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Moisture performance of thermally insulated basement walls in cold climates

Doctoral thesis

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Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
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Department of Civil and Environmental
Engineering

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Trondheim, October 2022

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Preface

This PhD was completed at the Department of Civil and Environmental Engineering, which is part of the Faculty of Engineering at the Norwegian University of Science and Technology (NTNU). It was written as part of the research project Klima 2050, a Centre for Research-based Innovation (SFI). The aim of Klima 2050 is to reduce the societal risks associated with climate change, enhanced precipitation, and flood water exposure within the built environment. This PhD project is a part of WP1: Climate exposure and moisture-resilient buildings. The thesis investigated the moisture performance of thermally insulated basement walls with an emphasis on the effect of outward drying.

The main supervisor of the PhD project was Professor Tore Kvande at NTNU. Dr.ing. Berit Time and Dr.ing. Stig Geving at SINTEF Community served as co-supervisors. SFI Klima 2050 is funded by the Research Council of Norway (grant number 237859) and the consortium partners. More information about the research project can be found at www.klima2050.no.

August 2022

Silje Kathrin Asphaug

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Summary

Climate change entails frequent and intense events of heavy rainfall and rain-induced floods in many regions with cold climates. In addition, present solutions for stormwater management involve the infiltration of surface runoff into the ground surrounding the buildings. Although sufficient drainage normally prevents water pressure on the basement envelopes in new buildings, the basement envelope is still prone to high moisture strain in the form of high relative humidity (RH) in soil/backfill, precipitation/stormwater, and water from snowmelt.

The primary objective of this thesis has been to make novel contributions to the scientific knowledge regarding the effect of outward drying of thermally insulated concrete basement walls. Several scoping and desktop studies were conducted to map the extent of scientific research available. Furthermore, a novel experimental method that involved applying load cells to monitor the outward drying and precipitated condensation of concrete wall segments insulated with different configurations of thermal insulation and dimpled membranes was developed. In the experiment, the wall segments were exposed to warm interior and cold and humid exterior conditions in a climate simulator. Subsequently, numerical simulations were conducted using COMSOL Multiphysics$^{®}$. The simulations were performed to investigate the concrete wall segments from the laboratory experiment and the long-term moisture performance of thermally insulated basement walls. The vapour permeability of the exterior thermal insulation, moisture performance of three types of concrete, effect of two dimpled membrane positions, and effect of interior vapour barriers were investigated.

The literature reviews and desktop studies provided an overview of the international recommendations for thermally insulated basements in cold-climate countries and studies focusing on the hygrothermal simulations of basement envelopes. Differences between the recommendations primarily pertained to the exterior damp proofing of the walls, use and position of dimpled membranes and vapour barriers, and use of vapour-permeable thermal insulation. Note that a method for the validation of the hygrothermal simulations of basements using full-scale physical measurements was not found in the literature. Therefore, it was concluded that a recognised method/procedure to determine the below-grade exterior boundary conditions is required. In the experimental study, the three basement wall segments exhibited similar drying rates. Thus, it was concluded that the outward drying was primarily limited by the concrete type and not the exterior thermal insulation or position of the dimpled membrane. This inference was validated by numerical simulations.

Using vapour-permeable thermal insulation on the exterior side of basement walls in dwellings might improve the moisture performance of the interior wall components; however, the effect of the insulation will primarily depend on the capillary moisture transfer of the concrete and the thickness and permeability of the exterior and interior insulation. If the concrete dries slowly, a dimpled membrane positioned between the concrete and exterior insulation might provide sufficient drying, assuming that the air gap behind the membrane is slightly ventilated. Therefore, the span of the moisture properties of concrete used in basements requires a thorough investigation.

Definitions

In this thesis, the following definitions are used:

- **Cold climate:** average temperatures below 0°C during the coldest months.
- **Basement:** one or more floors of a building that are completely or partially below grade.
- **Habitable basement:** basements fitted to a high standard and used as living spaces.
- **Semi-basement / English basement / daylight basement:** a basement where parts of the walls are partly or entirely below grade, and part of the floor is above the ground to provide reasonably-sized windows or doors. Semi-basements are typically used in sloped terrains.
- **Walk-out basements:** the basement is nearly entirely underground, and a stairwell with a vertical height of a floor leads up to the outdoors.
- **Building envelope / building enclosure:** the physical separator between the conditioned and unconditioned environments of a building. The building envelope protects the interior space from the effects of the environment, such as precipitation, wind, temperature, humidity, radon, and ultraviolet radiation.
- **Basement envelope:** exterior walls and floors in basements that protect the interior space from environmental effects.
- **Grade:** the surface of the ground surrounding buildings.
- **Below grade**: something that is below grade, which implies under the surface of the earth.
- **Above grade:** something that is above grade, which implies above the surface of the earth.
- **Ground:** earth or soil. "Ground" is commonly used to describe the surface of the earth in the area around a house or other types of buildings. However, in this thesis, “ground” implies the earth or soil surrounding a building.
- **Exterior ground / surrounding ground:** earth, soil, and rock in the ground surrounding a house or building.
- **Vapour-permeable thermal insulation:** thermal insulation materials with a water vapour resistance factor less than 10, such as boards of mineral wool or expanded polystyrene with special qualities.
- **Outward drying:** the amount of moisture drying from the building envelope to the exterior environment.
- **Inward drying:** the amount of moisture drying from the building envelope to the indoor environment.
- **Dimpled membrane:** a membrane (typically consisting of 1-mm polypropylene sheets) with approximately 7–10-mm dimples extruded on one side, which creates an air gap. Dimpled membranes/sheets are designed to provide capillary breaks and vertical drainage and have been used in basement walls since the 1950s [1].
- **Air gap**: an air cavity between two adjacent materials; for example, the cavity between a dimpled membrane and concrete basement wall.
- **Lower air-gap opening:** air-gap openings at the bottom of a dimpled membrane applied to a basement wall. Typically, they are close to the foundation.
- **Upper air-gap opening:** air-gap openings at the top of a dimpled membrane applied to a basement wall (between the dimpled membrane and the spacer profile attaching the membrane to the wall).
- **Groundwater table:** upper level of an underground surface in which the soil or rocks are permanently saturated with water.
- **Concrete wall segment:** part of a basement wall investigated in a laboratory experiment.

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1. Introduction

1.1. Basement walls in habitable basements

In many Nordic countries, basements comprise a significant share of the building volume. Basements can ensure better utilisation of plots with sloped terrains and improve the architectural expression of a building. In densely populated areas and areas with high property prices, basements in apartment buildings, rowhouses, and single-family dwellings are often fitted to a high standard and used as living spaces. Figure 1 shows a single-family dwelling with a semi-basement. Figure 2 shows a single-family dwelling with a semi-basement extended over two floors. In these types of houses, it is common to place the bathroom and laundry room at the rear with walls mainly below grade. The bedrooms and living rooms usually have one or more walls with a window.

Figure 1. It is common for house manufacturers to supply houses with semi-basements on sloping plots. In this single-family dwelling, half of the exterior walls of the lower floor is below grade, and the rest has access to the outdoors. Bathrooms, laundry rooms, corridors, and technical rooms are often located in the rear part. It is common for bedrooms and living rooms to have one or more walls facing the terrain and at least one wall with windows. Fossen is a house model designed and manufactured by Norgeshus (Image: Norgeshus).

Figure 2. Semi-basements in dwellings may feature basement walls extended over two floors.

In multipurpose buildings, it is becoming more common to furnish basements for commercial applications such as shops and restaurants, as shown in Figure 3. Basements have the advantage of low heating and cooling costs owing to earth sheltering. However, the moisture safety design of basements requires further development and innovation. Basements in small buildings, such as single-family dwellings and rowhouses, are rare in wet climates that are prone to floods. However, in locations with a cold or temperate climate, basements are much more common because a concrete foundation below the frost line is a necessity. In new buildings, water pressure on structures is normally prevented by ensuring sufficient drainage below the floor, foundations, and basement walls.

Figure 3. Multipurpose building with a restaurant located in the basement. A kitchen is located next to the below-grade exterior wall.

1.2. Norwegian recommendations for basement walls

Moisture-resilient design of the basement envelope is crucial because below-grade walls are prone to significant moisture strain and have a limited ability to dry compared to above-grade exterior walls. Consequently, the walls are subjected to high relative humidity (RH) in soil/backfill, precipitation, and snowmelt.

Many different strategies may be employed to achieve moisture-resilient basements. In Norway a recommended strategy involves outward drying. According to the principle, the moisture within the structures may dry outward through the insulation by vapour diffusion, condense on the cold side, and drain to the ground below. The difference in temperature and vapour pressure across the exterior thermal insulation layer is the main driving potential for moisture transfer.

Convection might also occur if the thermal insulation material used is air-permeable. However, the effect of outward drying on the overall moisture performance of the walls is uncertain and requires more thorough investigation. Among other factors, the local climate and external temperatures below grade may have a significant influence on the effect of outward drying. Therefore, prior to extensive long-term measurements, studying the outward drying from a theoretical perspective using numerical simulations is beneficial.

According to a Norwegian guideline, vapour-permeable thermal insulation with a water vapour diffusion resistance factor of less than 10 is recommended to increase the outward drying of basement walls [2]. The dimpled membrane was conventionally positioned directly on the basement wall. However, after the Norwegian guideline was revised in 2015, the recommended position of the dimpled membrane changed. Currently, the dimpled membrane is positioned on the exterior side of the exterior insulation. The two positions are illustrated in Figure 4 and 5.

The recommendations are communicated by the SINTEF Building Research Design Guides (Byggforskserien), which are influential within the Norwegian building industry. Byggforskserien consists of approximately 800 design guides that have been produced and continuously updated since 1958. Presently, Byggforskserien is the most-used planning and design tool among Norwegian architects and engineers. The design guides comply with the performance-based requirements in the building code and act as a significant reference for documented solutions in technical regulations. The principal objective of the design guides is to present the data and results from practice and research in a manner that can be implemented practically by the construction industry. Accordingly, the recommendations presented vary according to the framework conditions of the construction industry and research front of building physics.

According to the guidelines concerning thermally insulated basement walls [2], the conventional position of the dimpled membrane is not wrong and does not necessarily lead to damage; however, according to the guidelines, changing the position of the dimpled membrane can reduce the risk of moisture-related damage further by enabling outward drying. Because the recommended changes were primarily based on unpublished calculations and assessments, the improvements in the drying ability have not been experimentally validated [3,4]. Those in favour of the new recommendations argue that both the conventional and new position can form robust structures. According to others, the effect of outward drying is minimal and inadequately documented [5]. Additionally, the air gap behind the dimpled membrane positioned directly on the wall is likely to provide sufficient drying when the air gap is slightly ventilated [5]. Although the upper air gap is too small to be readily visible in Figure 4 and 5, in practice there is enough of an opening for some air to be vented out.

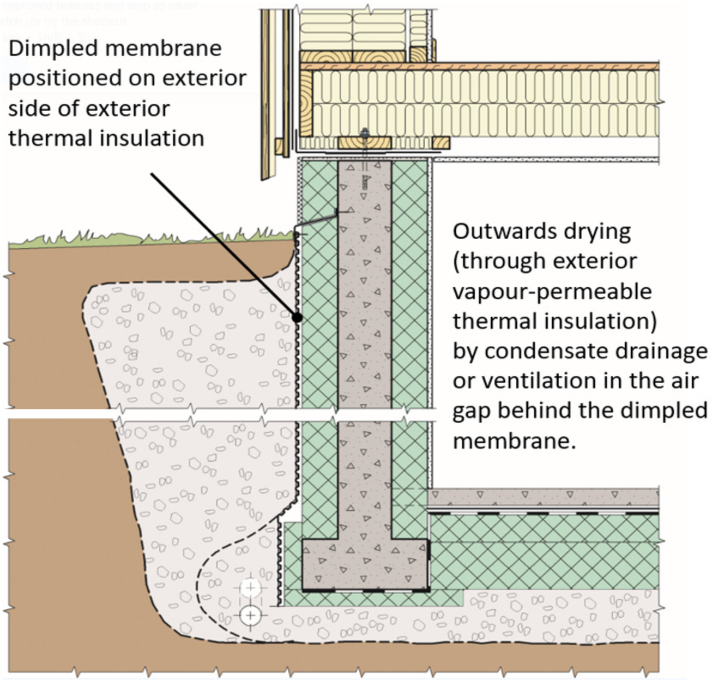


Figure 4. Current recommendation—dimpled membrane positioned on the exterior side of vapour-permeable thermal insulation [2].

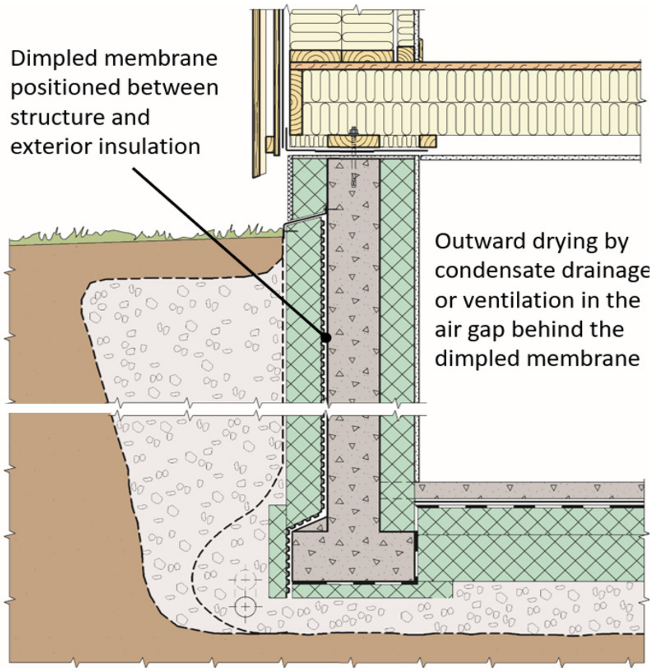


Figure 5. Conventional position—dimpled membrane positioned directly on the concrete wall and exterior thermal insulation as the outer layer [6].

1.3. Objectives and scope

The primary objective of this thesis is to make novel contributions to the scientific knowledge regarding the effect of outward drying of thermally insulated concrete basement walls. In this context, it is of specific interest to better understand how the moisture performance of basement walls is affected by;

- vapour resistance, thickness, and placement of thermal insulation,
- position of dimpled membranes, and
- use of interior moisture barriers.

To operationalize the objective, the following research questions are addressed:

1. What are the moisture-related challenges to overcome in order to ensure moisture-resilient habitable basements?

2. Can the use of outward drying improve the moisture performance of thermally insulated basement walls?

The scope of the study can be described as follows:

- The applicability of commercial simulation tools and recognised numerical models was investigated. However, the necessary improvements to the existing models and numerical techniques were not addressed.
- Habitable basements were investigated. Unheated basements and basements used for storage or industrial purposes were not addressed.
- Thermally insulated concrete walls and floors in basements and semi-basements were investigated. Slab-on-ground structures and intermediate floors were not considered.
- The moisture performance of concrete basement walls was investigated. However, other structures, such as light-expanded clay aggregate masonry, were not addressed.
- Buildings situated in cold climates are discussed. Buildings in warm climates were not addressed.
- Structures above the groundwater table were investigated. Structures below the groundwater level were not addressed.
- Recommendations for new buildings were investigated. However, the rehabilitation, restoration, and maintenance of existing buildings were not addressed.
- Issues related to the building process or geotechnical issues were not addressed.
- The numerical simulations included moisture transfer within the basement walls (concrete and thermal insulation) via capillary conduction and vapour diffusion. Moisture transfer by convection within the thermal insulation was not addressed. Issues related to the leakage of air and radon were not addressed.

The theory to be investigated is illustrated in Figure 6.

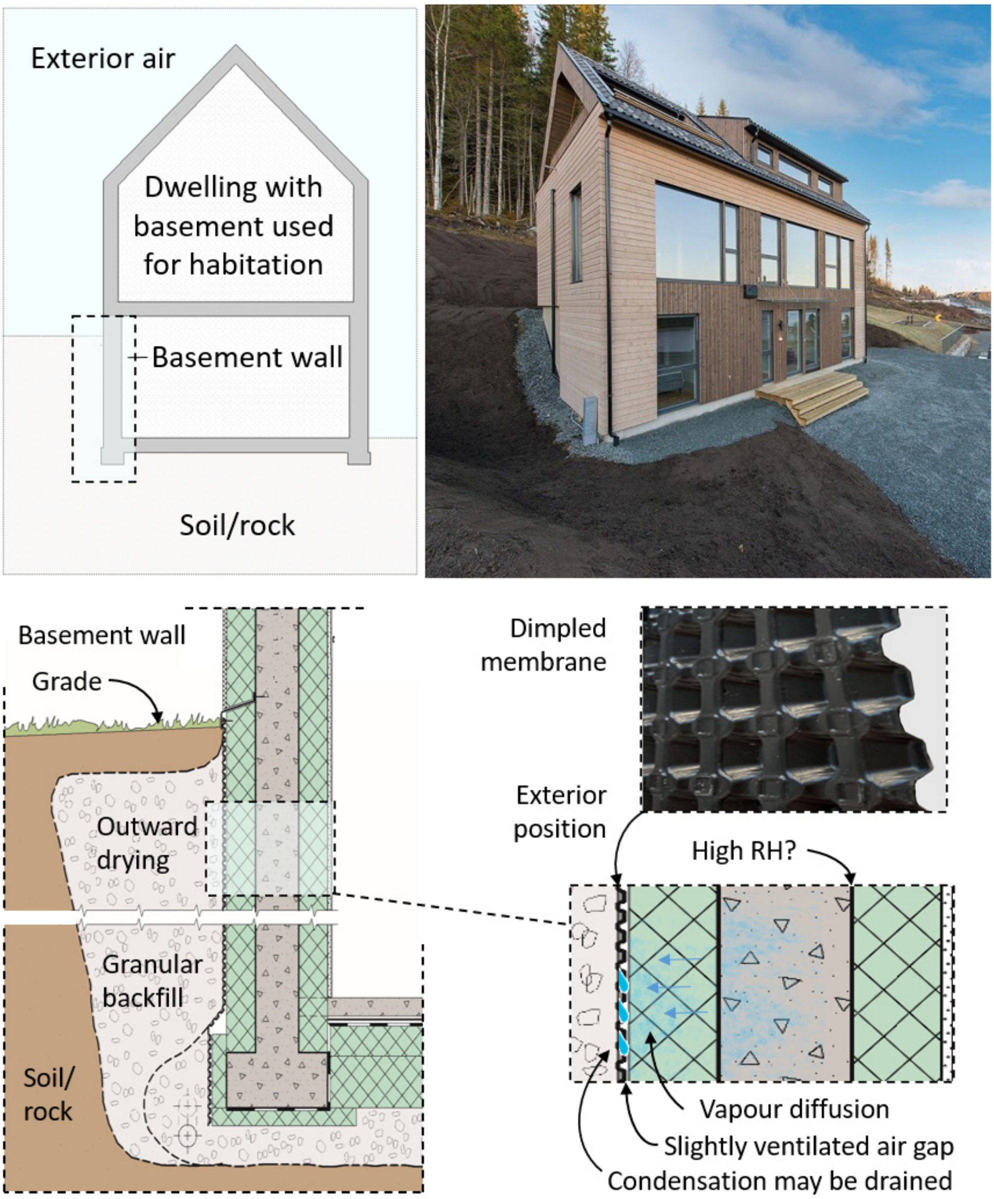


Figure 6. Illustration of the practice and theory to be investigated. Dwelling with a basement used for habitation (upper), basement wall with exterior vapour-permeable thermal insulation (lower left), and outward drying of a part of the concrete wall (lower right). The exterior side of the concrete wall may dry outward through vapour diffusion. Subsequently, the vapour may condensate within the air gap behind the dimpled membrane and is drained to the ground below through the bottom/lower air gap opening.

1.4. Structure of the work

The thesis is divided into two parts, corresponding to each research question.

Part 1: State of the art

Paper 1 charts the state-of-the-art research related to thermally insulated basement envelopes and recommendations for new basements used for habitation. However, most studies in the existing literature have primarily focused on the thermal performance, interior-insulated basement walls, or moisture damage in older buildings. Furthermore, the primary moisture control strategies for habitable basements in western cold climate countries were established based on the national building recommendations for new buildings. Considering the SINTEF Building Research Design Guides (Byggforskserien) [7] as a baseline, 10 key challenges were identified and compared with the recommendations given by experts in the field of building physics (building science) from four other countries with cold climates. **Paper 2** charts the state-of-the-art research related to the hygrothermal simulations of thermally insulated basement envelopes. Based on a detailed literature review, significant observations were made related to the numerical simulations of the ground surrounding buildings. It was concluded that predefined below-grade boundary conditions are required for hygrothermal tools.

Part 2: Potential for outward drying

Paper 3 documents the laboratory experiment performed to investigate the outward drying of concrete walls and generate data for the validation of hygrothermal simulations. The drying performances of three wall segments with different configurations of vapour-permeable insulation-dimpled membranes were compared. The segments were subjected to a steady warm interior and cold and humid exterior climate for six months in a climate simulator. The weight changes, precipitated condensation, and temperature data were monitored. **Paper 4** focused on the basement walls and the effect of outward drying. The study included numerical heat-air and moisture transfer simulations of concrete wall segments (from **Paper 3**) and long-term hygrothermal simulations of thermally insulated basement walls subjected to seasonal temperature and RH variations. The effects of different positions of the dimpled membrane and different concrete characteristics on the drying performance were compared. Furthermore, the effect of interior vapour barriers on the drying performance was evaluated.

2. Theoretical framework

2.1. Challenges to the modelling approach

The term building physics refers to the application of the principles of physics to the built environment. It includes the study of the transfer of heat, moisture, and air between indoor and outdoor environments. Mathematical equations expressing physical laws, such as Fick's law of diffusion, Fourier's law of heat conduction, and Darcy's laws for water and air flow in porous systems, can be used to describe the heat, air, and moisture transfer in building materials and components. When these equations are combined with the equations for the conservation of momentum, mass, and energy [8], a set of partial differential equations that describe the laws of physics for space and time-dependent descriptions is obtained [9]. The combination of several laws used to describe multiple, simultaneous physical phenomena of a system is called multiphysics [10].

Mathematical models can provide analytical solutions only for special cases (such as for certain combinations of simple transfer equations, boundary conditions and configuration geometries). However, modern numerical methods for solving partial differential equations can handle nonlinear problems and complicated geometries by providing approximate solutions to well-posed mathematical models. In other words, a numerical model for the described system can be obtained by discretising a mathematical model [10].

In building physics, numerical simulations are widely used to predict the hygrothermal performance of building materials, components, and entire buildings. Although large-scale in situ experimental examinations may provide realistic results, the costs may often be a limiting factor, and the measurements may often cover only small aspects of the real problem. Numerical simulations are thus a valuable tool for assessing and understanding complex building psychological processes and may be used prior to experimental examinations and in combination with measurement results. However, as described by several authors [11–14], a large number of hygrothermal tools are currently available. The tools vary in their degrees of mathematical sophistication and runtime requirements, that is, they are based on different mathematical models (physical descriptions), use different driving potentials, and utilise different numerical methods for space and time discretisation.

The commercially available tools WUFI®Pro and WUFI®2D are widely used by Nordic consultants and researchers to investigate coupled heat and moisture transfer in building components. The software utilises a simple and accurate modelling approach, the partial differential equations for heat, moisture transfer described by Künzel [15], and a finite volume technique for discretisation. However, WUFI® does not consider heat and moisture transfer owing to air flow, which has a significant impact on the building component performance. In addition, WUFI® does not feature three-dimensional modelling. Obtaining the solutions to partial differential equations (within a reasonable amount of time and computational costs) can be challenging, depending upon the type of equations, number of independent variables, boundary conditions, material properties and initial conditions [16]. In particular, consultants in the field of building science consider detailed two- and three-dimensional hygrothermal simulations of building components over long-term periods computationally expensive.

Powerful commercial solvers, such as COMSOL Multiphysics®, Fluent®, and ANSYS-CFD, are used to investigate the coupled heat and moisture transfer in porous media, including heat and moisture transfer by air flow and complex geometries up to three dimensions (e.g. [16–20]). However, advanced models require expertise and resources. In addition, climate data, boundary conditions, and material properties tailored to building physics (available through dedicated software such as WUFI® or DELPHIN) are not predefined and need to be incorporated into the solvers.

The motivation behind this study was to explore the applicability of advanced simulation tools (e.g. COMSOL) and perform long-term hygrothermal simulations to investigate the air flow in building components. In terms of building physics, the heat and moisture transfer in walls and floors in basements requires investigation. Basement walls consist of many layers of materials, and the optimal positions of the different barrier layers for optimal airtightness, radon, and moisture are disputed. In addition, considering the complex and varying exterior temperature and moisture conditions below grade, multiphysics solvers are the most appropriate tools for analysis.

2.2. Thermally insulated basement walls

Several noteworthy studies have focused on thermally insulated basements. Goldberg and Harmon [21] conducted a comprehensive large-scale experiment to investigate the moisture durability of basement walls retrofitted with interior insulation solutions. Straube [22] investigated interior insulation systems through in-situ measurements and hygrothermal simulations. Fedorik et al. [23] investigated the various refurbishment strategies for basement walls using hygrothermal simulations. Saber et al. [24] showed that air gaps in basement walls can be utilised to improve the thermal performance, and Blom and Holøs [25] evaluated the drying performance of internally insulated basement walls. However, these studies mainly focused on the performance of the interior insulation systems. They did not assess the effect of exterior vapour-permeable thermal insulation or the position of the dimpled membrane on the drying ability.

