,16</td>
<td>33,16</td>
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<td>Adva Flow 455</td>
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<td>1,81</td>
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<td>0,27</td>
<td>0,27</td>
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<td>Vatn</td>
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<td>20,16</td>
</tr>
<tr>
<td>Samtala-bynd (kg)</td>
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<td>3.283,26</td>
<td>3.283,26</td>
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<tr>
<td>Sement (kg/m³)</td>
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#### Steypuppurfrfr

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<th>Prófunard.</th>
<th>Aldur</th>
<th>Lengd (mm)</th>
<th>Breidd (mm)</th>
<th>Hæð (mm)</th>
<th>Pvermál (mm)</th>
<th>Bynd (g)</th>
<th>Flataflam (mm²)</th>
<th>Rúmmál (mm²)</th>
<th>Létb.-gildi</th>
<th>Rúmbynd (kg/m³)</th>
<th>C-strength (</th>
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<tbody>
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<td>28d</td>
<td>102</td>
<td>100</td>
<td>100</td>
<td>2425</td>
<td>10200</td>
<td>10200</td>
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<td>2377</td>
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| Geymsla | I vatn | Meðatal | 2390 | 49,0 |

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<th>Sýnatakandi</th>
<th>Bjarki</th>
<th>Undirskrift</th>
<th>Gauðastjóri</th>
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<tbody>
<tr>
<td>Þórður Ólafsson</td>
<td>Kristinn Lind Guðmundsson</td>
<td>Kai Westphal</td>
<td></td>
</tr>
</tbody>
</table>
C.2.2 Reinforcement steel of experimental T-beam
APPENDIX C. EXPERIMENT

Delivery no. : PB10099781  VO00055032  SH121771  Rolling mark : 221
Reference : Mail 29-11
Customer : STJÖRNUBLIKK EHF
Quality mark : RCNO  Process : Hot rolled - cold stretched
KOPAVOGUR

<table>
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<tr>
<th>Delivered Coils</th>
<th>Quality Grade</th>
<th>Production no.</th>
<th>Cost no.</th>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>Cross-sectional area (mm²)</th>
<th>Yield strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Elongation %</th>
<th>R Indie 符号</th>
<th>Relative Bend %</th>
<th>Re mark</th>
<th>Re mark</th>
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<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
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<td>1.22</td>
<td>0.24</td>
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<td>0.016</td>
<td>0.06</td>
<td>0.13</td>
<td>0.012</td>
<td>0.185</td>
<td>0.058</td>
<td>0.011</td>
<td>0.44</td>
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<td>1.20</td>
<td>0.24</td>
<td>0.011</td>
<td>0.016</td>
<td>0.07</td>
<td>0.13</td>
<td>0.012</td>
<td>0.196</td>
<td>0.043</td>
<td>0.011</td>
<td>0.44</td>
</tr>
</tbody>
</table>

It is hereby certified that products covered by this certificate have been tested and are complied with the requirements of the standard. All tests are according to ISO 18630:2010.

Quality assurance : J.Booijnk **During the internal inspection of production control it needs 1 test representatively for 10 coils. For example:

*****10 representativ for *****10 to *****19

*****20 representativ for *****20 to *****29**
C.3 Material data - WUFI experimental simulations

The following figures show the material data of the WUFI database concrete used to simulate the experiment.

Figure C.3: Material properties of the insulation used in the experiment.

Figure C.4: Material properties of the WUFI database concrete.
Figure C.5: Moisture storage function of the WUFI database concrete.