2.3. Outward drying through vapour-permeable thermal insulation

Improving the drying ability of basement walls is advantageous because high RH/moisture content in the basement walls may lead to the growth of mould and rot fungi and structural decay. Furthermore, high RH is detrimental to the thermal performance of the basement envelope [26–29]. However, the extent of the effect of permeable insulation on the outward drying ability is uncertain because there are many factors that affect the drying rate, such as the thickness and permeability of the exterior insulation, amount of interior insulation, and indoor temperature. Furthermore, the effect of the air flow through the air gap behind the dimpled membrane on the outward drying ability also requires evaluation.

Some existing studies have investigated the effect of outward drying of basement walls on the overall drying performance using vapour-permeable thermal insulation. Blom [30] measured the RH, moisture content, and temperatures of six different concrete basement wall designs in a small test house. The results did not show any significant increase in the drying effect for walls with exterior vapour-permeable thermal insulation compared with conventional walls.

Geving et al. [3] performed field measurements of the desiccation of two basement walls retrofitted with exterior vapour-permeable thermal insulation on the exterior side. The concrete wall, which was built in 1920, exhibited no drying after the first seven months. Instead, an increase in the moisture content of the lower part of the wall was observed. According to Geving et al. [3], this can be attributed to the low temperature of the unheated basement. Similarly, a "hollow brick wall" built in 1930 did not show any signs of drying over a period of 19 months. In this case, the average indoor temperature in the basement was 15°C. According to Geving et al. [3], the lack of drying can be attributed to the high moisture level of the bricks, perhaps up to capillary saturation, which requires a long time to reach the hygroscopic range.

Subsequently, Geving et al. [3] performed hygrothermal simulations of the desiccation of old wetted concrete basement walls retrofitted with vapour-permeable thermal insulation on the exterior side. The hygrothermal simulations were performed for a two-dimensional vertical wall section (above and below grade) using WUFI®2D [31]. The results showed that the walls with vapour-permeable exterior insulation (EPS, $\mu = 4.4$) dried faster and had a lower moisture content at equilibrium than the walls with less permeable insulation (traditional design). The results also validated that the drying rate depended on the indoor temperature, thickness, and position of the thermal insulation. Additionally, it was observed that the drying ability improved significantly when all thermal insulation was positioned on the exterior side. Moreover, using interior insulation or interior cladding decreased the outward desiccation. It was observed that increasing the thickness of the exterior insulation increased the outward desiccation effect; however, this effect was observed only up to an insulation thickness of approximately 100 mm. It was concluded that the desiccation increased because the temperature difference that drove the outward vapour diffusion increased. However, beyond approximately 100 mm, the vapour diffusion resistance of the EPS outweighed the increase in the temperature difference and increasing the insulation thickness decreased the desiccation effect. The impact of the insulation thickness was studied further by Lund [32] using the same simulation method as Geving et al. [3]. However, in contrast to Geving et al. [3], the study focused on new concrete structures containing moisture from casting. The results indicated that the optimum thickness for the exterior wall insulation was between 50–100 mm for the vapour-permeable insulation ($\mu = 4.4$) and approximately 50 mm for the semi-permeable variants ($\mu = 50$).

Pallin [33] used hygrothermal simulations to investigate the effects of outward drying of concrete basement walls retrofitted with exterior vapour-permeable thermal insulation for the climate of Gothenburg, Sweden. It was observed that the outward drying was slow, and only approximately 6 to 8 kg/m^2 of moisture in the wall could be dried annually. Note that the rain loads that directly hit the ground or drain from the upper wall surfaces can accidentally penetrate the drainage/insulation board; this can lower the expected drying potential. Therefore, Pallin [33] suggested replacing the landscape fabric with a water vapour barrier to increase the drying potential.

The impact of the air flow through the air gap behind the dimpled membrane is difficult to predict. The simulations performed by Geving [3], Pallin [33], and Lund [32] did not consider a dimpled membrane on the exterior side of the exterior insulation.

2.4. Position of the dimpled membrane

Dimpled membranes/sheets are designed to provide capillary breaks and vertical drainage, as illustrated in Figure 6. Few studies have focused on the ventilation and outward drying through the air gap of the dimpled membranes used on the exterior side of the basement walls. Some studies have investigated the exterior air gaps in above-grade walls. Although the scope of these studies is different, aspects of their findings are applicable to the present work.

Straube [34] performed a laboratory experiment to investigate the role of small gaps in ventilation drying and the gap size required to ensure drainage. According to the results, ventilation drying could play a role in small gaps of approximately 1 mm at a pressure difference of only 1 Pa. Straube and Smegal [35] continued their study and investigated the applicability of one-dimensional simulation models with source and sink enhancements to simulate the hygrothermal performance of wall systems with drained and ventilated air gaps. Their study also demonstrated the challenges of modelling the real moisture storage of air in the air gap and the moisture retained on the drainage gap surfaces.

Finch and Straube [36] investigated the drying of the ventilated claddings in above-grade exterior walls. They observed that the probable range of ventilation rates depended on the cladding type, cavity dimensions, and venting arrangement and was determined by the thermal and moisture buoyancy and wind pressures. They proposed that the vent openings should be as large as possible and unobstructed to ensure optimal drying.

Straube et al. [37] performed field studies of wooden-framed wall systems clad with bricks or vinyl siding. They observed that the drying rates varied significantly under different weather conditions, and the ventilation increased the drying potential of some walls. Furthermore, solar-driven vapour diffusion redistributed the vapour from within the wall to the interior (where it caused damage). The ventilation reduced the magnitude of the flow.

Rahiminejad and Khovalyg [38] reviewed the ventilation rates in air gaps behind the cladding of above-grade walls. They reported that the stack effect and wind effect are the two major mechanisms driving the air flow in ventilated air spaces. For basements, solar radiation may be most influential at the part of the walls above grade [33]. The wind effect may be less significant than in walls above grade; however, the stack effect may be more important because of the temperature difference between the top and bottom of the walls.

As described in Section 2.1, the effects of the basement walls drying outward and those of the position of the dimpled membranes on the drying rates need further investigation. If vapour condensation occurs within the air gaps behind the dimpled membrane, as illustrated in

Figure 6, the moisture should be able to drain down below the building. The bottom opening of the air gap should thus not be completely blocked. If blocked, moisture may accumulate within the thermal insulation. If not completely blocked, the air gap may be slightly ventilated. Thus, some moisture may be ventilated out owing to the air exchange with air in the backfilling. Thus, it can be concluded that the outward drying achieved by the two configurations presented in Figures 4 and 5 is dependent on the air exchange between the air gap and the air within the backfilling. The amount of this air exchange is, however, uncertain and difficult to predict.

The Norwegian recommendations introduced in 2015 were not sufficiently substantiated by the current research. However, before initiating large-scale in situ experimental examinations, the effect of the outward drying of basement walls should be investigated further through numerical simulations.

2.5. Predicting heat and moisture transfer in building components

Numerical simulations are widely used to predict the hygrothermal performance of building materials, components, and entire buildings. Although large-scale in situ experimental examinations provide more realistic results, they incur high costs, and the measurements may often address only small aspects of the real problem. Therefore, numerical simulations are a valuable tool for assessing and understanding complex building psychical processes and should be used prior to experimental examinations.

The standard NS-EN 15026:2007 [39], defines the practical applications of the hygrothermal simulation software and specifies the equations to be used for calculating the one-dimensional transient heat and moisture transfer in multilayer building envelope components subjected to non-steady climate conditions. The prescribed equations are based on the conservation of energy and moisture. The mathematical expressions of the conservation laws are the balance equations.

According to NS-EN 15026:2007 [39], heat transport inside materials shall be composed of sensible heat transport (calculated using Fourier's law and a moisture-dependent thermal conductivity) and latent heat transport. The heat flow from the surrounding environment into the building materials includes shortwave radiation (from the sun), long-wave radiation (from the sky and surrounding surfaces), and convection. Moisture is transported inside the materials via capillary forces and diffusion. The transport equations shall be formulated using the partial vapour pressure and the suction as the driving potentials. If the transport coefficients are transformed, and the suction and partial vapour pressures are handled in a way which makes it continuous across the interface between two materials, alternative potentials such as RH, moisture content and temperature may be used for the liquid transport. Factors influencing the liquid moisture transport at the contact surface between two material layers (e.g., small air gaps) may be described by an additional moisture resistance. At the exterior surface, coatings and paints can influence the water uptake and drying. An additional moisture resistance can be used to describe the impact on diffusion. The precipitation available for absorption and the amount of water which can be absorbed by the material at the surface, limit the uptake of driving rain.

The physical principles of heat and moisture transport were described by Künzel [15]. The primary objective of the study conducted by Künzel [15] was to develop a process to calculate the simultaneous heat and moisture transport in multi-layered components. The process could work with relatively simple storage and transport functions, and it was primarily derived from the standard material parameters. The following heat transport mechanisms were considered in the form of equivalent conductivities: thermal conduction, enthalpy flow through moisture movement with phase change, short-wave solar radiation, and long-wave radiation. The following moisture transport mechanisms were considered: capillary conduction, surface diffusion, and all the transport mechanisms for vapour transport. Note that the heat and moisture transport owing to air convection through joints and other leakages, seepage flow through gravitation, liquid transport through hydraulic flow, electrokinesis, and osmosis were not considered. According to Künzel [15], two independent driving potentials are necessary to calculate non-isothermal moisture transport. The potentials of temperature, vapour pressure, and relative humidity can be derived from the two independent variables, temperature, and relative humidity. Künzel [15] proposed that the aforementioned potentials were optimal for heat and moisture transport; this is because temperature and water content are only indirect moisture potentials (leading to relatively complex functions and resulting in transport coefficients, which are generally difficult to determine). Furthermore, the "capillary suction stress" of moist materials cannot be measured directly, and it cannot be defined for materials that are dry or not capillary active. Considering the above-mentioned factors, a closed differential equation system was developed to calculate the moisture behaviour of multi-layered building components under natural climate boundary conditions. The coupled equation system and numerical solution technique formed the basis for the commercial simulation tools WUFI®Pro and WUFI®2D [40].

2.6. Predicting heat and moisture transfer in basements walls

The tools WUFI®Pro and WUFI®2D are widely used by Nordic consultants and researchers to investigate the coupled heat and moisture transfer in building components. However, to thoroughly compare the effects of the two positions of the dimpled membrane, a simulation tool that includes moisture transfer by air flow is required, such as COMSOL Multiphysics®, Fluent®, or ANSYS-CFD. Some examples of studies concerning air flow in building components are provided in the reference section [17–20]. However, the use of more advanced models requires user expertise and resources [16].

The basement walls are different from the above-grade walls owing to the presence of soil and granular backfilling, as shown in Figure 7. The interior boundary conditions may be determined according to the measured data or recognised procedures (e.g. NS-EN 15026:2007 [39], NS-EN ISO 13788:2012 [41]. Similarly, the exterior above-grade boundary conditions may be determined according to measured data or recognised procedures (e.g. EN 15026:2007 [39]). However, determining the below-grade exterior boundary conditions can be challenging. The exterior below-grade RH may be set to 99% according to NS-EN 15026:2007 [39] and the heat loss from basements may be predicted according to the procedures proposed in NS-EN ISO 13370:2017 [42]. However, Janssen et al. [43,44] compared the results obtained from coupled simulations (coupled equations for the soil heat and moisture transfer and the full formulations of the surface heat and moisture balances) with those obtained from linear thermal simulations. The moisture contents in the linear thermal simulations were maintained at their respective yearly averages based on the coupled simulation (i.e., no moisture transfer was included; only thermal conduction was present). The comparison results showed that the coupled simulation, which included moisture transfer into the soil, yielded higher heat loss. Janssen et al. [38] concluded that the increased heat loss difference between the coupled and linear simulations cannot be regarded as insignificant, and the soil moisture transfer has an indisputable influence on building heat loss via the ground. Therefore, the impact of soil moisture transfer on the hygrothermal performance of basement envelopes requires further investigation.

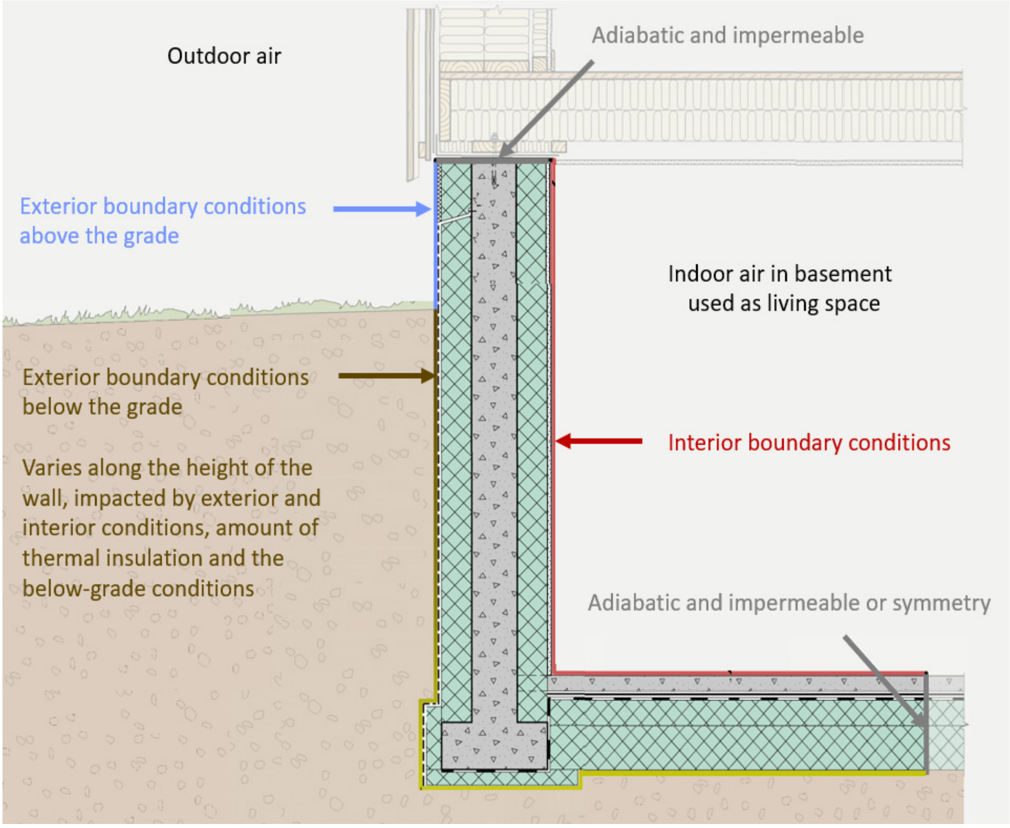


Figure 7. To investigate the heat and moisture transfer in basement walls, novel methods for determining the exterior below-grade boundary conditions are required.

2.7. Cold climates

In this thesis, geographical locations with average temperatures below 0°C during the coldest months are defined as locations with a “cold climate”.

The Köppen-Geiger climate classification system categorises different climate regions on Earth based on temperature [45,46]. The different climate regions can be divided into five main groups with several types and subtypes. Thodesen et al. [47] identified the relevant Köppen-Geiger climate classifications within the Nordic countries of Norway, Sweden, Finland, and Denmark. The three identified Köppen-Geiger subcategories and their corresponding locations within each country are shown in Figure 8. Sweden and Norway display all the three subcategories identified in the Nordic environment. Denmark (maritime temperate) and Finland (continental) can be classified as mono-climatic countries.

Subcategories:

🟩

C: Maritime climate
The average temperature is above 10°C during the warmest months and between -3°C and 18°C during the coldest months.

🟦

D: Continental climate
The average temperature is above 10°C during the warmest months and below -3°C during the coldest months.

⬜

E: Polar climate
The average temperatures are below 10°C during all 12 months of the year.

Figure 8. Climate classification map for Nordic countries according to the Köppen-Geiger system – all cities above 100,000 inhabitants marked out (2016) [47].

According to the definition in this thesis, all locations classified within the subcategories D and E exhibit a “cold climate”. Locations categorised as subcategory C (maritime temperate climate) mainly represent a cold climate, but may also include locations that are too warm (between 0°C and 18°C during the coldest months).

2.8. Relevance to Klima 2050 and climate changes

The primary goal of Klima 2050 is to reduce the societal risks associated with climate changes and enhanced precipitation and floodwater exposure within the built environment. Although the water pressure on basement structures can be reduced by sufficient drainage, the basement envelope is still prone to high moisture strain in the form of high RH from soil/backfill, precipitation/stormwater, and water from snowmelt. As climate change entails frequent and intense events of heavy rainfall and rain-induced floods in many regions with cold climates [48,49], these loads are likely to increase in the near future. The moisture strain on a basement envelope may increase further if the stormwater management strategy involves the infiltration of surface runoff into the ground surrounding the building [50]. In addition, the ability of the building envelope to dry out is reduced if the soil surrounding the building is constantly wetted by rain. Furthermore, the duration of dry conditions may be reduced in the future owing to climate change. Moreover, higher annual temperatures owing to climate change also have a detrimental effect on the outward drying ability of basement walls.

3. Methodology

3.1. Scoping literature reviews

The purpose of the first part of the thesis (**Paper 1 and 2**) was to chart the available literature on thermally insulated basement envelopes. For the literature review, a literature search method known as scoping study was adopted. As described in [51], a scoping study is an approach for literature review that maps the extent of scientific research available on a specific topic through systematic searches in scientific databases.

The method used for scoping studies in this thesis was based on the framework described by Arksey and O'Malley [51], which involved a six-step procedure: 1) identifying the research question, 2) identifying the relevant studies, 3) selecting the studies, 4) charting data, 5) collating, summarising, and reporting the results, and 6) consultation. In accordance with the framework described by Arksey and O'Malley [51], multiple databases were included in the search. ScienceDirect was selected as the main search engine for scientific papers and journal articles. Google Scholar was selected for complementary and broader searches (including results from additional scientific journals, scientific publications, and grey papers). The search terms (combinations of keywords) were carefully selected based on the main author's qualitative judgment and expertise.

Several scoping studies were conducted during the various phases of this PhD project, focusing on the different aspects of basements and numerical simulations. The two most thorough literature reviews formed the basis of **Paper 1 and 2**. For a more detailed description of the search procedure, please refer to the respective papers. In addition to these two reviews, the development and use of models and software for evaluating the heat and moisture transfer in building applications (simplifications, equations, potentials, and boundary conditions) were investigated.

3.2. Desktop studies

A desktop study of recommendations was conducted in the Norwegian context to identify the primary challenges pertaining to moisture control in habitable basements. The object of the study was the SINTEF Building Research Design Guides [3], which provides authoritative guidelines for industry practice. The guidelines are comprehensive and cover almost all the categories of buildings. A sample relevant to the study was selected based on a detailed selection process. The selected design guides were reviewed. The selection process is illustrated in Figure 9.

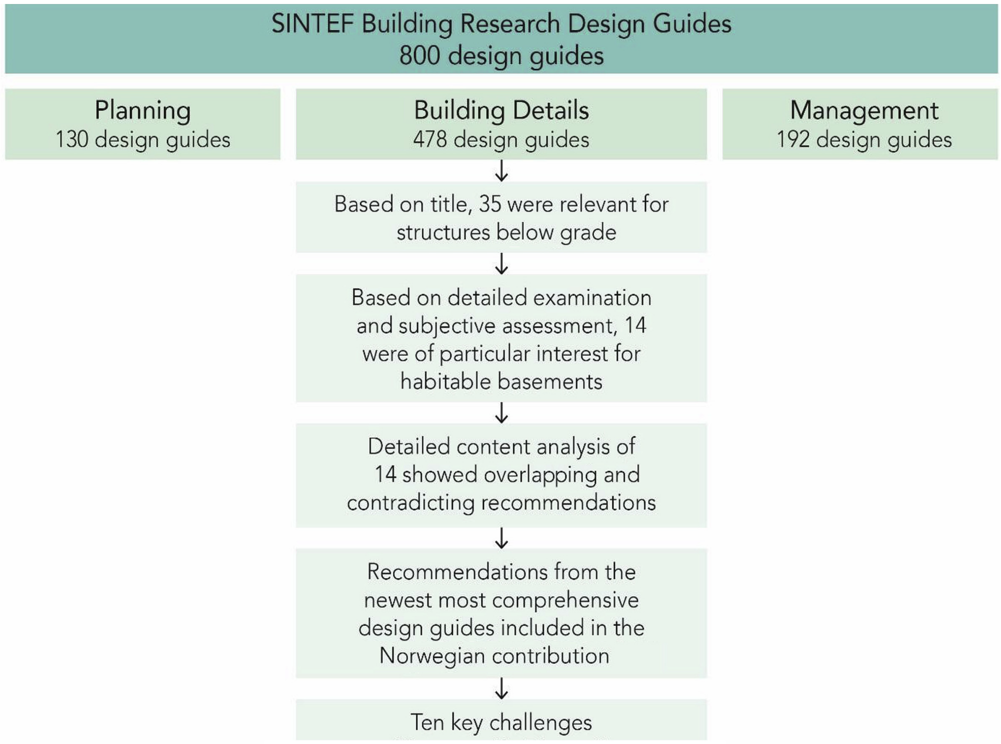


Figure 9. Sorting process used for the content analysis.

The desktop study results were presented as a table detailing the 10 key challenges and the Norwegian recommendations for moisture control in habitable basements, as shown in Appendix A in **Paper 1.** The table with Norwegian recommendations was used as a basis for collaboration with the international experts (described in Section 3.3).

An additional desktop study was performed in **Paper 2** to identify significant results from studies on hygrothermal simulations of walls in thermally insulated basements and slab-on-grade structures. The 10 most comprehensive studies were identified through two scoping literature studies. The scoping studies involved the following steps: (1) identifying the studies concerning the hygrothermal performance of basement envelopes; (2) investigating the methods, numerical tools, assumptions, simplifications, and exterior boundary conditions used in these studies; (3) investigating the validation procedures for the measurements; (4) identifying the significant results that can be used for improving the hygrothermal numerical simulations. Note that these studies were typically more concerned with the outcome of the simulations rather than the simulation methodology itself. Therefore, in some cases, the description of the methodology was inadequate.

3.3. Collaboration with international experts

The literature review in **Paper 1** did not provide a sufficient knowledge base for elucidating the national recommendations for moisture control in habitable basements in cold-climate countries. Therefore, five leading experts in the field of building physics (building science) from countries with cold climates (Denmark, Sweden, Canada, Finland, and Estonia) were invited to provide detailed information on recommended building practices. The five experts were directly contacted, based on the network of supervisors, and requested to provide overviews of the main recommendations for moisture control in their country and relevant literature. The experts were asked to provide the following:

1. The key elements and recommendations for achieving optimal moisture safety for habitable basements in new buildings in their country.
2. One or two detailed figures that exemplify the practical application of these recommendations.
3. A concise description of the use of basements in their country.

The experts were provided with the Norwegian exemplification of the above-mentioned information. All experts, except for the one from Finland, provided the required information. Subsequently, the recommendations from the four cold climate countries were compared with the Norwegian recommendations for each of the 10 key challenges. This comparison formed the basis for the investigations of moisture control strategies for habitable basements, which have been reported in **Paper 1**.

3.4. Laboratory experiment

General approach

Paper 3 reports the development of a novel experimental method. The primary objective of the experiment was to investigate the outward drying of thermally insulated basement walls and generate data for the validation of the hygrothermal simulations. A method was developed to compare the drying performance for two different positions of the dimpled membrane (illustrated in Figure 4 and 5) and two types of vapour-permeable EPS. A laboratory experiment was conducted instead of field measurements to ensure a thorough investigation of the outward drying and ascertain the most influential parameters before initiating long-term field measurements. Note that it may be easier to validate hygrothermal simulations using data collected under stable and equal climate conditions than under natural weather conditions.

In addition, the following considerations were made: 1) field measurements can be time-consuming because the conditions favourable for outward drying are only present during sufficiently cold periods. Thus, the measurements may require several years; 2) moisture content measurement devices and RH-sensors (e.g. moisture content electrical readings used in wood plugs in the concrete) have a limited accuracy above the hygroscopic moisture range of 95–98% RH; 3) irrespective of the accuracy of the RH values, the sensors may not endure the humid climate prevalent at below-grade levels; 4) the measurements should preferably be conducted on newly built basement walls to avoid uncertainties related to the initial moisture content, insufficient drainage, air leakages, and capillary transfer of moisture through the foundations.

The drying performance of two wall segments with vapour-permeable insulation and exterior dimpled membranes was compared with that of a segment with a dimpled membrane positioned between the concrete and exterior insulation. The wall segments were subjected to a steady warm interior and a cold exterior climate using a climate simulator. The changes in weight, precipitated condensation, and temperature data were monitored for six months. A general overview of the experimental setup and the diagrams of the wall segments are presented in Figure 10.

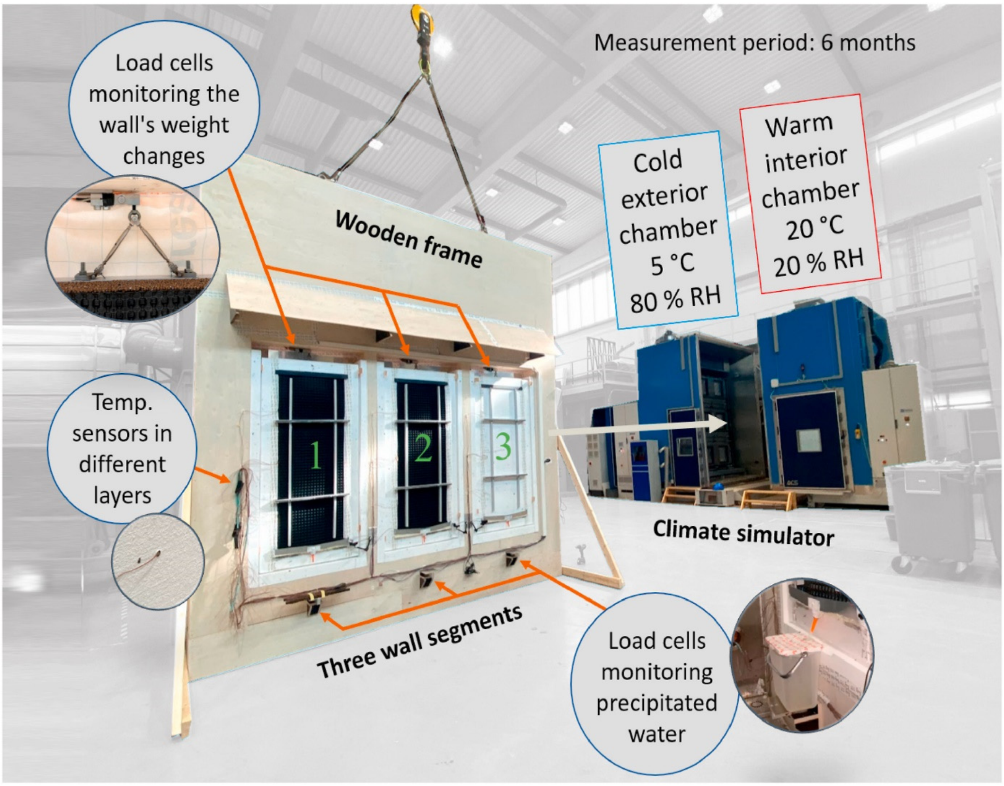


Figure 10. General overview of the experimental setup. The three wall segments were hung in the load cells in an insulated wooden frame and subjected to warm interior and cold exterior climates in a climate simulator for six months.

Experimental setup

Much effort has been devoted to the development of the research test setup. Hygrothermal simulations were performed in WUFI®Pro to 1) predict the potential drying of the concrete wall segments and 2) determine the applicability of the load cells to monitor the weight changes. Document studies were conducted to investigate and document the properties and applicability of the materials and products used in the experiment. Special emphasis was placed on determining the required properties of the standard and vapour-permeable EPS and the type of concrete used in the wall segments.

The overall size and composition of the wall segments were determined to 1) achieve drying within a limited amount of time using the climate simulator and 2) ensure appropriate initial weight. The size, dimensions, and composition of the wooden frame were determined to 1) bear the weight of the concrete wall segments, 2) fit the opening in the climate simulator between the cold and warm chambers, and 3) achieve sufficient airtightness between the chambers.

To ensure accurate weight measurements of the dried-out moisture, the wall segments were hung freely in the suspended load cells in the wooden frame. Thus, the attachments between the load cells and wooden frame and those between the load cells and concrete wall segments were custom made to enable adjustments vertically and horizontally after mounting. A method was developed to enable the wall segments to hang freely while still maintaining airtightness. In addition, the method reduced the impact of the thermal bridges on the transition between the wall segment and the wooden frame. Diagrams of the wall segments showing the dimensions and material configurations, along with one wall segment positioned in the wooden frame, are shown in Figure 11. More details regarding the development and execution of the laboratory experiment can be found in [52] and Klima 2050 Note 136 [53], supplementing **Paper 3**.

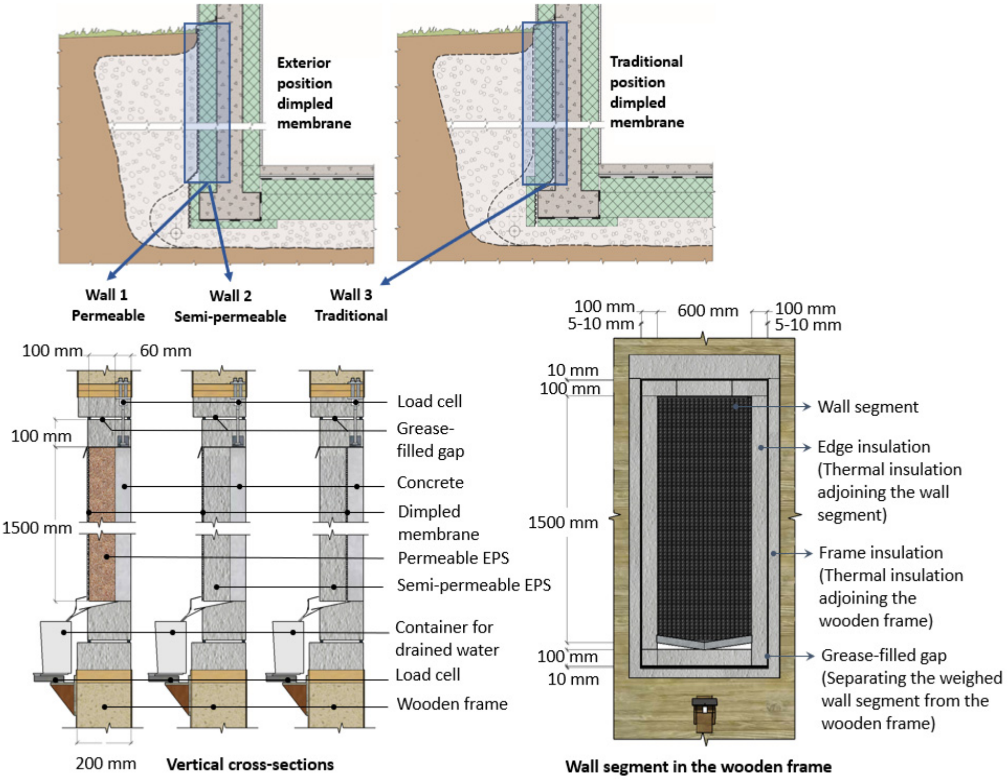


Figure 11. Diagrams of wall segments showing dimensions, material configurations, and one wall segment positioned in the wooden frame.

Experiences and challenges with the experimental method

The suspended load cells used to monitor the weight changes of the wall segments had a load capacity of 220 kg and an accuracy of 20 g. The applied load cells were observed to be well-suited for monitoring the wall weight changes. Note that the wall segments weighed approximately 150 kg, and the changes in weight were less than 1.3 kg. However, the wall segments were relatively sensitive to temperature fluctuations. Because the temperature in the climate simulator was not constant, some fluctuations in the monitored weights were observed.

Owing to freezing of the cooling pipes, RH in the exterior climate chamber could not be ~100% as intended, while maintaining a low temperature (below 5°C). Therefore, several test runs were conducted, and a temperature of 5°C and 80% RH were achieved by defreezing the pipes for 30 min each day. There were several challenges that had a detrimental effect on the stability of the climate simulator and measuring equipment. Thus, there were short periods of unconditioned climate in the interior and exterior chambers.

Operational challenges related to defrosting, humidification, temperature control, power outages, and logging made it difficult to run the experiment for long periods with stable conditions. An advantage of this experimental method was that the walls were tested simultaneously. Thus, the walls were subjected to the same climate, ensuring comparable results.

3.5. Numerical simulations

General approach

Numerical simulations were performed in **Paper 4**. The primary objective of the numerical simulations in **Paper 4** was the same as that of the laboratory experiment in **Paper 3**, i.e., to investigate the outward drying of thermally insulated basement walls. Numerical simulations were also performed to investigate the outward drying achieved by the wall segments in the laboratory experiment presented in **Paper 3.** The simulations were performed in three steps, referred to as Steps 1, 2, and 3, as shown in Figure 12 and 13. The purpose of the first two steps was to examine the effect of the dimpled membrane on the outward drying of the concrete wall segments and create input and data for the third and final step, which was a full-scale long-term simulation of a basement wall.

In Step 1, one-dimensional hygrothermal simulations were conducted to investigate the influence of the vapour permeability of the EPS, concrete characteristics, and position of the dimpled membrane (exterior or medial) on the outward drying of the concrete wall segments. First, the wall segments were studied by omitting the dimpled membrane from the simulations. Second, the influence of the air exchange behind the dimpled membrane was investigated for the exterior and medial positioning of the dimpled membrane. In Step 2, more advanced two-dimensional air flow models were established to further investigate the air flow in the air gap behind the dimpled membrane. The effect of the exterior and medial positioning of the dimpled membrane was investigated for different air gap opening thicknesses (2–5 mm) and two types of concrete. In Step 3, the effect of the outward drying of the concrete wall segments on the overall long-term moisture performance was investigated. Based on the input from Step 2, the exterior-dimpled membrane was omitted from these simulations. Subsequently, the basement walls were compared for the same climate location (Oslo). The boundary conditions are shown in Figure 14. Below grade, the RH was set to 99% according to NS-EN 15026 [39] and the variation in temperature was determined using a separate heat transfer simulation, as illustrated in Figure 14.

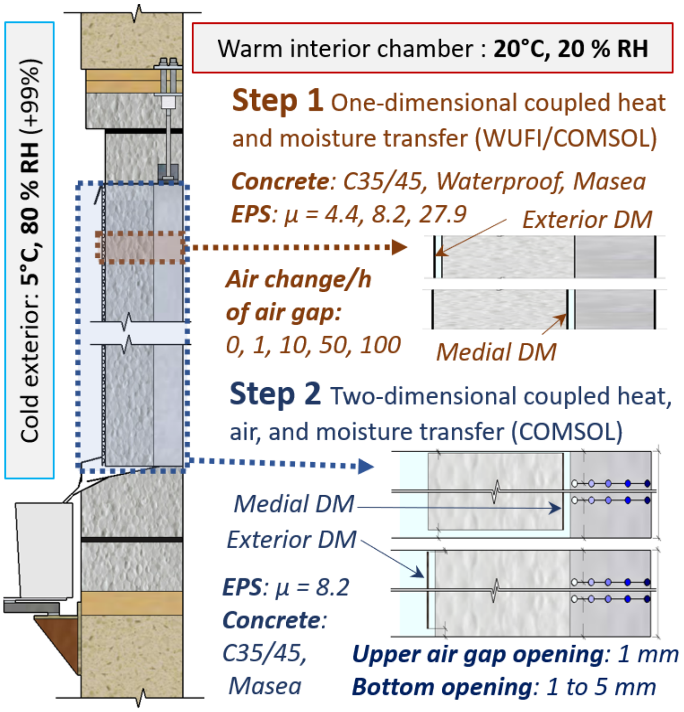


Figure 12.
Steps 1 and 2 were performed to investigate the outward drying of the concrete wall segments from the laboratory experiment described in section 4.4. The effect of two different positionings of the dimpled membrane (DM) was compared.

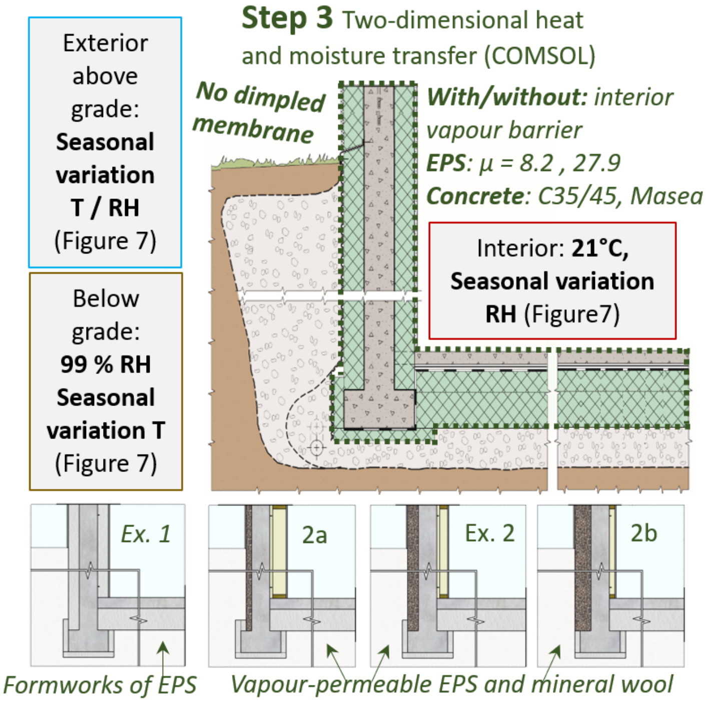


Figure 13.
Step 3 was performed to investigate the long-term moisture performance of the basement walls.

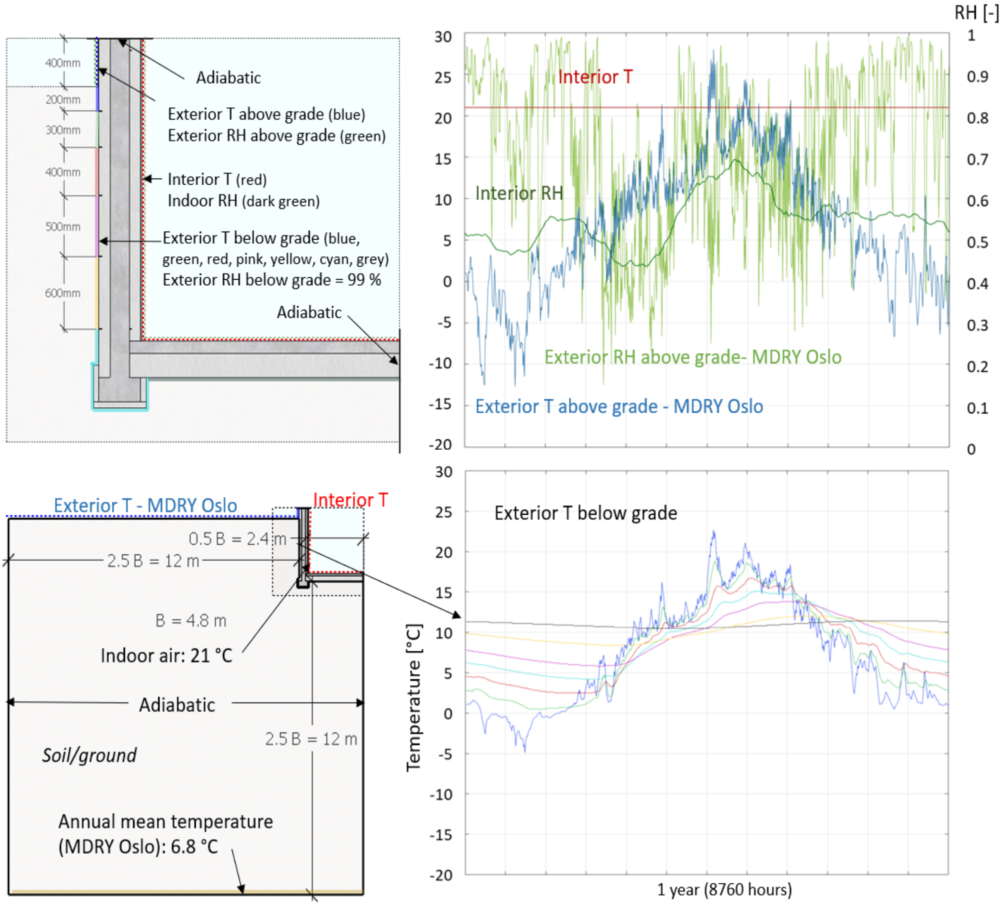


Figure 14. Boundary conditions used in Step 3 and illustration of the procedure of obtaining the below-grade temperature boundary conditions.

Simulation tools

The one-dimensional simulations in Step 1 were conducted using WUFI®Pro. WUFI®Pro is a commercially available tool previously used by the authors of this thesis. Note that it is widely used by researchers and consultants in the building industry to evaluate the moisture conditions in building envelopes [40]. The air flow through the air gap behind the dimpled membrane was modelled using a generic air layer and different air exchange rates.

The two-dimensional simulations in Steps 2 and 3 were conducted using COMSOL Multiphysics® [54] and the heat transfer and subsurface flow modules. COMSOL Multiphysics® was selected based on a thorough investigation of the available software, physical models, and methods adopted in the existing literature. The investigation was conducted as a scoping study, as described in Section 3.1.

Runtime and convergence

Note that as numerical models become larger and more complex, more computing resources are required to run the models efficiently. Improving the numerical settings and numerical model (geometry, mesh, boundary condition, initial conditions) may also significantly improve the convergence and runtime. The one-dimensional simulations in Step 1 were performed without convergence failures. In contrast, the two-dimensional air flow simulations in Step 2 experienced problems, especially as the height of the wall increased and the air gap openings reduced. Sufficient convergence and improved runtime were achieved by removing the unnecessary details and improving the mesh refinement around the air gap openings. In the long-term simulations in Step 3, implementing the boundary conditions was challenging because the climate varied with the height of the wall, and the climate data consisted of hourly values. Animations were created from the temperature (T), RH, and moisture content (MC) plots to analyse the results. An area on the exterior side of the exterior insulation, at the border separating the above and below grade, was identified as the primary cause of error. Acceptable convergences and runtimes were achieved by 1) reducing the number of data points in the climate files, 2) using an interpolated graph to implement the climate data for one year and repeating the data with a mod-function at each boundary, and 3) using a piecewise interpolation of the material data instead of linear interpolation; this reduced the calculation time by half.

3.6. Graphs and illustrations

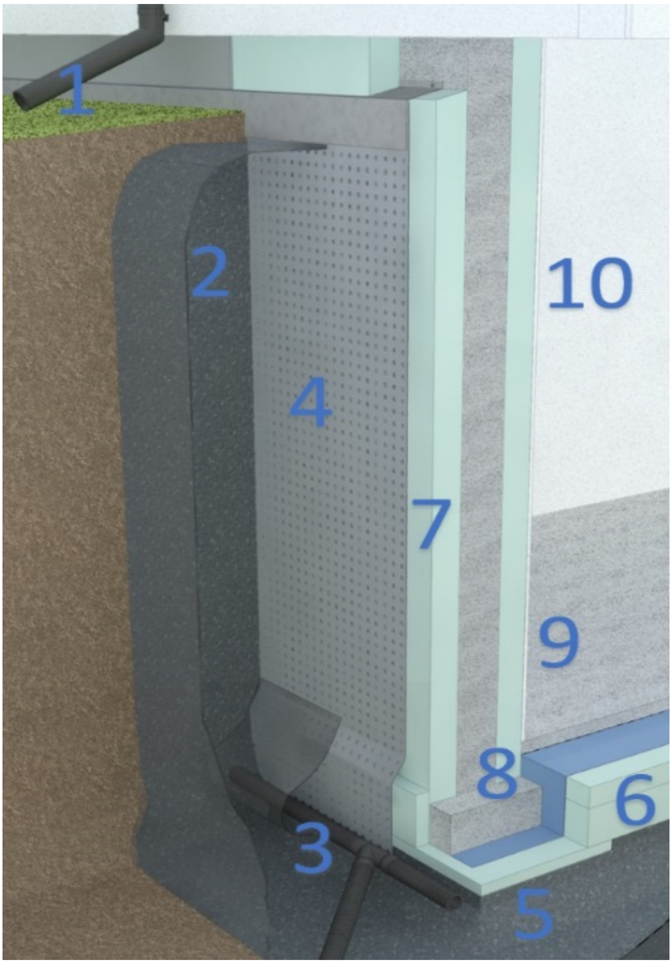
Figures 1–9 in **Paper 1**, Figure 1 in **Paper 2**, and Figure 1 in **Paper 3** were first sketched in detail by the author and then professionally drawn using a CAD-operator. The remaining illustrations were developed by the author using PowerPoint and Excel [55] to combine the various combinations of the previously drawn figures, text, photographs, and illustrations made using SketchUp Make [56].

4. Main findings

4.1. State of the art

Moisture control strategies for basements

As shown in Figure 15, an overview of the 10 main challenges related to moisture control in habitable basements was obtained from the thorough content analysis of the SINTEF Building Research Design Guides conducted in **Paper 1**.



1. Water from rain and snowmelt (including down-pipes).
2. Water pressure on the exterior walls below ground.
3. Water pressure against the construction owing to a rise of groundwater.
4. Water from the terrain surface or ground that reaches the surface of the wall.
5. Capillary rise of moisture from the ground through the floor and foundations.
6. Transfer of water vapour from the ground through the floor
7. Moisture condensation on the basement walls and drying capacity of the basement walls.
8. Thermal bridges.
9. Air leakages (moist air and radon gas) from the ground to the structure and indoor air (walls and floor).
10. High indoor moisture supply from drying clothes, cooking, and showering.

Figure 15. 10 main challenges in moisture control of habitable basements.

The 10 main challenges and corresponding Norwegian recommendations were combined in a table (see Appendix A in **Paper 1**). The Norwegian recommendations for habitable basements are shown in Figure 16.

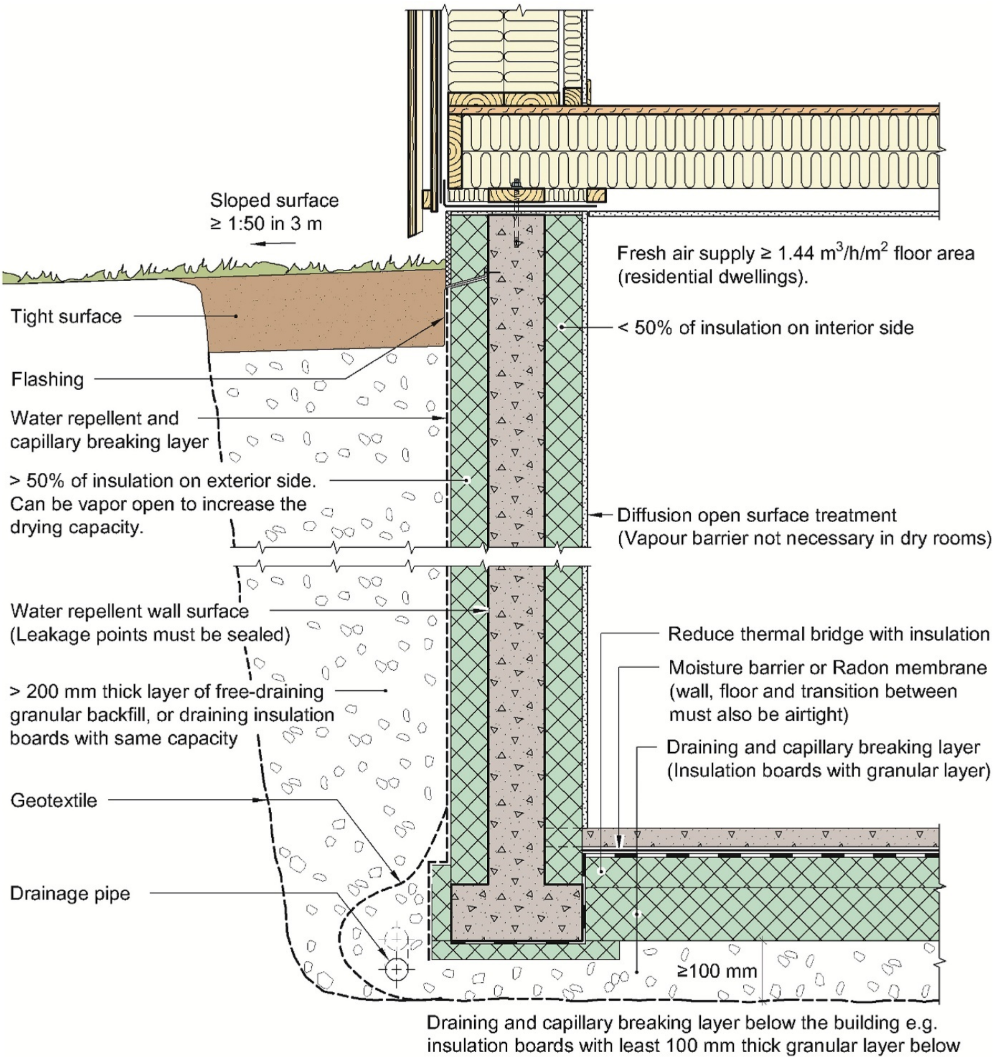


Figure 16. Main Norwegian recommendations for habitable basements.

Most studies in the existing literature have primarily focused on the relatively narrow technical fields, thermal performance of basements, and certain damage cases; however, few studies have focused on the recommendations for new habitable basements (see Table 1 **Paper 1**). Considering the gaps in the existing literature, it can be concluded that further investigation is required to evaluate the moisture control strategies. Therefore, the author collaborated with international experts. The 10 main challenges and Norwegian recommendations were compared with the challenges and national recommendations of the other cold climate countries, such as Denmark, Sweden, Estonia, and Canada. A full description of the international recommendations is provided in Appendix A of **Paper 1**. Based on the input from the four international experts, figures illustrating the main recommendations for the habitable basements were developed. To illustrate the diversity in the recommendations for the design of basement envelopes, small versions of these figures are shown in Figure 17. Full-size figures, which include the main recommendations, are presented in **Paper 1.**

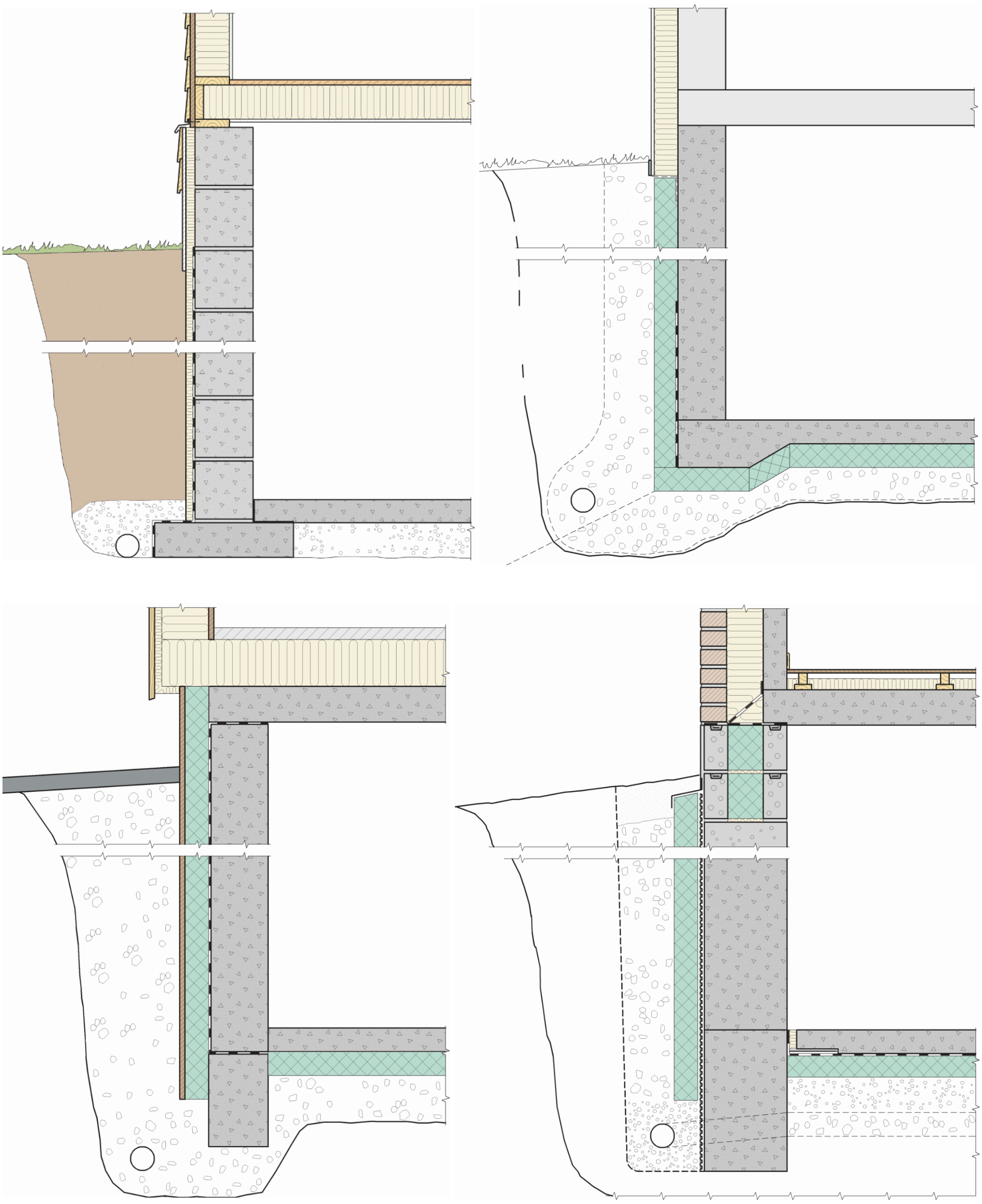


Figure 17. Examples of the designs of habitable basements according to the national recommendations in Canada (upper left), Sweden (upper right), Denmark (lower left), and Estonia (lower right).

To evaluate the international recommendations for basements, the 10 key challenges and corresponding Norwegian recommendations were used as a basis. The recommendations from the other cold climate countries were rated relative to the Norwegian recommendations and classified as more or less moisture safe, equal, contradicting, or lacking, as shown in Figure 18.

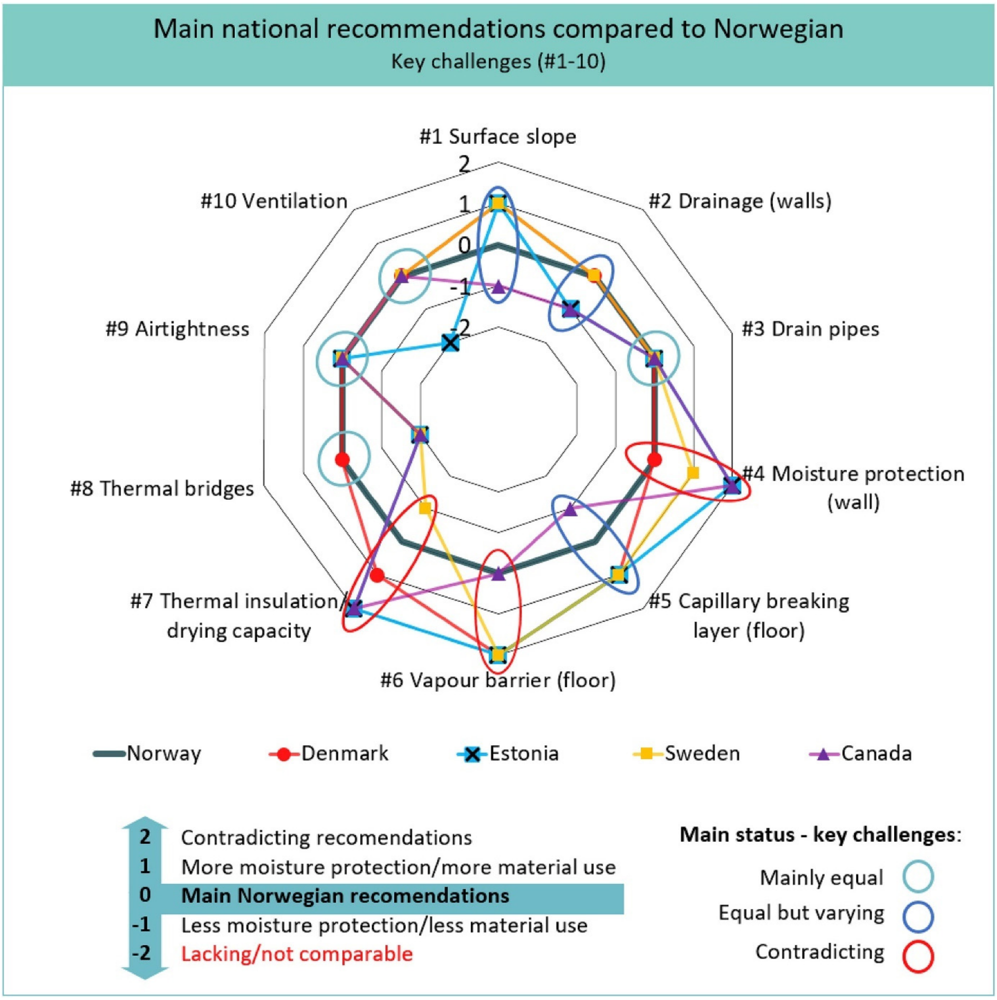


Figure 18. Main national building recommendations for habitable basements in cold climate countries (red, blue, yellow, and purple) compared with Norwegian recommendations (grey at level 0) for each of the 10 key challenges (#1–10, see Figure 15). The recommendations are sorted as the same as Norway (level 0), more moisture safe (level 1), less moisture safe (level −1), contradicting (level 2), or lacking (level −2). For each key challenge, the figure shows if the main recommendations are mainly equal (cyan circle), equal but varying (blue circle), or contradicting (red circle).

Similar but varying recommendations pertaining to ground surface slopes, drainage layers, drainage pipes, capillary breaking layers on floors, avoiding thermal bridges, airtightness, and ventilation were noted. The key differences pertained to the exterior damp proofing of the walls, the use and position of the dimpled membranes and vapour barriers, and the use of vapour-permeable thermal insulation. The primary inference was that different countries emphasize the 10 key challenges differently. Although the recommendations had many similarities, the weighting (or prioritizing) distinguishes the five countries' moisture control. Note that if a waterproof membrane is used on the exterior side, exterior drainage is prioritised less. If a sufficient drainage system is applied (i.e., a surface slope away from the building, draining backfill, and capillary-braking exterior thermal insulation), the exterior side of the wall can be kept diffusion open to enable outward drying.

Hygrothermal simulation of basement envelopes

Paper 2 investigated the applicability of the numerical simulations to the evaluation of the moisture performance of thermally insulated basement envelopes. Twenty-four relevant studies were identified through a scoping literature survey and were reviewed. Subsequently, significant data were obtained from the detailed review of the 10 most influential studies. Among the 10 studies, four studies investigated the hygrothermal performance of the basement walls, three studies investigated the heat and moisture transfer in the soil domain, and three studies primarily focused on the thermal performance of the basements but considered the varying moisture content in the soil.

This literature review provided an overview of the state-of-the-art hygrothermal simulation methods applied to the evaluation of the moisture performance of the basement envelopes. The following significant data were obtained.

1. The one-dimensional simulation results of the basement walls for three different wall heights showed a lack of correspondence with the measurement results. The near-grade location exhibited the largest deviation (Straube [22]).
2. Including the soil moisture transfer in the ground (fully coupled two-dimensional simulations) increased the heat loss (Janssen et al. [43] and Deru [57]).
3. The difference between the coupled and linear simulations of heat loss was mainly attributed to (1) the greater amplitude of the soil surface temperature, (2) the variation of the thermal conductivity with moisture content, and (3) the advection of sensible heat by liquid moisture transfer (Janssen et al. [43]). The difference increased with less insulation (Janssen [58]).
4. The high moisture content in the soil domain limited the applicability of the two-dimensional hygrothermal simulation tool WUFI®2D (Goldberg & Harmon [21]). Furthermore, the high moisture content often caused unstable convergence using DELPHIN 5.8 (Fedorik et al. [23]).
5. The transfer of heat and moisture in the soil observed using hourly data was approximately the same as that observed using daily average climate data (Janssen et al. [43]).
6. The below-grade hygrothermal boundary conditions for basement envelopes should account for the following:

- advection of sensible heat by liquid moisture transfer (Janssen et al. [44]), Straube [22]
- liquid uptake of precipitation on the soil surface (Pallin and Kehrer [43]);
- moisture transfer at the lower boundary (infinite ground) (Pallin and Kehrer [43]);
- heat and moisture coupling (Janssen et al. [43] and Deru [57]);
- convection and evaporation at the surface of the Earth (Pallin & Kehrer [43]) (Zoras et al. [59]),
- phase changes owing to freezing (Zoras et al. [59]), Deru [57] (Saaly et al. [60]),
- snow cover (Pallin and Kehrer [43]; Zoras et al. [59]), and
- inefficiencies associated with the inevitable multi-year simulations, which are needed to approximate realistic initial conditions (soil temperature and moisture fields) (Zoras et al. [59], Dos Santo & Mendes [61]).

7. High RH (RH ≈100% ↔ w<0.5% by weight) has been observed in the drainage layers below the slabs (Rantala & Leivo [62])
8. Solar radiation should not be neglected when considering the drying-out capacity of basement walls, as solar radiation can cause inward moisture transfer (Pallin [33]).
9. COMSOL Multiphysics® can be used for three-dimensional simulations of heat transfer from a basement, including variable thermal conductivity for the soil (Saaly et al. [60]).
10. The hygrothermal properties of 12 different soil textures have been defined (Pallin & Kehrer [63]).

The literature review documented a lack of thorough validation of the hygrothermal simulations of basements using full-scale physical measurements. Furthermore, the review highlighted the need for a recognised method/procedure to determine the exterior boundary conditions for the hygrothermal simulations, which can account for the varying below-grade influencing factors. The key uncertainties include the varying composition and moisture content of the soil, liquid uptake at the soil surface, transfer of precipitation, and computational costs.

Below-grade exterior boundary conditions / knowledge derived from existing literature

In the numerical simulations of the heat and moisture transfer in building components, the transfer occurs owing to the variations in the interior and exterior boundary conditions, initial conditions, and transfer and storage properties of the material layer(s) [64]. The below-grade exterior boundary conditions are challenging to include in the numerical setup; this is primarily because of the uncertainties associated with the heat loss to the ground (as described in **Paper 2**), the varying conditions with the height of the below-grade basement walls, amount of insulation, and variation in the interior temperature. Considering these challenges, it can be concluded that the heat and moisture transfer simulations should be conducted for a building envelope and a large part of the earth surrounding the building simultaneously. However, the data obtained from the literature suggest that this approach would be inappropriate; this is because the mathematical descriptions most appropriate for the soil moisture transfer include the matric head as a driving potential. Note that the mathematical descriptions are accurate because the soil typically has a high moisture content, which occasionally dries [13]. Furthermore, the liquid transfer due to gravity should also be considered in the simulations. The most appropriate driving potential for building components, on the other hand, is RH because the components are generally dry and only occasionally wetted by the liquid uptake of precipitation. Furthermore, the RH is continuous over the layers of different materials [13].

4.2. Potential for outward drying

Experimental approach

Paper 3 presented a novel experimental method for monitoring the drying rates of basement walls. The drying rates of three concrete wall segments with different thermal insulation configurations and dimpled membrane positions were compared. The results showed that the drying behaviours of the three walls were similar. However, the observed drying rates were considerably less than the drying rates predicted by the simulations. Moreover, no condensed water was detected during the measuring period of six months. The weight changes of the three wall segments are presented in Figure 19 and 20.

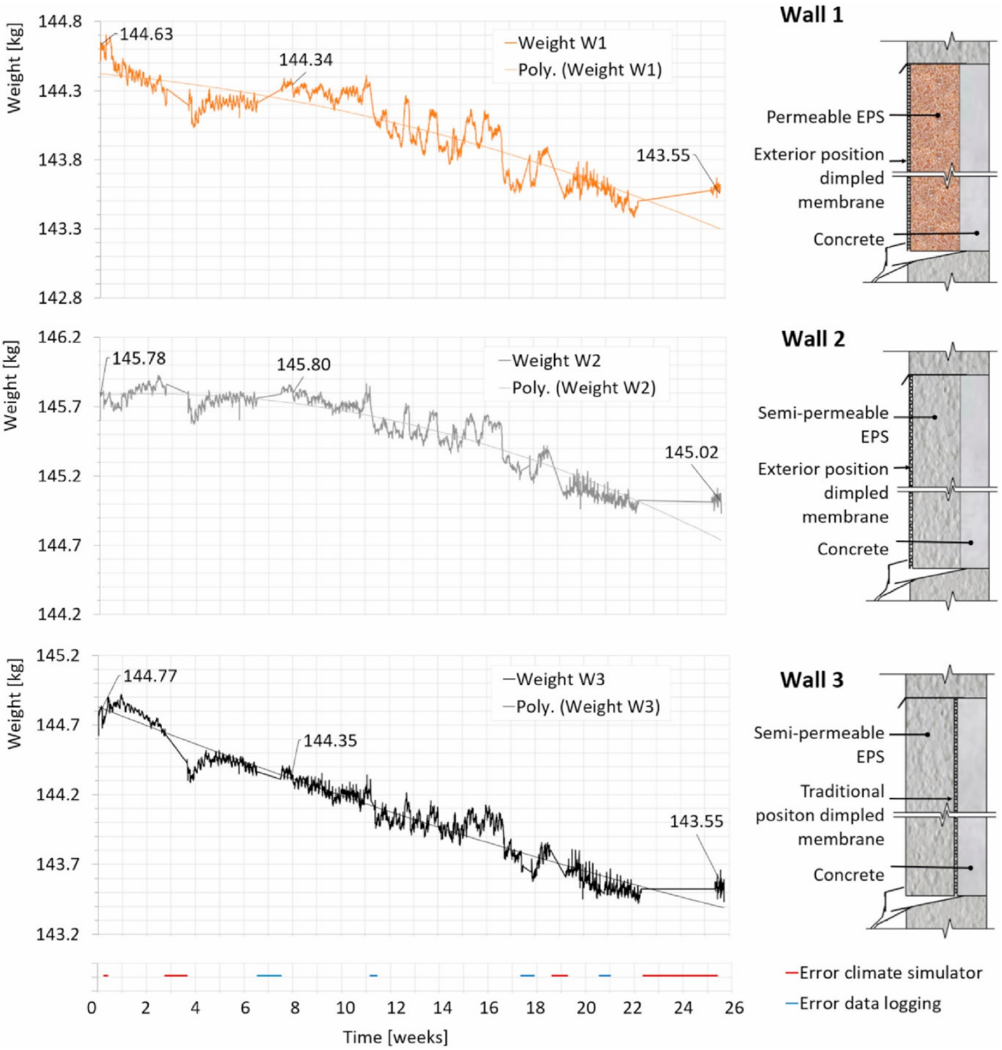


Figure 19. Weight changes of the three wall segments during the measuring period of six months. The flattening exhibited by the three wall segments at the end of the measurement period was primarily due to the difficulties in maintaining the exterior chamber cold (5°C).

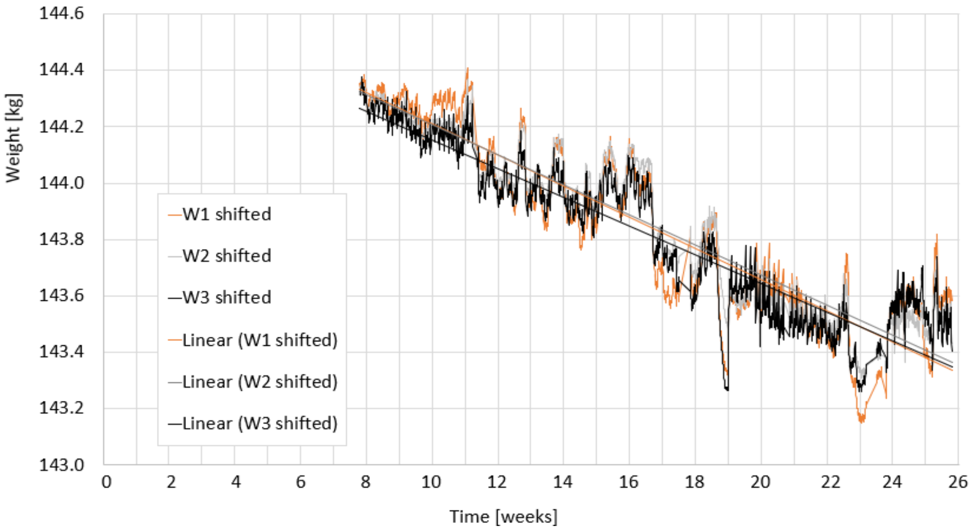


Figure 20. Weight changes of the three wall segments during the last four months of the measuring period. The graphs have been superimposed for comparison.

From the results, it can be inferred that the ability of the concrete to transfer moisture to the drying surface affected the outward drying significantly. Furthermore, it was observed that the effects of the vapour permeability of the insulation and the membrane position were less significant. Therefore, it can be concluded that the moisture transfer properties of the concrete used in basements require further investigation to ensure a more accurate prediction of the long-term moisture performance of thermally insulated basement walls. Numerical simulations performed by Asphaug et al. [65] have previously shown that the concrete type has a significant impact on the moisture performance of facade systems for retrofitting based on concrete and thermal insulation. Investigations by Knarud et al. [66] further illustrated the difficulties in predicting and/or measuring the capillary transfer properties of porous building materials.

Numerical approach

The numerical simulations in **Paper 4** were conducted in three steps, as illustrated in Figure 12 and 13 of section 3.5. From Step 1, it can be inferred that the concrete with a high liquid transfer coefficient and high vapour resistance (C35/45) dried faster than the concrete with a low liquid transfer coefficient and low vapour permeability (Masea), as shown in Figure 21. The concrete with low vapour permeability (Masea) dried faster at the exterior surface; however, the drying rate was slower deeper into the concrete owing to the low rate of capillary moisture transfer. The concrete with a high liquid transfer coefficient (C35/45) dried slower at the surface; however, a faster drying rate was observed deeper into the concrete, which resulted in an overall faster drying rate at high moisture content. The results also showed that the effect of the air exchange in the air gap behind the dimpled membrane needs further investigation. The outward drying of the concrete wall segments for different positionings of the dimpled membrane and different air exchange rates with the air in the cold and humid climate chambers are shown in Figure 22.

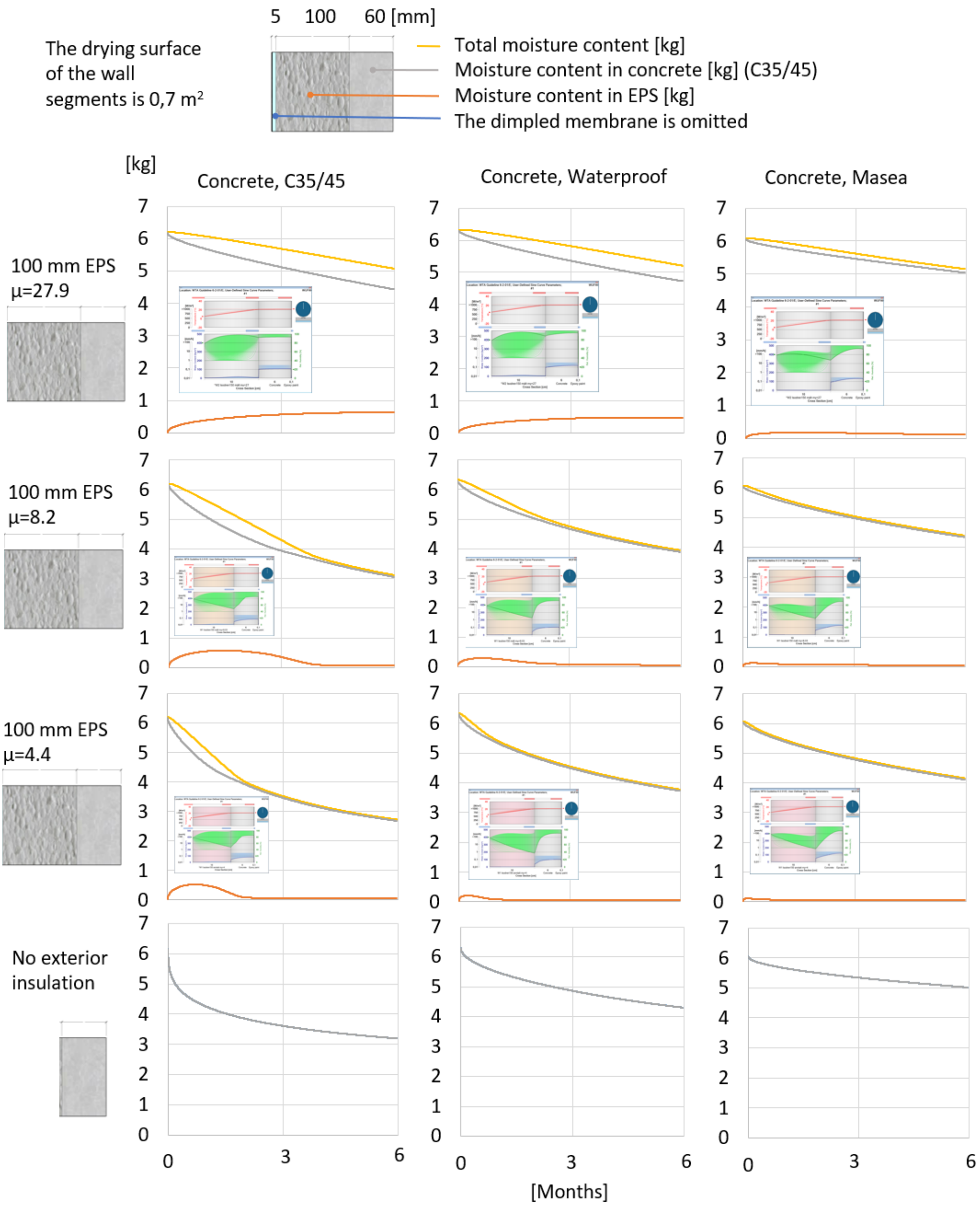


Figure 21. Simulation of the decrease in MC in the concrete wall segments over a measurement period of six months for thermal insulations with three different water vapour diffusion resistance factors (μ) and three concrete types. The air in the cold chamber was maintained at 80% RH/5°C; the air in the war chamber was maintained at 20% RH/20°C.

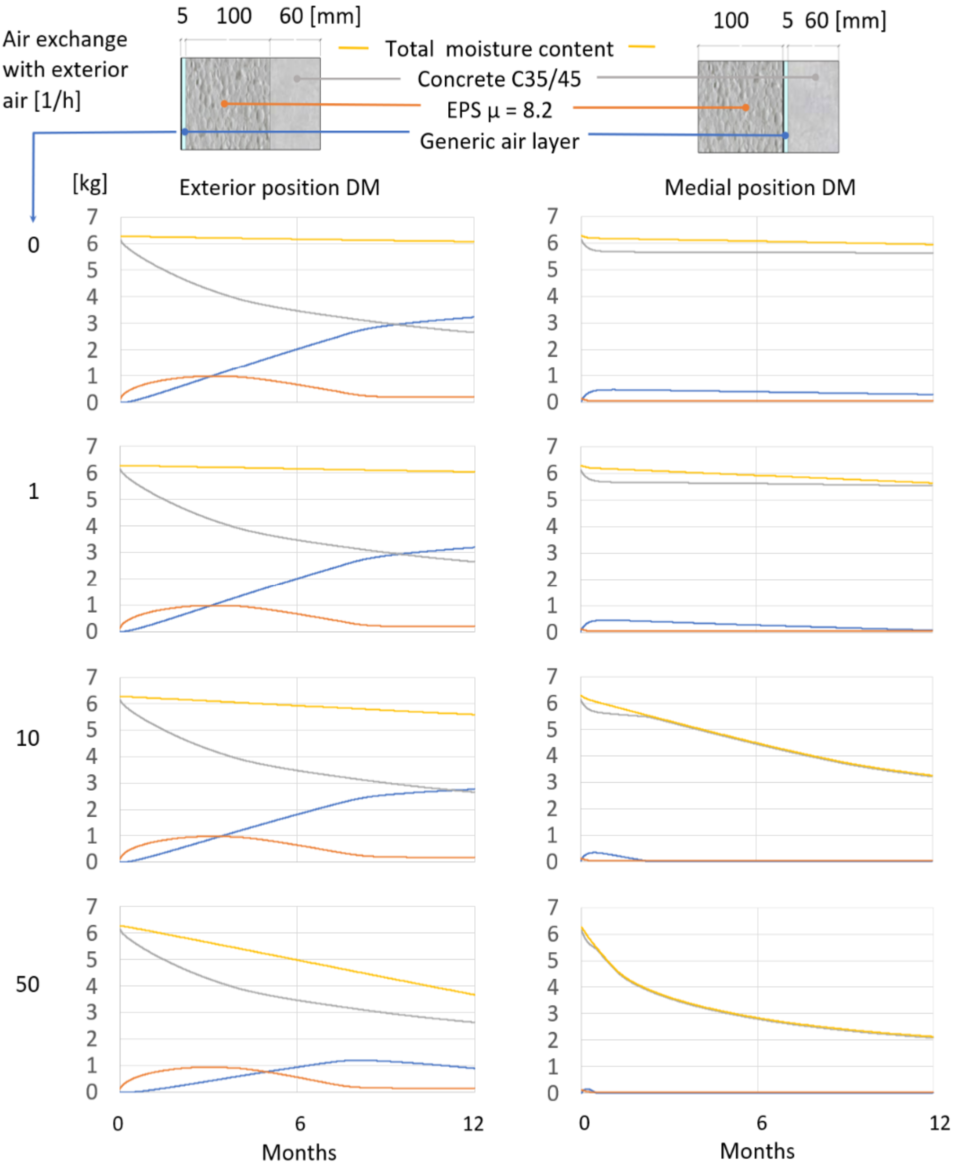


Figure 22. MC decrease in the concrete wall segments for various air exchange rates in the air layer behind the dimpled membrane (DM).

Figure 22 shows that for the exterior positioning of the dimpled membrane, the moisture in the concrete dried at the same rate regardless of the air exchange rate behind the dimpled membrane. However, the MC of the generic air layer was unrealistically high in the simulations, which suggests that condensation occurred. For the medial positioning of the dimpled membrane, the concrete dried slowly at low air exchange rates. Note that the results for the medial positioning were similar to the results for the exterior positioning for an air exchange rate of approximately 10 / h. However, the air exchange rates are difficult to predict for slightly ventilated air gaps. Concrete C35/45 was used for these assessments. Thus, it can be concluded that concretes that dry slowly, such as Masea, would exhibit smaller differences between the drying rates for the two positionings of the dimpled membrane.

The results from Step 2 showed that the concrete wall segment with a medially positioned dimpled membrane dried much faster at the bottom than at the top, whereas the wall segment with an exteriorly positioned dimpled membrane dried uniformly along its height. The results also indicated that the basement wall with an exteriorly positioned dimpled membrane exhibited a slightly reduced drying rate compared with the wall without the exterior dimpled membrane. Figure 23 summarises the predicted outward drying of the concrete wall segments for the two positions of the dimpled membrane and two bottom air gap openings.

The exterior cold and humid chamber was conditioned to 80% RH instead of approximately 100% as intended; this was primarily due to the freezing of the cooling pipes. Subsequently, the outward drying of the wall segments with 99% RH was compared with that of the wall segments with 80% RH, as illustrated in Figure 24. Note that the comparison was conducted for only one type of concrete (C35/45). Slightly slower drying rates were exhibited by the concrete in the wall segments for both positions of the dimpled membrane. Furthermore, higher moisture accumulation was observed on the exterior side of the thermal insulation.

From the one-dimensional simulations, it can be inferred that the conditions for condensation were present in the air gap behind the dimpled membrane, even with 80% RH in the cold exterior chamber, as shown in Figure 22. This was also validated by the two-dimensional simulations that included the air flow through the air gap behind the dimpled membrane from the air in the exterior chamber, as shown in Figure 24 and 25.

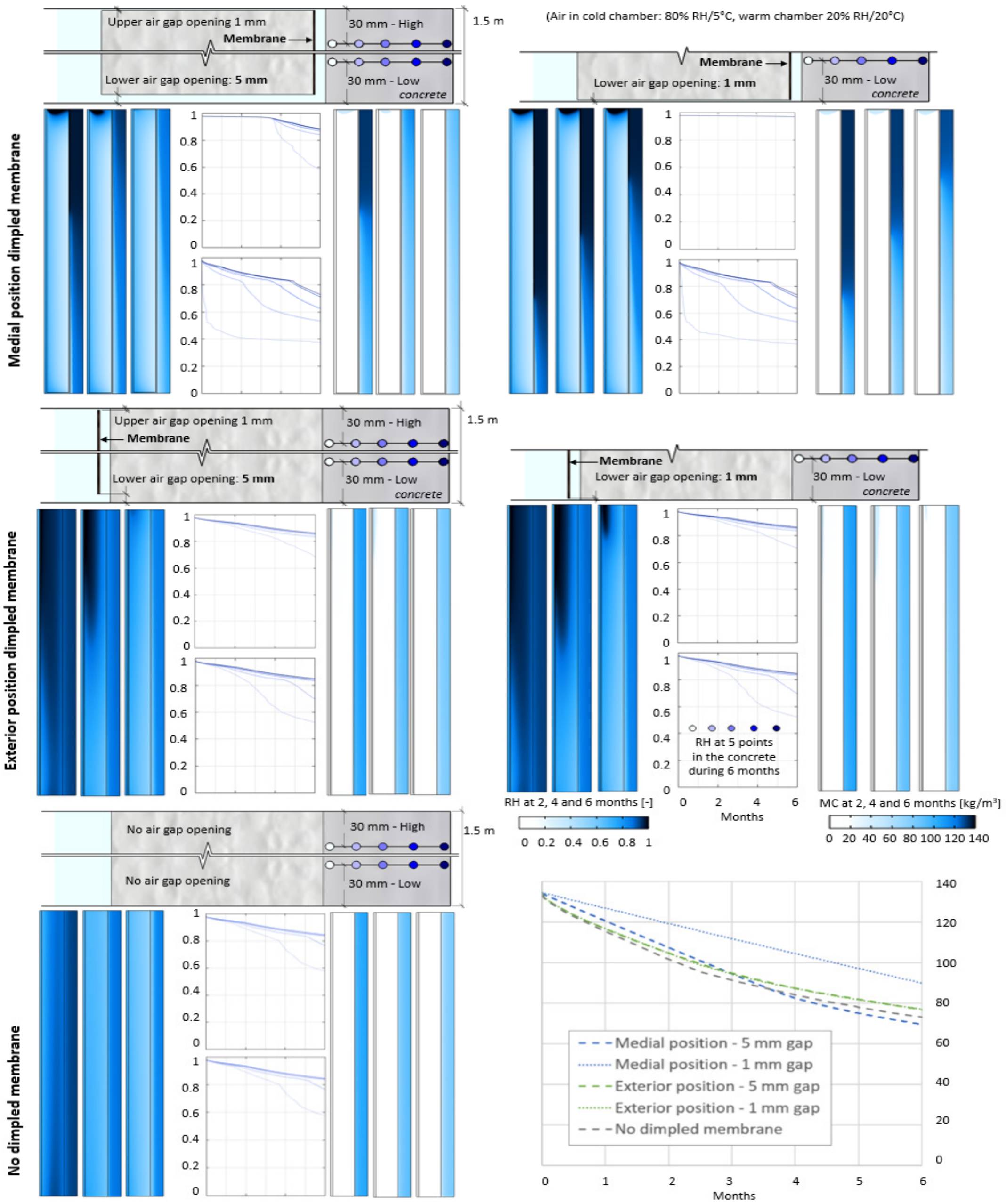


Figure 23. Concrete wall segments with medially positioned dimpled membrane and two lower air gap openings (upper left and right), exteriorly positioned dimpled membrane and two air gap openings (middle left and right), and no dimpled membrane (lower left). The upper and lower graphs show the decrease in the RH at the five points in the upper and lower part of the concrete. The left and right plots show the RH and MC after two, four, and six months of drying. The graphs (lower right) show the decrease in the average MC of the concrete segments in the five illustrated situations during six months of drying.

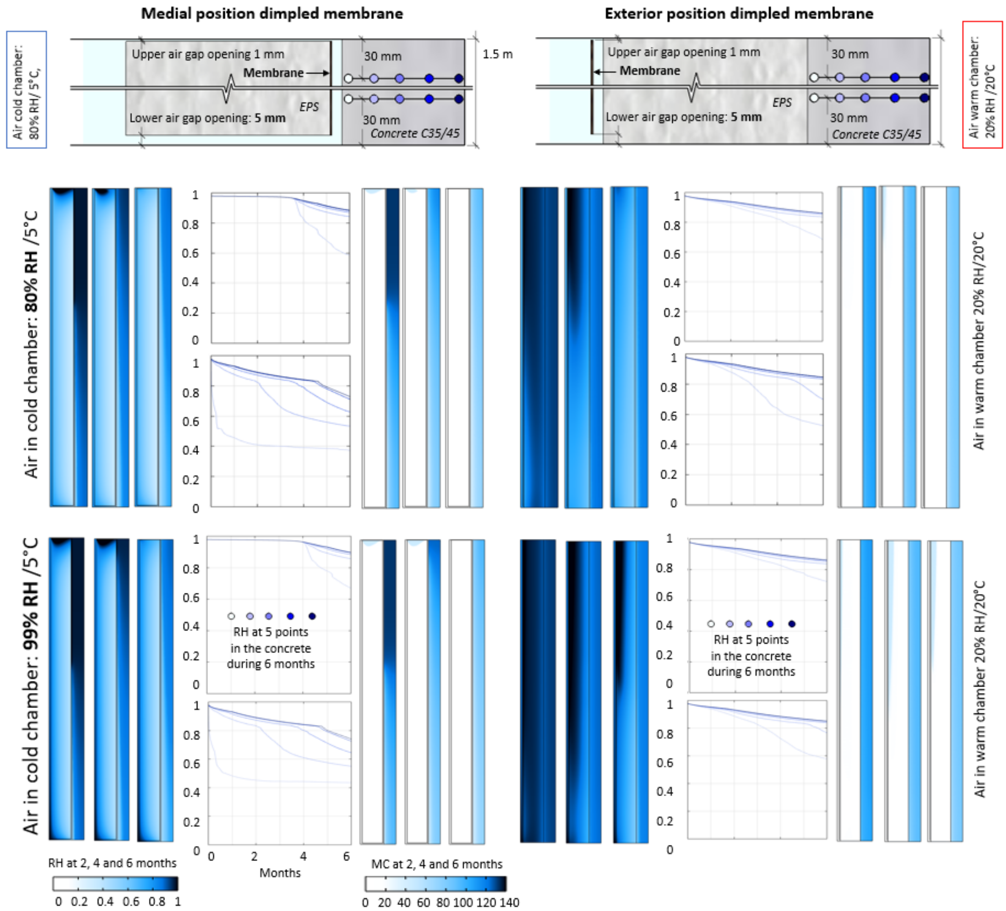


Figure 24. Drying of the concrete wall segments in the laboratory experiment with 80% RH (upper) and 99% RH (lower). The concrete wall segments with medially positioned dimpled membrane (left) and exteriorly positioned dimpled membrane (right). The upper and lower graphs show the decrease in the RH at the five points in the upper and lower part of the concrete over six months of drying. The left and right plots show the RH and MC at two, four, and six months of drying.

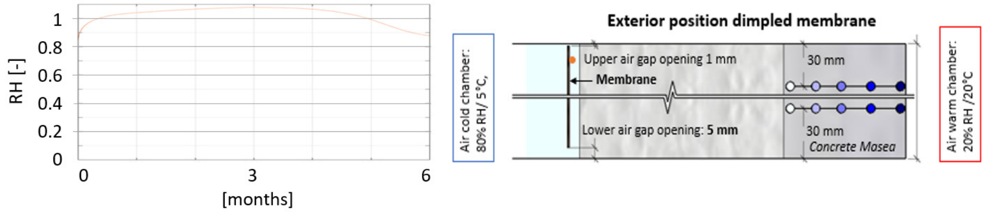


Figure 25. RH in the air gap behind the exteriorly positioned dimpled membrane.

Moisture performance of basement walls

In Step 3, the long-term moisture performance of thermally insulated basement walls was investigated. Note that the dimpled membrane was omitted from these simulations based on the significant data collected in Step 2. The results showed that positioning more insulation on the interior side rather than the exterior side of the walls reduced the moisture performance of the basement walls significantly, as shown in Figure 26.

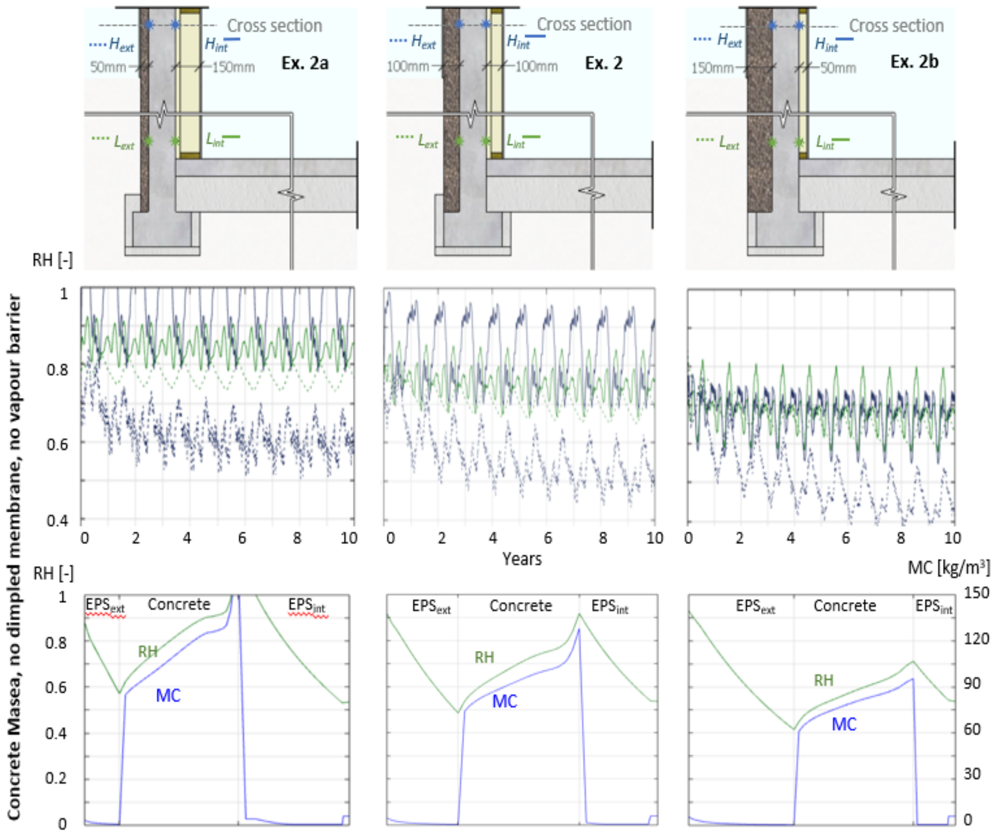


Figure 26. The decrease in RH in the four monitoring points (at the intersection between the concrete and insulation) over 10 years (upper). Note that the y-axis span from 40 – 100 % RH. The MC and RH in a cross-section of the upper part of the basement walls after 10 years (lower). The position of the monitoring points and cross-section is illustrated in the upper sketches.

The numerical simulation results indicated that positioning the dimpled membrane on the exterior side of the vapour-permeable thermal insulation facilitated outward drying. However, the overall drying effect depended on the type of concrete used. For the concrete with a slow drying rate, the effect of the vapour-permeable thermal insulation was less pronounced. Positioning the dimpled membrane between the concrete and exterior insulation is easier and can ensure better protection for the concrete and dimpled membrane. For the concrete with a slow drying rate, placing the dimpled membrane between the concrete and external insulation facilitated outward drying when the air gap was slightly ventilated. When the bottom air gap openings were not blocked, this positioning also increased the drying of the lower part of the wall.

5. Discussion

5.1. Existing literature

Moisture control strategies for habitable basements

The measurements performed by Blom [30] did not show any increased drying effect for the walls with exterior vapour-permeable thermal insulation compared with the walls built with a medially positioned dimpled membrane. Other studies pertaining to the outward drying by vapour-permeable thermal insulation primarily focused on the rehabilitation of basement walls. These studies did consider an exteriorly positioned dimpled membrane in the simulation models. In the existing literature, most studies have focused on the thermal performance of basements, relatively narrow technical fields, new material attempts, and building defects. Moreover, studies focusing on the moisture performance of thermally insulated basements were primarily concerned with the measures for rehabilitation purposes or walls with thermal insulation on the interior side of the load-bearing structure. Few studies have focused on the moisture control of basements with exteriorly insulated walls. Note that rehabilitation of basements entails greater challenges than building new well-drained basements. As the primary objective of this thesis was to identify strategies for new basements, studies focusing specifically on recommendations for rehabilitation were not targeted.

To investigate the moisture control strategies, recommendations for habitable basements from four cold climate countries were compared with those for Norway. The recommendations exhibited various similarities. However, the recommendations differed in terms of the priority assigned to the different aspects of the moisture control strategies. Similar but varying recommendations pertaining to ground surface slopes, drainage layers, drainage pipes, capillary breaking layers on floors, avoiding thermal bridges, airtightness, and ventilation were also noted. The key differences pertained to the exterior damp proofing of walls, the use and position of dimpled membranes and vapour barriers, and the use of vapour-permeable thermal insulation. A novel aspect of this thesis is that it illustrates the diversity in the design of basement envelopes. A more accurate evaluation of the recommendations can be performed by consulting more experts.

Hygrothermal simulations of walls and floors in habitable basements

The literature review of the studies on the hygrothermal simulations of the walls and floors of basements included both new and old buildings. However, no recognised method to determine the exterior boundary conditions of the below-grade basement walls and floors was found in the existing literature. Existing studies have applied various approaches; however, the results obtained from the existing studies illustrated that the soil surrounding the buildings requires a thorough investigation. The key uncertainties included the varying composition and moisture content of the soil, liquid uptake at the soil surface, and transfer of precipitation. Computational costs were also identified as a challenge in this context. The experimental work in [21] illustrated the challenge of validating simulations with measurements for below-grade structures. More relevant existing research focusing on the modelling of soil moisture may be found in the soil science literature; however, this was beyond the scope of the present study.

Owing to the aforementioned challenges, it can be concluded that the heat and moisture transfer simulations should be conducted for the building envelope and a large part of the earth surrounding the building simultaneously. However, significant data gathered from the literature suggest that this approach would be inappropriate owing to the different mathematical descriptions used for soil moisture transfer and multi-layered building components.

Hence, a more advanced soil moisture transfer model is required to thoroughly investigate the impact of various soil factors on the hygrothermal performance of basements envelopes. However, the local climate and annual temperature variations are likely to have a more significant impact on the outward drying performance. This is because the moisture transfer in basement envelopes is a slow process associated with a large number of uncertainties. Therefore, it can be concluded that a detailed description of the smaller fluctuations in the exterior temperatures might be inconsequential. In a new building, the material in close contact with the basement is primarily gravel. Hence, the air transfer within this part requires a more thorough investigation.

5.2. Outwards drying of thermally insulated basement walls

Outward drying of concrete wall segments

The measured weight decreases of the three concrete wall segments in the laboratory study were similar and considerably smaller than those predicted prior to the experiment. Surprisingly, no drained condensation was detected during the experimental period. Note that although the RH in the exterior chamber was 80% instead of 99%, the simulations indicated that there would be conditions for condensation within the gaps.

The numerical simulations demonstrated that the type of concrete had a significant effect on the drying behaviour of the concrete wall segments. Note that the concrete in the experiment (B30M60 0.25 % red. Cl 0.10, w/c = 0.54) was selected to represent conventional concrete used in basement walls. However, a slightly higher water/cement ratio was used to ensure slightly faster drying during the limited experimental period (a higher water/cement ratio entails higher liquid transfer). Thus, the concrete used in real concrete basement walls might dry even slower, and the hygrothermal simulations could have overestimated the potential for outward drying. This observation is of particular significance for future long-term measurements of basement walls. Moreover, this demonstrates the need for additional data on the moisture transfer properties of concrete used in basement envelopes.

The difference between the total drying exhibited by the two types of concrete decreased as the vapour resistance of the exterior thermal insulation increased. This indicates that the difference between the drying of the walls could have been larger if the difference in the vapour-permeable thermal insulation had been larger. The water vapour resistance factor (μ-value) of the vapour-permeable thermal insulation and standard EPS was unknown prior to the experiment. Subsequently, it was measured to be 8.2 and 27.9, respectively. The vapour-permeable EPS used in the experiment is used for both walls and floors in basements. Note that vapour-permeable EPS intended for only walls may have obtain a lower water vapour resistance factor. Future long-term measurements focusing on outward drying should consider using more vapour-permeable EPS or mineral wool boards.

The two-dimensional simulations of the air flow through the air gap behind the dimpled membranes may explain the similar weight changes exhibited by the wall segments. The concrete wall segment with a medially positioned dimpled membrane dried much faster at the bottom than at the top, whereas the wall segment with an exteriorly positioned dimpled membrane dried uniformly along its height. The concrete wall segment with a medially positioned dimpled membrane exhibited relatively slower drying when the bottom air gap opening was reduced from 5 mm to 1 mm. The wall segment with an exteriorly positioned dimpled membrane was less affected by the changes to the bottom air gap opening; however, more moisture accumulated in the exterior parts of the exterior thermal insulation. Thus, the impact of the moisture content in the exterior thermal insulation on the thermal performance of basement walls requires further investigation.

Note that a thorough investigation is required to elucidate the conditions for moisture condensation in the air gaps behind the dimpled membranes. Furthermore, the effect of condensation on the outward drying performance of real basement walls also requires investigation. Hence, future measurements of the drying performance of real basement walls should include the effect of different temperatures between the top and bottom parts of the walls. For the medial positioning of the dimpled membrane, the bottom air gap opening should be used to enable drying by air flow. For the exterior positioning of the dimpled membrane, the bottom air gap opening should be used to facilitate the drainage of the condensate moisture to the ground below without moistening the footing.

Long-term simulation of thermally insulated basement walls

The simulated concrete wall segment with an exteriorly positioned dimpled membrane exhibited a slightly slower drying rate compared with the wall without a dimpled membrane. The impact of the dimpled membrane on the drying performance of full-scale basement walls depends on the air gap openings and realistic rate of air flow. Ideally, the dimpled membranes and air gaps would have been included in the full-scale simulations of the basement walls to fully compare the effect of the two positionings. However, this was difficult with the present model because of the complexity of the boundary conditions. Optimization the model to include the dimpled membrane is part of future works.

To investigate the impact of outward drying on the moisture performance of the basement walls, long-term simulations were conducted by omitting the exterior dimpled membrane. Note that only one climate location (Oslo) was considered in the simulations. Therefore, locations with a higher annual mean temperature may yield less outward drying; this will be included in future works.

The moisture performance of the basement walls with EPS formwork (Ex. 1) was compared with that of the basement walls with vapour-permeable exterior insulation (Ex. 2). These two examples represented commercially used basement walls. Compared with Ex. 1, a relatively greater difference between the characteristics of the two types of concrete with and without a vapour barrier was observed in Ex. 2. Note that Ex.2 exhibited a lower interior RH than Ex. 1 after 10 years for the fastest drying concrete (C35/45) and an interior vapour barrier. In contrast, for the Masea concrete, Ex. 2. exhibited a higher RH on the interior side, even up to 100% in the first year. The results demonstrated the need to further investigate the span of the moisture properties of the conventional concrete used in basement walls. Moreover, the results demonstrated that the thickness and permeability of the interior and exterior wall parts had a significant influence on the moisture performance. Note that the thermal insulation should be positioned on the exterior side for optimised outward drying solutions for rehabilitation purposes. Furthermore, placing the thermal insulation on the exterior side can ensure more use of organic materials (such as wood) in new buildings.

5.3. Numerical simulations

The main motivation behind this thesis was to explore the applicability of advanced simulation tools to perform long-term hygrothermal simulations and enable investigations of air flow in building components. The results obtained validated that COMSOL Multiphysics® is an effective and efficient tool for long-term hygrothermal simulations of building components. COMSOL Multiphysics® can address and analyse heat, air, and moisture transfer. Furthermore, the air transfer within the air gap and air-permeable materials can be considered simultaneously in COMSOL Multiphysics®, which is of great interest and significance in the field of building physics. As long as the geometry and boundary conditions are relatively simple, optimal convergence and results with adequate resolution can be achieved in a relatively short runtime. However, as the models become more detailed and complex (e.g. air transport is included), more knowledge and experience are required from the user to be able to set up, perform, and obtain convergence with sufficient accuracy within a reasonable time. Material characteristics have a significant impact on the required runtime. By using piecewise-cubic interpolation rather than linear interpolation on the sorption curves and liquid transfer coefficients, the runtime can be reduced significantly.

6. Conclusions and future work

To establish moisture-resilient basements, various moisture-related challenges need to be overcome. These challenges are given different priorities in different cold-climate countries. Therefore, recommendations to mitigate these challenges, such as exterior damp-proofing of walls, use and position of dimpled membranes and vapour barriers, and use of vapour-permeable thermal insulation, vary depending on the country. Research on the comparison of the effects of various recommended measures is scarce. Much of the existing research concerns the moisture performance of interiorly insulated basement walls. However, only a few studies have investigated the effects of outward drying or the use of vapour-permeable thermal insulation. Existing measurements are not sufficient to elucidate the difference between the drying effect of exterior vapour-permeable thermal insulation used in combination with an exteriorly positioned dimpled membrane and that with a medially positioned membrane. The existing numerical studies mainly focused on the rehabilitation of the basement walls and did not include (or omit) an exteriorly positioned dimpled membrane in the numerical simulation models. Moreover, no method or procedure has been established to determine the below-grade exterior boundary conditions. Furthermore, existing research shows that large uncertainties pertaining to the varying composition and moisture content of the soil, liquid uptake at the soil surface, and transfer of precipitation require further investigation. Note that these uncertainties and subsequent large variations make it challenging to validate hygrothermal simulations of basements by full-scale physical measurements.

The numerical and experimental investigations performed in the present study demonstrated the dependency of the outward drying effect of the basement walls on the thickness and permeability of the exterior and interior insulation. Furthermore, the results obtained showed that the moisture performance of basement walls was affected by the capillary moisture transfer of the concrete. In the experimental investigation of the concrete wall segments, the conventional concrete used in the basement walls exhibited a lower drying rate than the predicted drying rate obtained using numerical simulations. Moreover, it was observed that for the slowly drying concrete, reducing the vapour resistance of the exterior thermal insulation had no significant effect. Note that the dimpled membrane positioned between the concrete and exterior insulation provided sufficient drying when the air gap was slightly ventilated. This position of the dimpled membrane also increased the drying of the lower part of the wall when the air gap openings at the bottom were not completely blocked. To enable a more accurate prediction of the moisture performance of basement walls, additional data regarding the span of moisture properties of conventional concretes used in basement walls are required.

Future work should focus on investigating the span of the moisture transfer properties of different types of concrete currently used in basements. The two-dimensional numerical model of the full-scale basement wall should be further improved to include the dimpled membrane, air flow through the air gap, air transfer within the air-permeable thermal insulation (e.g. mineral wool), and climate data from other cold climate locations. Long-term physical measurements should be performed to determine the reliability of the numerical simulations to realistically replicate the moisture transfer in concrete basement walls during the drying process. The 10 moisture-related challenges for basements identified in this thesis can be used as a basis for further investigation and development of strategies for moisture-resilient design in the future.

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Papers

Paper 1

Moisture control strategies of habitable basements in cold climates
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Moisture control strategies of habitable basements in cold climates

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ABSTRACT

In many countries with a cold climate, basements are used as dwellings. This presents a major challenge concerning moisture safety design. Climate change is expected to increase the risk of moisture-related damage in basements owing to increasing amounts of stormwater, annual precipitation, and annual temperatures. This study examines the primary moisture control strategies for habitable basements in western cold climate countries by identifying the main differences and similarities in national building recommendations for new buildings. Using Norwegian design guides as a baseline, we identified ten key challenges and compared them with four other cold climate countries' recommendations given by experts in the field of building physics (building science). The results showed that other countries' recommendations differ from those of Norway in various key challenges. However, similar but varying recommendations pertaining to ground surface slopes, drainage layers, drainage pipes, capillary breaking layers in floors, avoiding thermal bridges, airtightness, and ventilation were noted. The key differences pertained to the exterior damp proofing of walls, use and position of dimpled membranes and vapour barriers, and use of permeable thermal insulation. The outcome is that countries emphasize the ten key challenges differently. Although the recommendations have many similarities, the weighting (or prioritizing) distinguishes the five countries' moisture control strategies.

1. Introduction

Moisture control is a fundamental aspect of building design; it involves avoiding the damage caused by moisture and the decay and extra heat loss caused by wet materials. Most importantly, it aims to ensure occupants' health and comfort.

Climate change scenarios predict more frequent and more intense precipitation events with heavy rainfall and rainfall-induced floods in many geographical regions with cold climates [1]. Precipitation during the year might also be distributed differently compared to the current situation. To endure increasing amounts of stormwater alongside the increasing annual precipitation, buildings must be adapted to these loads.

Habitable basements can provide many advantages, e.g., reduced heating- and cooling-demands, maximizing the main living area and providing increased weather protection at exposed sites. In Norway, especially in densely populated areas, utilizing basements for more than just storage is desirable. Moisture-related damages, however, are a major challenge in basements, and likely to increase with climate change [2]. The risk is associated with the increasing amounts of stormwater alongside the increasing annual precipitation and annual temperatures. In many municipalities in Norway, restrictions have also been introduced on roof water runoff, meaning that water no longer can be carried to the municipal stormwater grid, but should be infiltrated/delayed on site.

Norwegian recommendations for moisture control in habitable basements are provided in the SINTEF Building Research Design Guides [3]. They comply with the performance-based requirements in the Norwegian building code [4] and are an important reference to documented solutions in the technical regulations. The design guides adapt experience and results from practice and research into practical benefits to the construction industry. However, due to both increasing moisture

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Table 1
International research sorted on the ten key challenges for habitable basements.

Key challenges	International research for habitable basements
1. Water from rain and snowmelt	- Roof drainage systems [14] (ch. 1, p. 34–35)
	- Site drainage [14] (p. 28–31)
	- Site grading [5] (ch. 4.1) [15], (ch. 4.1.1.2)
	- Infiltration [15] (ch. 4.1.1.3) [16],
	- Modelling of stormwater management [17]
	- Flood protection [18]
2. Water pressure on exterior walls below the ground	- Drainage [15] (ch. 4.1.1.4)
	- Draining backfill [19]
	- Draining insulation [19]
	- Moisture in drainage layers [20]
	- Foundation drainage [14] (ch. 1, p. 34–35)
3. Water pressure against the construction from raising of groundwater	- Drain pipes [15] (4.1.1.4)
	- Ground conditions [19,21]
	- Water content distribution beneath building foundations [22]
	- Flood Risk Associated with Basement Drainage [23]
4. Water from the terrain surface or from the ground that reaches the surface of the wall	- Capillary breaking layer, wall [15] (ch.4.1.3.5)
	- Draining insulation [15] (ch. 4.1.3.5) [24],
	- Drainage and Capillary Rise in Glass Fibre Insulation [25]
	- Moisture transfer [26] (ch. 2.4)
	- Vapour transfer [26] (ch. 2.3)
5. Capillary rise of moisture from the ground through the floor and foundations	- Capillary breaking layer, floor [15] (4.1.1.5)
	- Moisture transfer [26] (ch. 2.4)
	- Soil material properties [19]
	- Capillary rise in concrete floors [27]
6. Transfer of water vapour from the ground through the floor	- Vapour barrier, floor [15] (3.4.1 and 4.1.2.1)
	- Heat, air, and moisture conditions of slab-on-ground [28]
	- Vapour transfer [26] (ch. 2.3)
	- Thermal performance [10,29,30]
7. Moisture condensation on, and drying capacity of the basement walls	- Thermal insulation below grade [15,31–34] (ch.4.1.3)
	- Basement Condensation [14] (p. 34–35)
	- Moisture transfer [26] (ch. 2.4)
	- Moisture diffusion [35]
	- Coupled heat and moisture transfer [36]
	- Moisture/air/vapour/soli gas barrier/retarders [5] (ch. 2.7 & 2.8.)
	- Surface condensation and drying [26] (ch. 2.3.6.3.)
	- Heat and moisture flow in soil [37]
8. Thermal bridges	- Dynamic modelling of thermal bridges
	- Thermal bridges [26] (ch. 1.2.3.4 & 1.5.4) [38], (ch. 3.4.1.)
	- Performance of Rigid Polystyrene Foam Insulation [39]
9. Air leakages (moist air and radon gas) from the ground to the structure and indoor air (walls and floor)	- Radon barriers [40]
	- Radon and moisture infiltration [15,15] (ch. 4.1.1.7)
	- Air transfer [26], (ch. 2.2)
	- Air transfer through the building envelope [38] (ch. 4.2.)
	- Factors influencing airtightness and airtightness modelling (review) [41]
	- Dynamic wall system [42]
	- Radon transport [43,44]
10. High indoor moisture supply from cloth drying, cooking, showering.	- Ventilation of a building [38] (ch. 4.3.) [45],
	- Ventilation strategies [46,47]
	- Indoor moisture supply [48,49]
	- Moisture supply [50,51]

loads and increasing insulation thicknesses in basements, new knowledge, methods, and tools are needed to substantiate and improve current recommendations. These design guides constitute the baseline for an international comparison of cold climate strategies for habitable basements.

The aim of this study is to provide an overview of main moisture control strategies for habitable basements in cold climate countries, investigate differences and identify main learning potential.

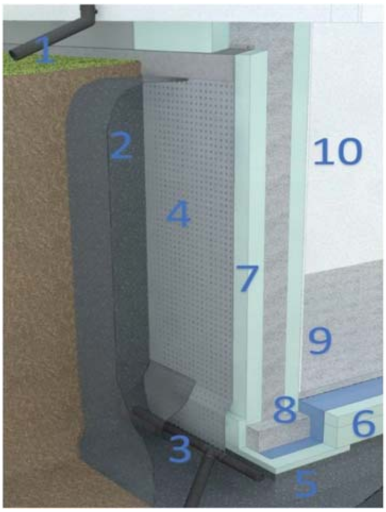
The study includes: (1) recommendations for moisture control in habitable (heated) basements in new buildings above the groundwater level, (2) recommendations for the terrain surface next to the building, (3) recommendations for exterior drainage (drainage outside basement walls, floor or foundation), (4) recommendations for thermal insulation, airtightness, damp proofing and moisture protection of walls, floor and the transition in-between and (5) recommendations for the ventilation of indoor air in the basement (as this affects the moisture conditions in the basement envelope). More specifically, ten centres of interest have been identified throughout this research, see Table 1.

To address these general inquiries, the following research questions are raised:

1. Using Norwegian guidelines as a baseline, how do the western cold climate countries building recommendations differ with regard to habitable basements?
2. What main differences and similarities can be identified?
3. What main learning potential can be identified?

1.1. Limitations

Given the extent of the research field, certain limitations are determined. We do not address: (1) recommendations for rehabilitation, refurbishment, and restoration, (2) recommendations for structures exposed to permanent water pressure, (3) recommendations for interior



1. Water from rain and snowmelt (including down-pipes).
2. Water pressure on exterior walls below the ground.
3. Water pressure against the construction from a rise of groundwater.
4. Water from the terrain surface or from the ground that reaches the surface of the wall.
5. Capillary rise of moisture from the ground through the floor and foundations.
6. Transfer of water vapour from the ground through the floor
7. Moisture condensation on, and drying capacity of, the basement walls.
8. Thermal bridges.
9. Air leakages (moist air and radon gas) from the ground to the structure and indoor air (walls and floor).
10. High indoor moisture supply from cloth drying, cooking, showering etc.

Fig. 1. Key challenges in habitable basements.

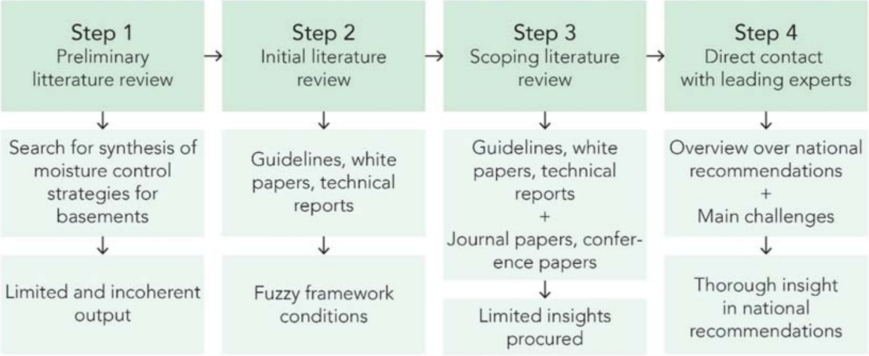


Fig. 2. Research procedure.

walls and intermediate floors, (4) recommendations for interior lining (aesthetic recommendations) beyond what concerns the moisture protection/air sealing as this affects the moisture protection, (5) recommendations for excavation, ground stabilization and other groundwork outside the draining layer and (6) recommendations concerning the structural elements beyond what concerns the moisture conditions, i.e. the elements normally contain moisture that must be able to dry inwards, outwards or both.

The main national recommendations for habitable basements provided in Appendix A-E are independent of the design of the structural elements unless otherwise specified in the tables. Figs. 5–9 illustrates how basements can be designed to meet the national recommendations, hence the structural elements in these figures are just one of several different solutions.

2. Theoretical framework

The main focus of this chapter is to establish an understanding of moisture control strategies for habitable basements in cold climates based on international research. Arriving at such an understanding is not a straightforward task because:

- recommendations for basements vary according to several factors, e.g. local building practice, local climate, local ground conditions, national regulations, material availability, and economy.
- the basement envelope system consists of several elements that separate the indoors from the outdoor environment, both above and below grade, e.g. basement walls (both above and below ground), basement floor slab, joints, intersections, and drainage.
- the basement envelope elements consist of several sub-systems, materials, and components that have many different and sometimes contradicting performance requirements to fulfil.

Our strategy has been to understand the acknowledgment and weighing of different factors concerning such building elements. The main idea is to articulate how moisture resilience in habitable basements is sought and ensured in five cold climate countries. The vocabulary outlined is based on a thorough analysis of the Norwegian SINTEF Building Research Design Guides [3] and what challenges are found to be the most important there. These design guides do not, however, constitute any significant limiting factor to the analysis. Rather, they serve as a point of departure on which the analysis can be made useful. The key challenges can be defined as in Fig. 1.

1. Water from rain and snowmelt (including down-pipes).
2. Water pressure on exterior walls below the ground.
3. Water pressure against the construction from a rise of groundwater.
4. Water from the terrain surface or from the ground that reaches the surface of the wall.
5. Capillary rise of moisture from the ground through the floor and foundations.
6. Transfer of water vapour from the ground through the floor
7. Moisture condensation on, and drying capacity of, the basement walls.
8. Thermal bridges.
9. Air leakages (moist air and radon gas) from the ground to the structure and indoor air (walls and floor).
10. High indoor moisture supply from cloth drying, cooking, showering etc.

The literature sources regarding the key challenges differ. More existing literature was found on the subject of relatively narrow technical fields. These are explained in Table 1. Certain studies cover the topic in a more general manner [5–9]. These broader studies are to a certain extent included in the table but are also discussed more extensively below. Some other studies are more concerned with thermal conditions [10–13].

Although much research has been done on all the identified key challenges, little work seems to have been done so far on their interrelations. For assessments, national recommendations within chosen cold climate countries have been subjected to scrutiny.

3. Methodology

3.1. Research procedure

The methodological approach for the study has been somewhat complex (Fig. 2). Related literature articles could not be found; thus, we established an overview through initial literature review from February to May 2017. The literature review proved challenging because little research was found about the subject field. To advance the work, a thorough scoping literature review was carried out, systematically examining the leading journals within the field although the outcome was disappointing. The limited insights achieved indicated the need for a more direct approach. Leading experts from cold climate countries were directly contacted. These were challenged to provide overviews over main recommendations within the field for their respective countries. The analysis exposed in this article is mainly based on these insights provided.

In the following section, we distinguish between three main sources of information concerning the overall strategies on the subject of moisture control strategies for habitable basements. The first is regarding the description of common practice within the different countries examined. The second concerns the main recommendations for practice from authoritative sources. The last concerns descriptions of special cases. The analysis of international literature did not yield information to be characterized as a proper source of information.

3.2. Preliminary literature review

A preliminary literature review was carried out in February 2017. We first attempted to identify literature articles about the subject field; the lack of such work initiated an attempt to establish such an overview through an initial literature review. Search words, search engines and databases included in the preliminary literature review are given in Table 2.

Studies concerning moisture in building parts other than basements, heat and moisture transport in general, and damage caused by moisture were easily found. Scientific studies dealing directly with moisture control strategies or recommendations for new and habitable basements were harder to find.

3.3. Initial literature review

Considering the limited and incoherent results from the preliminary literature review, a more thorough literature review focusing on official guidelines, white papers, and technical guidelines/reports was carried out in the spring of 2017. In addition to basements, this review has also included recommendations for crawlspaces and slab on the ground.

Table 2

Search words and combinations included in the literature review.

Literature review	Search engines and databases	Search words				
Preliminary (Step 1)	- Science Direct - Oria (Norwegian library database) - Google - Google scholar	basement* (basement, basements), cellar* (cellar, cellars), “foundation wall*" (foundation wall, foundation walls), moisture, moisture safety, “moisture control strateg*" (“moisture control strategy”, “moisture control strategies”), design guide*, (design guide, design guides) guideline*, (guideline, guidelines) recommend* (recommend, recommending recommendations).				
Initial (Step 2)	Same as Step 1	basement, “basement wall below ground”, “basement wall below grade”, “basement wall below-grade”, “foundation wall”, crawlspace, “slab on ground”, “insulated basement”, “exterior insulated basement".				
Scoping (Step 3)	Same as Step 1 and Step 2 + Tailor & Francis Online	**Different searches combining one search term from each column**				
		Search term 1	**AND**	**Search term 2**	**AND**	**Search term 3**
		basement*(basement, basements)		moisture		design guide* (design guide, design guides)
		cellar* (cellar, cellars)		moisture safety		guideline* (guideline, guidelines)
		“foundation wall*"		“moisture control strateg*" (“moisture control strategy”, “moisture control strategies")		recommend*(recommend, recommending recommendations)
		“wall* below ground"				
		“wall* below the ground"				
		“wall* below grade"				
		“wall* below-grade"				
		“building* below ground"				
		“building* below the ground"				
		“building below grade"				
		“building below-grade"				

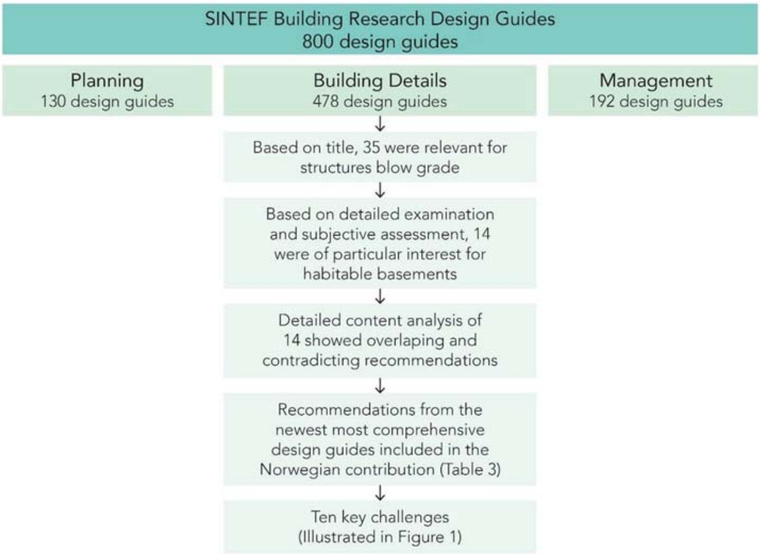


Fig. 3. Illustration of the sorting process used for content analysis and final table (Table 1).

Fig. 4. Detailed illustration of the involvement of international experts.

The publications identified proved to be highly heterogeneous. From Science Direct, the results were quite limited, i.e. mainly focusing on special foundation cases, new material tryouts or building defects. Using Google and Google Scholar, examples of actual practice were easily found, e.g. drawings and recommendations from material manufacturers. Overall recommendations, however, proved hard to find for most countries. The exception was Denmark where design guides regarding moisture in basements could be found [52,53].

Search words, search engines and databases included in the initial literature review are given in Table 2. The search focused on the following countries;

Norway, Sweden, Denmark, Netherland, Belgium, USA, Canada, and Germany.

3.4. *Scoping literature review*

Given the unclear national legacy of the results in the initial literature review, a more thorough literature review of scientific publications, reports, drawings, internet pages, and design guides was carried out spring of 2017. The review was carried out as a scoping study according to the prescriptions [54]. As commented by these authors, scoping studies differ from systematic reviews in that they typically do not assess the quality of included studies. This might be considered a significant disadvantage, however, as is further underlined by these authors [55:1], "scoping studies may be particularly relevant with disciplines with emerging evidence".

The review was conducted to obtain an overview of recommendations for the moisture control of habitable basements in cold climate countries (Norway, Denmark, Sweden, Belgium, Netherland, Germany, Canada, and the USA.). However, the review showed that it was hard to find relevant information regarding general national recommendations in other countries than in Norway and Denmark. One particular reason for this was that they do not have design guides such as the SINTEF Building Research Design Guides [3], DBRI Guidelines [56] and BYG-ERFA [57]. USA and Canada equally stand out since they have national guidelines covering the topic [5,14].

Scientific papers and journal articles generally address special cases (i.e. specific projects and new solutions, measurements, calculations, details), and are therefore not a good source of more general national recommendations. Google and Google Scholar searches were also performed, and it yielded more relevant results; however, the information was of variable quality and thus was not optimal to provide an adequate overview of national recommendations.

A particular challenge entailed identifying recommendations and guidelines in languages not familiar to the researchers (e.g. Dutch).

Search words, search engines and databases included in the scoping literature review are given in Table 2.

3.5. *Assessing the main challenges within the Norwegian context*

To identify the main challenges for moisture control of habitable basements, a desktop study of recommendation within the Norwegian context was conducted. The object of the study was the SINTEF Building Research Design Guides [3], which provides authoritative guidelines for industry practice.

The guidelines are very comprehensive in nature, covering almost all the fields of buildings. Providing a sample found relevant for the study was based on a detailed selection process. First, planning and building

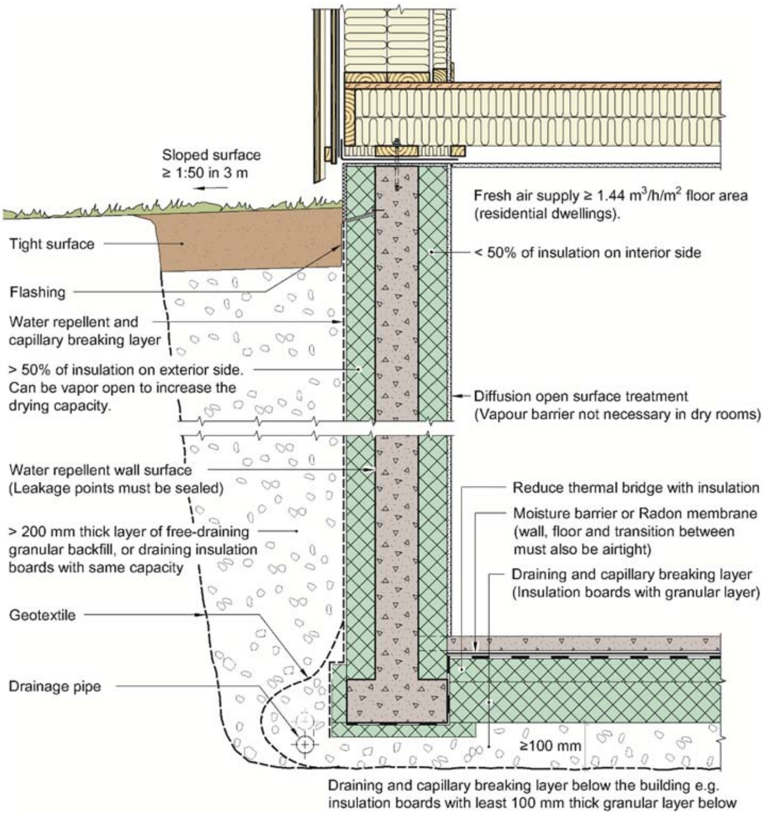


Fig. 5. Main recommendations for habitable basements in Norway.

details titles were distinguished. The building detail series was subsequently scrutinized in detail. For the analysis, habitable basements and year of publication were chosen as selection criteria. This process is illustrated in Fig. 3 and resulted in the development of the ten key challenges illustrated in Fig. 1.

3.6. *Involvement of international experts*

The scoping literature survey was conducted to obtain an overview of the recommended solutions. This did not, however, provide a sufficient knowledge base for understanding national recommendations. Therefore, experts within the field of building physics (building science) from countries characterized by cold climates were invited to contribute with detailed information on recommended building practice.

Based on the ten key challenges identified in the analysis [3], experts were asked to contribute, with detailed information on recommended building practice in their respective countries, to the following three requirements:

1. Describe the key elements and recommendations to achieve optimal moisture safety for habitable basements in new buildings in your country.
2. Attach 1–2 detailed figures that exemplify how these recommendations can be built.
3. Write a short introduction to the use of basements in your country.

The experts were also given a Norwegian exemplification of the required contribution. The Norwegian exemplification is based on a content analysis [3] according to the prescriptions [58].

The involvement of international experts in the research process is illustrated in Fig. 4.

3.7. *Choosing leading experts*

Results and implications are based on contributions from the invited experts.

When deciding on what experts to involve in the work, selection criteria were established.

First, 5 countries, Finland, Denmark, Sweden, Estonia, and Canada, were chosen based on the following selection criteria;

1. Geographical location.
2. Climatic conditions.
3. Availability.

Secondly, one expert from the field of building physics (building science) from each respective country was selected according to prior knowledge of their contribution within the field from the originators of the research. The experts were contacted and invited to participate in the analysis. Of the five selected experts, one did not submit his contribution.

3.8. *Limitations to the analysis*

Several limitations to the analysis have to be acknowledged. Firstly, within each country, there might exist other main recommendations than those that the expert have included in their contribution. If we could have asked more than one expert from each country, perhaps this

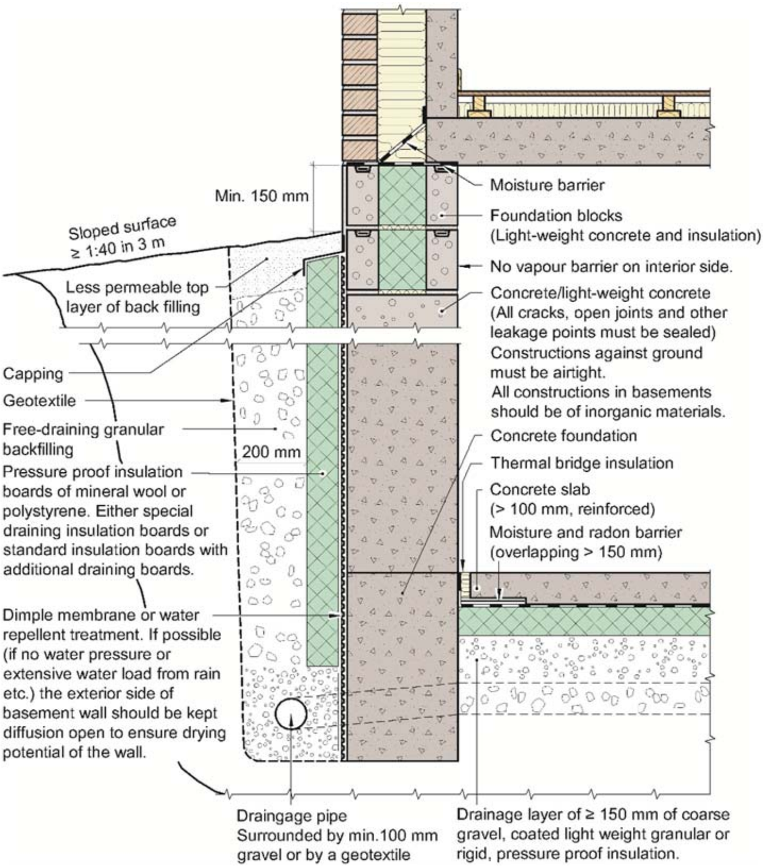


Fig. 6. Main recommendations for habitable basements in Denmark (adapted from Figures 35 and 36 in Ref. [61]).

source of error could have been less. Secondly, the ten key challenges in the Tables are based on the content analysis [3] and what Norwegians experience as challenges. Initially, we thought other countries would make their own list of challenges, but they all based their contributions on the Norwegian challenges and added none of their own. If we had made the table differently, we might have left one box at the bottom open and asked the experts to add their own challenge(s) if they had any. Thirdly, the expert might have misinterpreted the content of the Norwegian Table.

Whilst all these limitations might have some bearing on the analysis, their influence does not seem sufficient to significantly undermine the main conclusions presented in this article.

4. Results

4.1. Summary of main findings

In the following section, the main results sorted by the ten key challenges, see Fig. 1, are presented.

#1: Canada recommends that the building shall be located so that water will not accumulate at or near the building. Norway, Denmark, Sweden, and Estonia additionally recommend that the ground surface next to the building is levelled with a slope at a distance of 3 m. Differences in the size of the slope are from 1:20 to 1:50. Norway recommends the sleekest slope (1:50). Denmark additionally recommends that the top layer of the ground should be less permeable than the draining layer on the exterior side of the insulation. Estonia recommends a dense covering of the paved surfaces.

#2: All countries recommend a drainage layer on the exterior side of the basement walls. Norway, Sweden, and Canada recommend free-draining granular backfill or draining insulation. Denmark recommends both. Norway, Denmark, and Sweden additionally recommend a geotextile to protect the draining layers against fine-grained material from the ground. The recommendations for the type and thickness of the drainage layer also has interesting variations. Estonia recommends a drainage layer ≥200 mm thick. Sweden recommends a drainage layer ≥200 mm thick composed of sand or gravel. Norway recommends either at least 200 mm free-draining granular backfill or draining insulation with the same capacity. Canada recommends either at least 100 mm free-draining granular backfill or ≥19 mm mineral fibre insulation. Denmark recommends either special draining insulation boards or standard insulation boards with additional draining boards and an additional layer of >200 mm backfilling with good draining capacity.

#3: All countries recommend drainage pipes with some differences in the given details e.g. use of geotextile, pipe-dimension, and position. Norway recommends drainage pipe surrounded by gravel and enclosed by a geotextile, while in Denmark one of these options can be chosen. Sweden recommends drainage pipes with an internal diameter ≥70 mm with drainage layers around and a geotextile to protect the draining layer. Canada specifies drainage tile or pipe of ≥100 mm diameter with

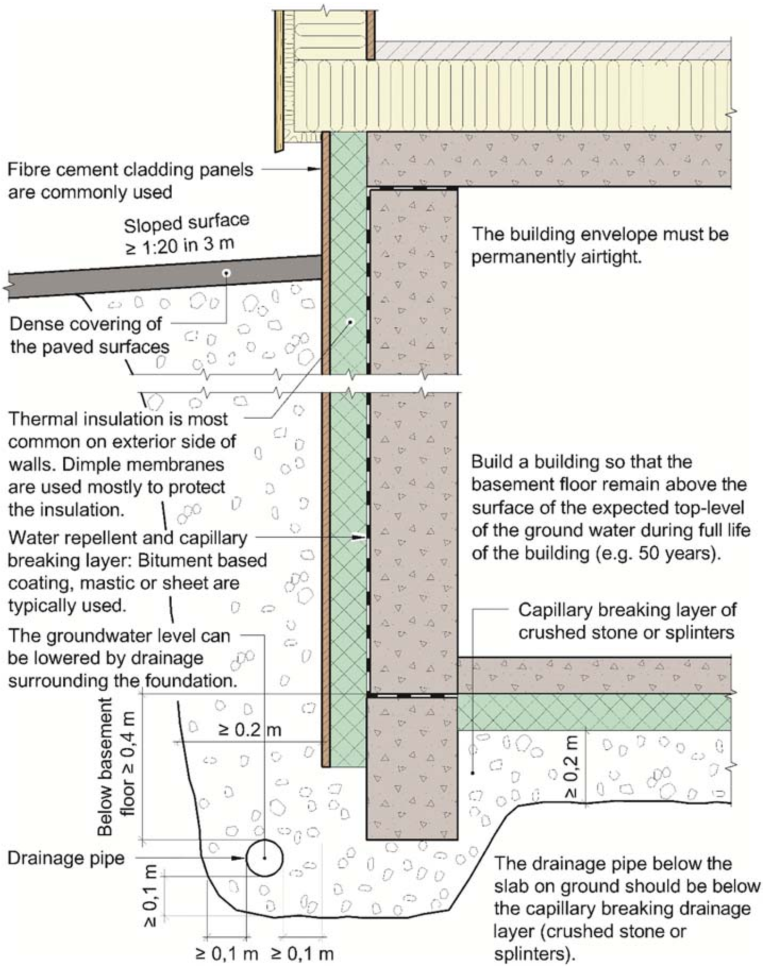


Fig. 7. Main recommendations for habitable basements in Estonia (adapted from Ref. [63]).

top and side covered with ≥150 mm gravel. Estonia recommends that the highest point of the drainage pipe must be at least 0.4 m below the lower surface of the slab on ground and that the drainage pipe below the slab on the ground should be below the capillary breaking drainage layer (crushed stone or splinters) and below the lower surface of the basement wall.

#4: All countries have one or several different recommendations regarding this challenge. They all recommend a water repellent capillary breaking layer of some kind, on the exterior side of the wall or on the exterior side of exterior insulation. However, the material, design, and position vary among the countries. The capillary breaking layer can either be dimpled membranes, some kind of water repellent treatment/ rendering or both, or it can be bitumen-saturated membrane. Canada recommends a water repellent layer on the exterior wall surface and a bitumen-saturated membrane where hydrostatic pressure occurs. Denmark recommends that if possible (if not water pressure or extensive water load from rain), the exterior side of the basement wall should be kept diffusion open in order to ensure the drying potential of the wall. Norway recommends dimpled membranes on the exterior side of exterior vapour permeable thermal insulation. In Estonia, dimpled membranes are used more for the protection of insulation. Sweden recommends an additional waterproof membrane from the bottom of the concrete slab and 500 mm up on the outside of the wall.

#5: All the countries recommend a capillary barrier of some kind in the floor to avoid capillary rise of moisture from the ground, but the type, thickness, and position vary. Sweden recommends a layer of coarse crushed stone material ≥150 mm thick and a geotextile. Canada recommends ≥100 mm coarse clean granular material beneath the floor. Norway recommends both insulation and ≥100 mm thick granular layer below the building and a geotextile if there is a risk of rising groundwater or very soft building ground. Denmark recommends ≥150 mm coarse gravel, coated lightweight granular or rigid, pressure-proof insulation. Estonia recommends ≥200 mm thick layer of crushed stone or splinters and a geotextile below that layer if the base ground is clay or silt,.

#6: All the countries have different recommendations regarding water vapour from the ground through the floor. In Denmark, no moisture barrier is needed for the typical construction with reinforced concrete slab, unless moisture-sensitive flooring materials are used. Norway recommends a moisture barrier between the insulation and concrete floor. Canada recommends damp proofing below the floor of ≥0,15 mm PE. If a separate floor is provided over a slab, damp-proofing

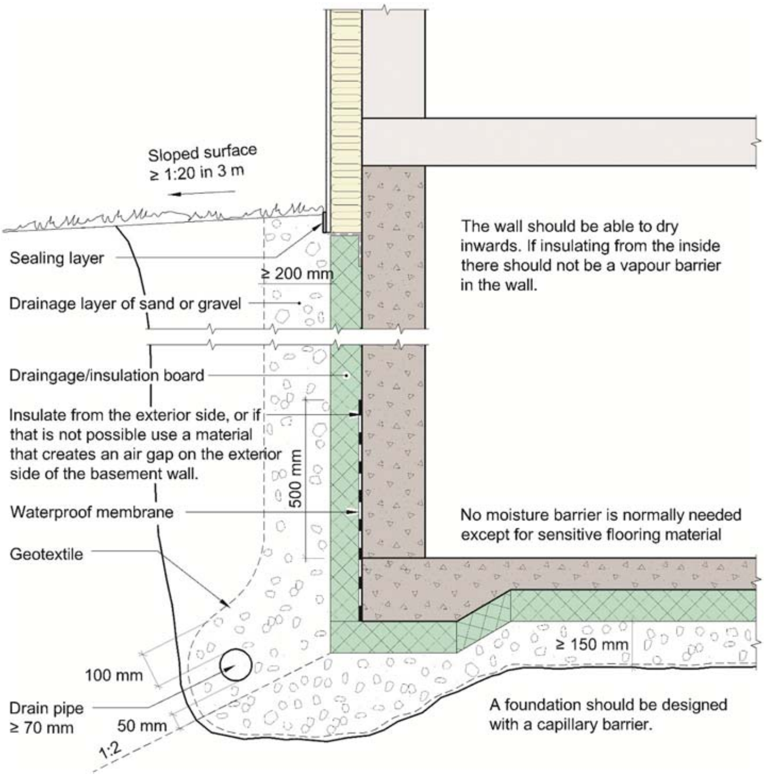


Fig. 8. Main recommendations for habitable basements in Sweden (adapted from Figure 35 in Ref. [24], Figure 4.1.36 and 4.1.34 in Ref. [15] and Figure 11 and Typritning nr. 5 in Ref. [68].

is permitted to be applied to the top of the slab. In Estonia, it is either recommended to use a moisture barrier between the insulation and the concrete floor (typically PE foil), or not to use a foil to allow dry out the concrete toward the ground. Sweden recommends thermal insulation below the whole concrete slab to protect the foundation from water vapour from the ground. A moisture barrier is normally not recommended except for sensitive flooring material.

#7: All the countries recommend thermal insulation, but the thickness and position vary among the countries. Recommendations to use or not to use vapour/moisture barriers also vary. In Norway, no moisture barrier is necessary on the interior walls (in normal dry rooms) as long as least 50% of the insulation is on the exterior side of the exterior walls. It is recommended to put the dimpled membranes on the exterior side of exterior vapour permeable insulation to optimize outwards drying. Denmark recommends that all constructions in basements be of inorganic materials and no vapour barrier is recommended in order to ensure drying capacity of the construction. Canada recommends combined interior/exterior insulation for basement walls and if a separate interior finish is to be applied to the foundation wall, a moisture protection layer shall be applied on the interior foundation wall surface to minimize the ingress of moisture from the foundation wall. The common practice in Estonia is to use insulation on the exterior side of the basement wall. Sweden recommends that walls with moisture from the construction process be given the opportunity to become dry by exterior insulation, dimpled membrane or combination of both, and do not recommend a vapour barrier on the interior side of the wall.

#8: In Canada, thermal bridges in new houses basements are not a common issue, but they tend to be more significant in those basements that are converted in residential spaces to accommodate the increasing urban density and house shortage. Sweden has not given any specific recommendations. Estonia points out the recommended temperature factor to avoid a risk of mould growth [59]; however, it does not give specific recommendations on measures to achieve this. Norway has provided specific recommendations on how to avoid the thermal bridge in the transition between wall and foundation (either minimum of 50 mm insulation below the concrete foundation or applying insulation between wall and floor). Denmark recommends placing insulation on the exterior side of the construction and to reduce the thermal bridge on top of the basement wall by ensuring an overlap of >200 mm for wall insulation and insulation on the exterior side of basement walls.

#9: All the countries recommend airtightness for constructions against terrain (moisture, heat loss and radon).

#10: The recommendations for ventilation in basements vary among the countries. In Norway, the recommended fresh air supply for basements is the same as residential dwellings is general, e.g. minimum 1.44 m^3 each hour per m^2 of floor area. The ventilation rates shall be adapted to the contamination and moisture load and can thus be higher. In Sweden, the minimum outlet airflow is a bit lower: 1.26 m^3 per m^2 floor area (converted from 0.35 l/s per m^2 of floor area). In Denmark, ventilation in basements must fulfil normal requirements for air change in dwellings. In Canada each habitable room shall be assigned a fan capacity of 5 L/s (18 m^3/h) apart from the master bedroom which needs 10 L/s (36 m^3/h). To compare with other national recommendations, two examples are provided;

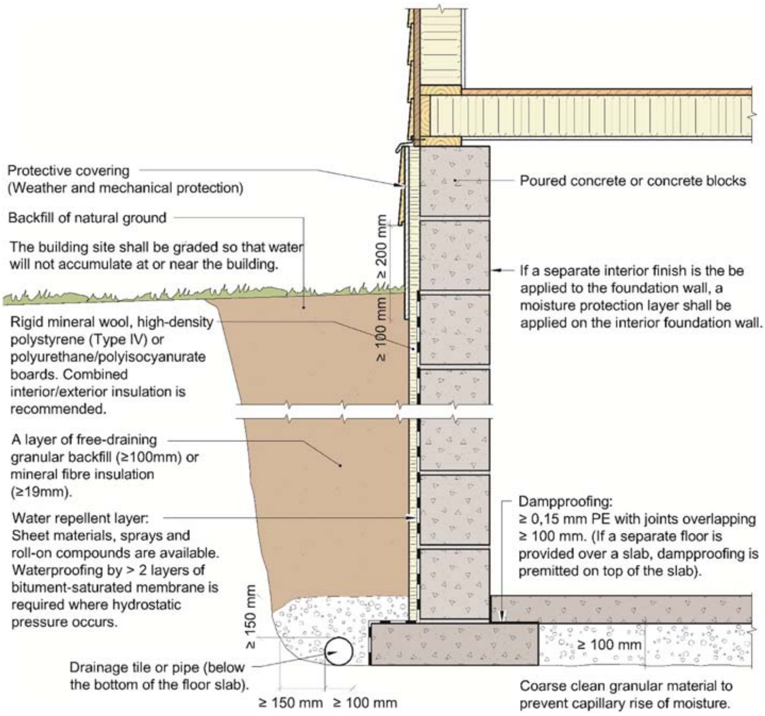


Fig. 9. Main recommendations for habitable basements in Canada (adapted from Ref. [70]).

- Habitable room (floor area from 10 to 30 m^2): fan capacity from 1.8 to 0.6 m^3/h per m^2 floor area.
- Master bedroom (floor area from 10 to 20 m^2): fan capacity from 3.6 to 1.8 m^3/h per m^2 floor area.

4.2. Habitable basements in Norway

In Norway, 50% of the residential building stock consists of single-family dwellings. An additional 9% are houses with two dwellings and 12% are row houses, linked house or other small houses [60]. A large proportion of these homes is built with a living space in the basement. Such basements are normally built above the groundwater level with a concrete foundation on a free-draining layer of “gravel”. The densest parts of Norway are characterized by frequent freeze-thaw conditions.

The identified recommendations for Norway are based on the SINTEF Building Research Design Guides [3]. These consist of 800 design guides that have been produced and continuously updated since 1958. The design guides are the most used planning and design tool amongst Norwegian architects and engineers because they comply with the performance-based requirements in the building code and are an important reference to documented solutions in the technical regulations.

The main national recommendations for habitable basements in Norway are depicted in Fig. 5 and described in detail in Appendix A. According to the view of the authors, Fig. 5 and Appendix A present the key elements to optimal moisture safety in habitable basements in Norway.

4.3. Habitable basements in Denmark

In Denmark, habitable rooms and kitchens must be above ground and therefore no habitation is allowed in basements. For special site conditions, e.g. sloping site, it is possible to have habitable rooms in a basement if the floor lies above ground level along at least one wall with a window. When part of the room is below the ground, a special focus must be paid on the constructions against the ground regarding penetration of moisture and radon.

In general, basement walls are made of concrete or light-weight concrete blocks. The basement floor is always a concrete slab. Thermal insulation must be placed on the exterior side of the construction and the backfilling must be suitable for draining and preventing capillary rise.

The main national recommendations for habitable basements in Denmark are depicted in Fig. 6 and described in detail in Appendix B. The basic guidelines about moisture safe construction principles are found in DBRI Guideline 224 Moisture in buildings [53]. The other guidelines referred to in Appendix B can be found [56].

4.4. Habitable basements in Estonia

In Estonia, residential buildings comprise up to 60% of the total building stock [62]. Apartment buildings account for 51% (34 282 × 10^3 m^2) of the total net area of dwellings. The second large group of dwellings is detached houses with 41% (26 447 × 10^3 m^2) of the total net area of dwellings. The groundwater level is high in Estonia; in most cases, the basement is below. There are no official statistics about buildings with or without a basement. Based on common knowledge nowadays:

- Detached houses and row houses are mainly built without a basement, mainly because the inhabitants do not need so much storages in the basement; construction below the ground is more expensive, and the foundation does not need to go deeper because solutions exist to prevent frost rise.

- Apartment buildings and offices typically use basements for garage, technical rooms or for storage.

In Estonia, good recommendations and guidelines as in Norway (SINTEF) and in Finland (RT-cards) do not exist. Instead, Estonian designers use quite a lot of Norwegian and Finnish guidelines. It is designer's responsibility and target to fulfil essential requirements on construction and building.

The main national recommendations for habitable basements in Estonia are depicted in Fig. 7 and described in detail in Appendix C.

4.5. Habitable basements in Sweden

The Swedish building stock consist of 1.2 million single-family houses and 166,000 multi-family buildings. Of the single-family houses, 30% have a basement, as do 50% of the multi-family buildings. The average U-value for basement walls below grade is 0.74 W/(m^{2}K) and for basement walls above the ground, it is 1.65 W/(m^{2}K). Of the single-family houses, 29% suffered some kind of damage; of the multi-family buildings, 8% suffered damage [64]. Around 8% of all basements in Sweden have mould odours [65]. Before the 1970s, basements were mainly used for storage and not heated, but today it is common to furnish the basement.

The Swedish building regulations have been performance-based since the end of the 1980s. This means the contractor is free to suggest and choose any solutions and construction techniques as long as the basic performance criteria are fulfilled: 'Buildings shall be designed to ensure moisture does not cause damage, odours or microbial growth, which could affect human health'. If the critical moisture level is not well-researched and documented, a relative humidity (RH) of 75% shall be used as the critical moisture level. The requirements can be met and verified using moisture safety planning and monitoring of the design to ensure that the intended moisture safety is achieved. When planning, designing, executing and monitoring moisture safety, the industry-standard ByggaF – method för fuktsäker byggprocess (ByggaF – method for moisture safe building process) can be used as guidance [66]. Buildings, construction materials, and construction products should be protected from precipitation, moisture, and dirt during the construction period [67]. The main national recommendations for habitable basements in Swedish are depicted in Fig. 8 and described in detail in Appendix D.

4.6. Habitable basements in Canada

Residential construction in the Greater Toronto Area (GTA) has been booming over the last few years. The majority of these houses have been constructed by large "tract" homebuilders in accordance with the Ontario Building Code (OBC). Under such production conditions, the emphasis is placed on achieving the lowest initial capital cost. Many researchers in Canada have looked at detailed construction cost data and floor plans for popular models to assess the value of insulating the basement properly or "upgrading" from Ontario Building Code minimum standards to the R2000 standard. These currently mean:

- Ontario Building Code: R-6 basement wall insulation to a depth of 0.6 m below grade (obligation)
- R2000: R-12 full height basement wall insulation (no obligation).

Unfortunately, the primary problem in Ontario (and the Greater Toronto Area) is housing booming. Given housing costs, basements are

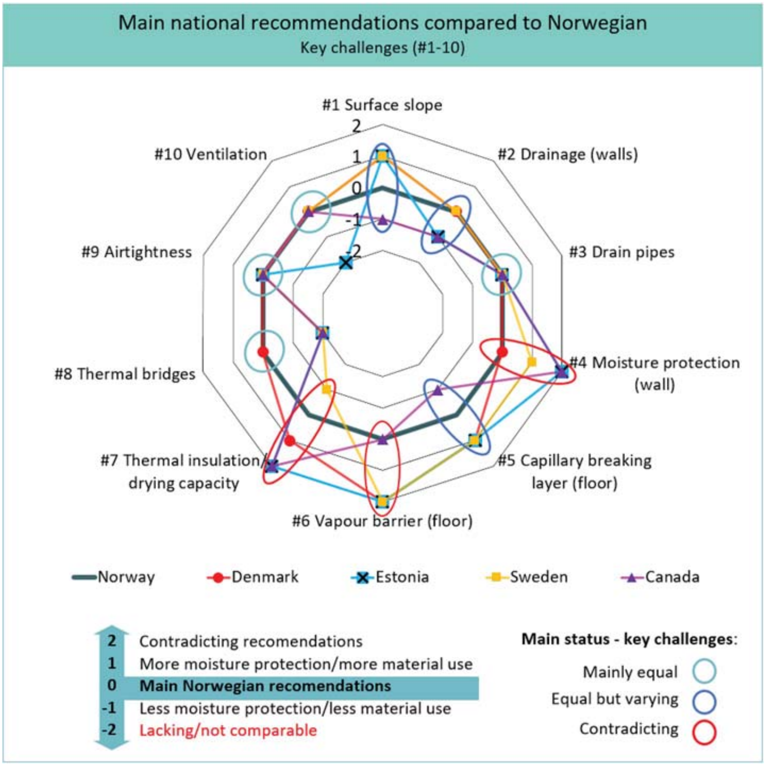


Fig. 10. Main national building recommendations for habitable basements in cold climate countries (red, blue, yellow and purple) compared to Norwegian (grey at level 0) for each of the ten key challenges (#1–10, see Fig. 1). Recommendations are sorted as either the same as Norway (level 0), more moisture safe (level 1), less moisture safe (level −1), contradicting (level 2) or lacking (level −2). The figure shows, for each key challenge, where the main recommendations are mainly equal (white circle), equal but varying (blue circle) or contradicting (red circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

now no longer just used as storage spaces but are often utilized as part of the interior space. Poor moisture management across these walls often leads to mould and mildew growth and poor air quality in basement spaces [69].

Nova Scotia does not have a provincial building code. Instead, this province relies on the National Building Code of Canada (NBC). However, the National Building Code does not mandate a minimum value of thermal insulation.

The main national recommendations for habitable basements in Canada are depicted in Fig. 9 and described in detail in Appendix E.

5. Discussion

5.1. Recommendations for habitable basements

In this study, we set out to investigate the differences and similarities in national building recommendations for habitable basements. The Norwegian design guides were used as a baseline to identify main learning potentials concerning moisture control strategies. Ten key challenges (#1–10) have been identified and used in the comparison of the main national recommendations in five western cold climate countries, see Fig. 1.

5.2. Norwegian recommendations compared to other cold climate countries

This study shows that the main national building recommendations in the western cold climate countries differ from the Norwegian at different key challenges, see Fig. 10.

Danish recommendations have the most in common with the Norwegian, but there are differences regarding (#1), (#5) and (#7) and contradicting recommendations regarding (#6). Sweden has differences regarding (#1), (#4), (#5) and (#7) and contradicting recommendations regarding (#6). Canadian recommendations mainly differ regarding (#1), (#2) and (#5) and had contradicting recommendations regarding moisture protection in walls (#4) and thermal insulation and vapour barrier in walls (#7). Estonian recommendations differ regarding (#1), (#2) and (#5) and are contradicting regarding the use of dimpled membranes (#4), vapour barriers in floors (#6) and dry out capacity (#7).

Norway also stands out by recommending a diffusion open exterior wall surface, vapour permeable thermal insulation and dimpled membrane positioned on the exterior side of the exterior thermal insulation (#7). This is recommended in order to increase the drying potential of the construction against the exterior [71]. Denmark also recommends that, if possible, the exterior side of the basement wall should be kept diffusion open in order to ensure the drying potential of the wall. However, according to the Danish illustration, the dimpled membrane is positioned between the wall and exterior insulation. Estonia typically uses bitumen-based coating, mastic or sheet on the basement wall surface to prevent water transfer from the ground and into the wall. Dimpled membranes are used mostly to protect the thermal insulation. Estonia also stands out by not having national recommendations such as Norway, but generally base their recommendations on practice.

Considering only the comparable recommendations provided, the countries have similar and varying but not contradicting recommendations regarding the ground surface slope (#1), drainage layers (#2), drainage pipes (#3), capillary breaking layers in floors (#5), thermal bridges (#8), airtightness (#9) and ventilation (#10). The most interesting variations are found for #1: recommended ground surface slope varying from 1:20 (Sweden and Estonia) to 1:50 (Norway) #2: recommended drainage on exterior side of walls vary from ≥19 mm mineral fibre insulation (Canada) to special draining insulation boards or standard insulation boards with additional draining boards and a layer of >200 mm backfilling with good draining capacity (Denmark) and #5: recommended capillary breaking layer beneath floor vary from ≥100 mm coarse clean granular material (Canada) to 200 mm thick layer of crushed stone or splinters (Estonia) and from ≥100 to ≥150 mm with additional insulation (Norway/Denmark).

5.3. Contradictions

The main recommendations have interesting differences regarding water that reaches the surface of the wall (#4), water vapour from the ground through the floor (#6) and partly (#7) moisture condensation on, and drying capacity of, the basement walls. Not surprisingly, this applies to use and position of foundation boards, moisture/vapour barriers/membranes and type, thickness and vapour permeability of thermal insulation in walls and floors.

More precisely, Norway and Denmark recommend a diffusion open basement wall surface to ensure drying outwards, while Canada and Estonia mainly recommend damp proofing (#4). Sweden recommend a waterproof membrane from the bottom of the concrete slab and 500 mm up on the outside of the wall. Canada recommends interior moisture protection, while Norway and Denmark recommend no interior vapour barrier (#7). Norway and Canada recommend a vapour barrier in the floor structure, while in Estonia, some designers recommend no foil and Denmark recommend no moisture barrier unless moisture-sensitive flooring materials are used (e.g. wooden floor) (#6).

The countries included might have other main national recommendations not included in the expert contributions. This source of error could have been reduced if more than one expert from each country had submitted their version of the main recommendations.

5.4. Further research needs

Basements used as dwellings represent a major challenge concerning moisture safety design. The risk of moisture-related damage in these constructions is also expected to increase due to climate change. This study shows that cold climate countries recommend different strategies for moisture control in basements. The ten key challenges identified can be considered a basis on which future strategies for optimization of basements can be developed and evaluated.

This study shows that recommendations concerning ground surface slope (#1), drainage layers in walls (#2) and capillary breaking layers in floors (#5) vary. The risk of moisture damages in vulnerable structures, in particular, might be reduced by combining the strictest of the varying recommendations presented in the study, e.g. steeper surface slope next to the building and thicker draining and capillary breaking layers adjacent and underneath the building.

It is mainly the recommendations for key challenge #4, #6 and #7 that distinguish the moisture control strategies from each other. This is quite intriguing because barely any research was found in the literature concerning a holistic consideration of their correlation. After comparing the five countries' recommendations, new insight has substantiated the need to answer some general concerns. These include (1) are vapour permeable thermal insulation preferable? (2) can convection or moisture in exterior vapour permeable thermal insulation significantly reduce the heat resistance? (3) can exterior thermal insulation perform as a capillary breaking layer and thus replace the traditional dimple membrane? and (4) what thermal insulation thickness, position, and permeability are favorable?

Not only can research concerning such subjects provide significantly improved technical solutions; but also, they can imply significant pecuniary reductions.

6. Conclusion

A significant part of this work has been the development of the research methodology to be able to study moisture control strategies in habitable basements in different cold climates countries. Hence, we identified ten key challenges that should be included in national moisture control strategies for such constructions. The study shows that the main national building recommendations in western cold climate countries differ from the Norwegian at different key challenges.

Considering only the comparable recommendations provided, the countries have similar recommendations regarding drainage pipes (#3), thermal bridges (#8), airtightness (#9) and ventilation (#10). Interesting variations are found regarding the ground surface slope (#1), drainage layers in walls (#2) and capillary breaking layers in floors (#5). Contradicting recommendations are found regarding moisture protection of walls (#4), vapour barriers in floors (#6) and thermal insulation and drying capacity (#7).

The main learning potential from the review is that the five cold climate countries emphasize the ten key challenges differently. The recommendations have many similarities, but it is this weighing (or prioritizing) that distinguishes the five countries' moisture control strategy from each other. As an example, if a basement wall is protected against water intrusion with a bitumen-based watertight membrane on the exterior surface, exterior drainage might not need to be as efficient. Likewise, one might not have the same need to seal the wall surface if good site drainage, ground surface slope, thick draining layers and exterior vapour permeable thermal insulation provides good drying conditions.

Yet another consequence of these diverging national recommendations is a challenge for importing/exporting commercial and "well-known" solutions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2019.106572.

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Paper 2

Hygrothermal simulations of thermally insulated basement envelopes - Importance of boundary conditions below grade

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Hygrothermal simulations of thermally insulated basement envelopes - Importance of boundary conditions below grade

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ABSTRACT

Hygrothermal simulations are widely used to predict and optimise the hygrothermal performances of building envelopes. For the walls and floors in basements, however, determining the variation of the exterior hygrothermal boundary conditions below grade are challenging due to the various and complex heat and moisture loads and the large area needed to simulate the surrounding ground. A scoping literature review is conducted to provide an overview of current state-of-the-art methods for the addressing of these boundaries. Ten of the most comprehensive studies are selected and scrutinised. The review shows that there is a lack of thorough validation for hygrothermal simulations of basements using full-scale physical measurements. The most valuable experiences from studies with somewhat different perspectives are identified. Key uncertainties include the soil's varying composition and moisture content, liquid uptake at the soil surface and transfer of precipitation, and computational costs. Finally, the review highlights the need for a recognised method/procedure to determine the exterior boundary conditions for hygrothermal simulations of basement envelopes, which can account for the varying influencing factors of the ground. Not only can a better understanding and prediction of heat and moisture performance of basement envelopes contribute to improving building durability and energy efficiency; it can also potentially result in significant economic savings, as expensive repairs below grade can be avoided or delayed.

1. Introduction

In many Nordic countries, basements comprise a significant share of the building volume. Historically, they have been important for the storage of food, owing to low summer temperatures and moderate winter temperatures. Nevertheless, the usage and design of basements has changed significantly in recent decades. Nowadays, especially in dense areas, it is desired to inhabit and use the basement space like the rest of the house. The regulatory requirements for energy efficiency, moisture control, and indoor climate control in basements are, therefore, becoming much stricter. The requirements lead to increased thicknesses of thermal insulation layers in basement walls and floors. Barrier layers and membranes (moisture, air, radon [1]) are also seeing more widespread adoption and stricter requirements. The recommended thicknesses, positions, and uses of such layers, however, differ between cold climate countries [2]. New innovative materials and products have also entered the market. Concepts are proposed to provide an increased drying capacity for basement walls [3]. A standardised approach for evaluating and comparing these performance and risk reduction measures, however, appears to be lacking.

Moisture from precipitation and snowmelt, along with the high relative humidity (RH) of the soil/backfill, inflicts a large moisture strain on basement envelopes. The ability of structures to dry outwards is also limited as compared to structures above ground, owing to the presence of the ground. Much moisture can potentially accumulate in basement envelopes wetted by leakages or flood, envelopes with insufficient drainage, poorly designed envelopes, or in newly built structures. Without the ability to dry, this moisture can lead to mould growth, bad smells, decay, and efflorescence [4,5]. Large amounts of moisture can also gradually accumulate in the thermal insulation used below grade when exposed to moisture over time [6,7], significantly reducing the thermal conductivity [8], and thus the overall thermal performance of the basement envelope.

In the field of building physics, hygrothermal simulations are widely used to predict the hygrothermal performances of building materials, components, and entire buildings. However, as described by many

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authors [9–12], a large number of hygrothermal tools are currently available. At least 57 different hygrothermal numerical tools existed in 2013 (14 generally available) [9]. The tools vary in their degrees of mathematical sophistication and runtime requirements i.e. based on different mathematical models (physical descriptions), use different driving potentials, and utilise different numerical methods for the space and time discretisation. Accordingly, the tools have different potentialities, strengths and weaknesses, e.g. the ability to include air transfer [13], 2D or 3D phenomena [14], or the ability to simulate a high number of zones in a reasonable execution time. Selecting the tool best suitable for a specific problem can thus be challenging. For basement envelopes, another challenge is to adequately determine the exterior boundary conditions below grade. Essentially, the contact with the ground distinguishes the basement envelope parts from those building components solely above grade (i.e. exterior walls and roof), see Figure 1. For exterior walls and roofs, much research has been conducted on the development of numerical models and validation with experimental data [15] and the determination of exterior and interior boundary conditions [16–19].

Adequately determining the exterior boundary conditions below grade is more challenging because the conditions; (1) varies along with the height below grade, (2) depends on soils' varying hygrothermal properties, composition, moisture content and freeze/thaw, (3) depends on the thermal resistance of the envelope and the indoor temperature, (4) depends on the exterior climate including solar radiation, shading, precipitation, snow cover, and (5) are affected by the height of the ground water table. According to EN 15026:2007 [18] a RH of 99% can be assumed for the ground surrounding buildings, however, to the authors' knowledge, no recognised methods/procedures exist to determine the exterior boundary conditions for hygrothermal simulations of basement envelopes. The heat loss from buildings to the ground has been investigated by many authors (e,g. [20]) and can be calculated according to NS-EN ISO 13370:2017 [21]. The methodology, however, aims at assessing the energy performance, and its simplifications might not be optimal for predicting the exterior hygrothermal boundary conditions of basement envelopes. Geving et al. [22] used a two-step approach to perform 2D hygrothermal simulations of a basement envelope retrofit. First, temperature variations along the exterior side of the envelope below grade was determined by heat transfer simulations of the envelope and surrounding ground. Second, the temperature variations along with the exterior surface of the envelope were used as boundary conditions in the hygrothermal simulations along with a RH of 98%. Geving et al. [22] included a large part of the ground in the heat transfer simulations, however, constant soil thermal properties for saturated soil was used.

The inadequacy of existing simulation tools to replicate actual conditions below grade results in great uncertainty concerning the suitability of risk reduction methods for basement envelopes. As an example, simulations performed by Geving et al. [22] indicate that using vapor permeable thermal insulation on the exterior side of the basement walls, in cold climates, increases the outwards drying rate of the basement wall and results in dryer wall at equilibrium. However, the potential drying effect is strongly dependent on the temperature on the exterior side of the exterior insulation below grade. Using a constant (high) soil thermal conductivity and neglecting solar radiation and snow cover results in a conservative estimate for the heat loss and risk of condensation within the basement wall during winter. The outwards drying rate below grade, on the other hand, is overestimated because it

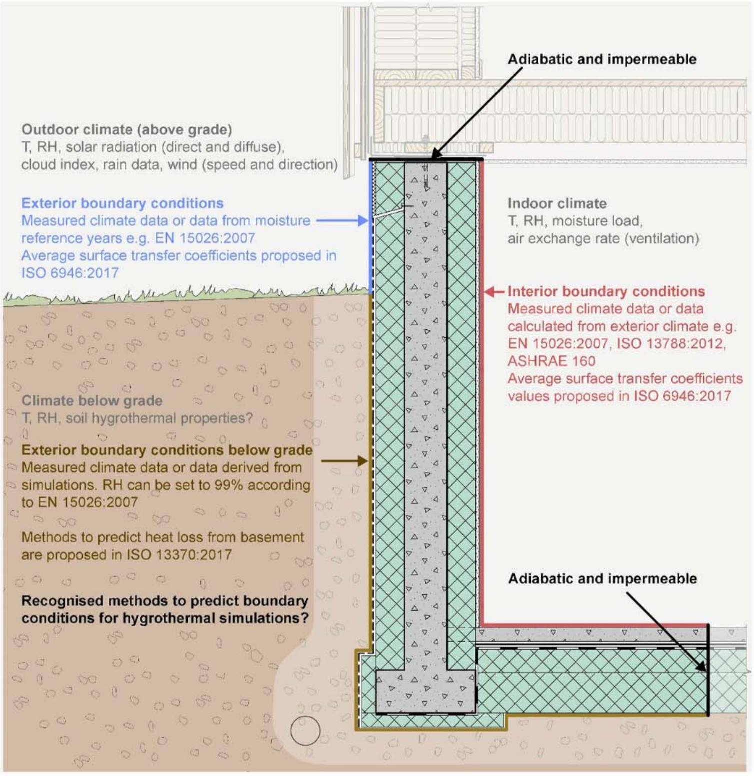

Fig. 1. Interior and exterior boundary conditions required for simulations of basement envelopes.

increases with decreasing temperatures. Inwards moisture flow due to solar radiation are also underestimated. A more thorough assessment of the exterior boundary conditions, considering different locations/climates, soil compositions and effects of moisture transfer would aid in providing more accurate assessment of the suitability of various risk reduction measures.

This paper seeks to investigate the current methodology of determining boundary conditions below grade for hygrothermal simulations of thermally insulated basement envelopes. The main objectives of this study were to (1) identify studies concerning the hygrothermal performance of basement envelopes, (2) investigate the methods, numerical tools, assumptions, simplifications, and exterior boundary conditions used below grade in these studies, (3) investigate how such simulations have been validated with measurements, and (4) identify valuable experiences for improving hygrothermal numerical simulations of thermally insulated basements.

To address these general inquiries, the following research questions were raised:

1. How is the performance of thermally insulated basement envelopes addressed through hygrothermal simulations in the existing literature?
2. How are the hygrothermal simulation procedures (physical models) for basements verified with full-scale measurements?
3. How may the exterior boundary conditions below grade for basement envelopes be determined?

Certain limitations were determined. Literature focusing on crawl spaces, air leakages through the building envelope, heat transfer simulations not accounting for moisture content in the ground, whole building energy simulations or heating and cooling systems, the drying of porous materials (particularly for foods), or the hygrothermal behaviours of masonry walls, wood, or other bio-based materials commonly used above grade or in moisture buffering research, is not addressed.

2. Theoretical framework

The fluid flow, heat transfer, and mass transfer can be described using mathematical descriptions [23]. Typical examples of diffusive equations include Fick's law of diffusion and Fourier's law of heat conduction. Typical examples of diffusion-like transport equations are Darcy's law for water flow and Darcy's law for air flow in porous systems [24]. This knowledge is combined with the laws for the conservation of momentum, mass, and energy [23]. This combination of equations results in a set of partial differential equations (PDEs) for describing the laws of physics for the space and time-dependent descriptions [24]. When laws from several different physical descriptions are combined to describe systems where several phenomena interact, they are called multiphysics systems [25]. The mathematical model of such a system can consist of one or several PDEs (describing the relevant laws), together with boundary and initial conditions. Normally, the right-hand side of the PDE represents the transfer of heat and moisture, as quantified by different material properties and different potentials. The left-hand side represents the storage [26]. The solution to the PDEs is represented by dependent variables (e.g. temperature fields, RH fields, or velocity fields) described in space and time along the independent variables x, y, z, and t [25].

Although mathematical models have a limitation in that analytical solutions can only be found in very special cases (such as in certain combinations of equations and simple geometries), modern numerical methods for solving PDEs can handle nonlinear problems as well as complicated geometries, by providing an approximation of the solution to a well-posed mathematical model. Put another way, discretisation of a mathematical model results in a numerical model for the described system [25]. The numerical methods commonly used for this discretisation are the finite element method, finite difference method, finite volume method, and boundary element method [27]. A numerical model is a discrete approximation of a mathematical model, and the difference between the solutions to the numerical and mathematical models is called the truncation error. The error approaches zero when the element size (determined by the mesh refinement) approaches zero, if the model is stable and consistent [25]. To obtain the solution to the PDEs (within a reasonable amount of time and computational costs) can be challenging, depending on the type of equations, number of independent variables, boundary, initial conditions, and other factors [25]. In particular, detailed 2D or 3D hygrothermal simulations of building components (e.g. a basement envelope part) over long-term periods are considered computationally expensive by consultants in the field of building science.

The commercially available tools WUFI® Pro and 2D (applying the PDEs described in Künzel [28]) is widely used by Nordic consultants and researchers to investigate the heat and moisture performance of building components. New heat and moisture models have also been developed in the last few years (e.g. Refs. [29–31]), that can be applied for complex geometries (up to 3D) using powerful commercial solvers such as COMSOL Multiphysics, Fluent®, or ANSYS-CFD. The drawback of advanced models, however, is that they require much knowledge/resources from the user to implement them in the solver. Another drawback of adopting these advanced solvers is that climate data, boundary conditions and material properties tailored to building physics (available through dedicated software like WUFI® or DELPHIN), are not predefined and need to be implemented in the solver.

Regardless of the physical/solver/tool chosen for a simulation, determining the exterior boundary conditions below grade (as illustrated in Figure 1) constitutes an even bigger challenge, since no recognised methods/procedures seem to exist for this purpose. Great uncertainty is also associated with the ground's variable composition and moisture content, among other factors. These uncertainties suggest that the boundary conditions for thermally insulated basement envelopes should be addressed through a best case/worst case approach, to account for the varying hygrothermal loads inflicted during summer and winter, and upper and lower parts of the basement envelope, in various climates. Addressing the conditions below grade also requires knowledge concerning the physical descriptions of heat and moisture transfer in soil and soil boundary conditions, which may differ from those normally used for building components.

3. Methodology

First, a scoping literature study was performed, targeting scientific research concerning hygrothermal simulations or measurements of thermally insulated basement envelopes. Second, ten comprehensive studies were subjected to scrutiny, and valuable experiences from their methodologies and results were identified. After completing the evaluation of the ten studies focusing on basement envelopes, an additional search was conducted, focusing on hygrothermal simulations of slabs-on-grade. Citation chaining was further used to identify comprehensive studies not caught by the initial searches. Two additional studies were selected and included in the results.

The method used in this scoping study is based on the framework described by Arksey and O'Malley [32] and involves a six-step procedure: 1) identifying the research question, 2) identifying relevant studies, 3) selecting studies, 4) charting data, 5) collating, summarising, and reporting the results, and 6) consultation. According to Arksey and O'Malley [32], multiple databases should be included in the search. In this study, Science Direct was selected as the main search engine for scientific papers and journal articles. Google Scholar was selected for complementary and broader searches (including results from additional scientific journals, scientific publications, and grey papers). The search terms (combinations of keywords) were carefully selected based on the main author's qualitative judgment and on experience from previous work. The search terms, search engines, and limitations are shown in

Appendix A for the initial search and Appendix B for the complementary search.

The initial search identified 22 studies relevant for the scope of this review. Several of these concerned the same research, the same method, or were conducted by the same authors. A thorough description of the selection process that determined the ten particularly interesting studies for further review is also included in Appendix A. The additional search identified two studies. The selected studies addressed hygrothermal simulations from somewhat different perspectives. To identify valuable experiences from these perspectives, each study was subjected to scrutiny. A challenge in this context is that these studies are typically more concerned with the outcome of the simulations, rather than the simulation methodology itself. As such, in some cases, the description of the methodology was deficient.

4. Results

4.1. General overview of the material

Ten particularly interesting studies focusing on basement envelopes were selected for detailed review. Because the ten studies vary in terms of scope and objectives, they are examined in detail to enable a thorough comparison of their approach. Four studies investigated the hygrothermal performance of basement walls, three studies investigated the heat and moisture transfer in the soil domain, and three studies mainly focused on the thermal performances of basements but considered the varying moisture content in the soil. Two studies focusing on slabs-on-grade were also selected for detailed review.

Table 1 summarizes the selected studies and their main methodologies. Detailed descriptions of the boundary conditions of the studies are too substantial to include in a simple manner in Table 1. Instead, this is described in the following chapters (4.2–4.5), along with the studies' purposes, methods, results, and physical measurements. It is chosen to recount the methodology of the studies with a high level of detail, so that the implications of the individual choices in their simulation methodology can be adequately understood.

4.2. Hygrothermal performance of basement walls

Only two of the four studies focusing on the hygrothermal performances of basement envelopes performed both hygrothermal measurements and hygrothermal simulations and compared the results (Goldberg & Harmon [33], Straube [34]). Both mainly concerned the hygrothermal performances of interior insulation systems for walls.

A comprehensive study was reported by Goldberg and Harmon [33], concerning the hygrothermal performance of retrofitted thermally insulated hollow masonry block foundations. Both hygrothermal measurements and simulations were performed. The objectives were to test different retrofit systems, and to develop long-term hygrothermal performance data for foundation walls in cold climates. The experimental work was conducted in Minnesota (2.5 year period). The test setup included five 'bays' with identical walls in the north and south directions. The walls had either interior insulation or exterior insulation on the upper half of the wall. Different backfill types and waterproofing membranes were investigated. The indoor temperatures were set to 20 °C in the heating season and 15.6 °C in the cooling season (no air conditioning). The climate data, below grade soil moisture content, and temperature profiles were thoroughly collected. The experimental data was used to investigate the validity of the hygrothermal simulation program 'WUFI®2D' and the 'Building Foundation Energy Transport Simulation' (BUFETS) program (3D). The authors found that WUFI®2D might not be capable of modelling soils directly, as it failed to yield a solution to the moisture transport equation. According to Goldberg and Harmon [33], WUFI®2D uses a single transport equation with RH as the transport variable for both water vapor and liquid water diffusion fluxes. Although this method is satisfactory for most building materials, it becomes problematic in the soil regions above the groundwater table, where the soil RH generally exceeds 99%, and where the dew point depression is less than 0.2 °C. It was not possible to resolve the problem with program developers but deactivating the bulk water capillary hydraulic conduction transport was a partially successful solution. Approximately 3 months of data were obtained before the simulation failed. A comparison of the measured and simulated heat flux data from BUFETS demonstrated that the experimental data were effective for evaluating the accuracy of thermal simulation programs. The agreements between the measured and simulated wall and soil temperatures were better in the heating season than in the cooling season, and the wall temperature discrepancies decreased with the height above the slab. The likely causes for the discrepancies (as recognised by the authors) were the BUFETSs inability to model buoyant cavity flow loops in hollow masonry block walls, and their inability to model a water table with a seasonally varying height and temperature. The absence of a soil moisture transport model (enabling the calculation of seasonally varying thermal conductivities as a function of soil moisture content) was also recognised as a possible cause. The simulated masonry block core RH profiles for the 3 months simulated by WUFI®2D were compared to those measured; however, a very substantial difference between the simulation and measurements was shown.

Another study comparing hygrothermal measurements and simulations was conducted by Straube [34]. Both field monitoring and 1D hygrothermal simulations were performed. The aim was to increase the understanding of the hygrothermal performances of concrete basement walls with different interior insulation systems. Four concrete test walls with different insulation and varying vapor control layers were monitored for 1 year. Spray-applied damp-proofing and a dimpled drainage mat were applied on the exterior side. The newly built basement was unfinished but heated (approximately 20 °C), and the construction moisture load remained significant. The wood moisture content, temperature, and RH sensors were located in groups at three different heights: near grade, in the middle, and at lower locations below grade. The soil temperature and moisture content were measured at three depths at two lateral locations. The temperature and RH were also measured indoors and outdoors. Hygrothermal 1D simulations were performed using WUFI®Pro for the near grade, middle, and lower locations of the four walls. The validation of the temperatures at the near-grade location (insulation–concrete interface) showed a lack of correspondence. Much lower temperatures were predicted as compared to the measurements, especially during winter. The deviations were far too large to be explained by wetness or compacted insulation, or a dryer concrete than that simulated. The measured soil temperatures were used to further investigate the deviations. It was likely that the heat flow to/from the soil affected the upper parts of the walls. Straube [34] concluded that the lack of temperature correlation in the above-grade simulation prevented full validation, and that a 1D simulation simplification was unfavourable. The below grade simulated temperatures had a better agreement with the measurements, probably owing to the lack of solar influence and slow temperature variations over time. The simulations and measurements of the RH in the middle of the insulation–concrete interface were compared. The RH levels were quite different, especially for low-permeance systems. Possible reasons for this deviation included air leakage, vapor diffusion, 'flanking,' or dryer concrete in the measurements than indicated by the simulations. All the RH values were high, however, and a cause for concern. Two other studies (Fedorik et al. [35] and Pallin [36]) investigated the hygrothermal performances of retrofitted basement walls using only hygrothermal simulations. Fedorik et al. [35] investigated the impacts of multiple refurbishment strategies for concrete basement wall designs from different decades. The main objective was to compare the thermal insulation performance, structural drying, and mould growth risk. The hygrothermal simulations were performed using 'DELPHIN' 5.8 and run for 5 years (the first 4 years were to achieve hygrothermal stability). The underground structure and soil, where the humidity was mainly 100%

Table 1
The studies selected for detailed review.

		Main focus	Simulations				Validation/ verification	Measurements					
			Hygrothermal	Only thermal	Component included	Exterior boundary condition below grade		T	RH	Moisture content	Precipitation	Other	Duration
Hygrothermal performance of basement walls, see Chapter 4.2	Goldberg & Harmon [33] USA (2015)	Hygrothermal performance of hollow masonry block foundation retrofit	WUFI®2D	BUFETS6 (2D)	Wall, floor and ground	From measurements	Yes	Interior, exterior, in wall, soil	Interior, exterior, in wall,	Soil, masonry block, wood	yes	Snow depth, solar radiation, wind, barometric pressure	1.5 years
	Straube [34] USA (2009)	Hygrothermal performance concrete walls with interior insulation systems	WUFI®Pro 4.0 (1D, 3 heights)		Walls	From measurements	Yes	Interior, exterior, in wall	Interior, exterior, in wall	Soil, wood	no		1 year
	Fedorik et al. [35] Finland (2019)	Hygrothermal performance of refurbishment strategies for old concrete basement walls	DELPHIN 5.8 2D and/or 1D?		Walls and ground separately	From fully coupled simulation of ground	No	Not addressed					
	Pallin [36] Sweden (2013)	Risk assessment of hygrothermal performance of a concrete wall retrofitted with exterior vapor permeable EPS	WUFI2D (+ Pro?)	WUFI®2D	Walls and ground	From thermal simulation of ground	No	Not addressed					
Heat and moisture transfer in the ground adjacent to basements, see Chapter 4.3	Pallin & Kehrer [37] Sweden & USA (2013)	Soil properties applicable for simulation and thermal behaviour of 20-m-deep soil column	WUFI®Pro		Ground		Yes	In air, soil		n.a.	?	?	4 years
	Janssen et al. [38] Belgium (2004)	Influence of soil moisture transfer on heat loss via the ground for insulated basements (wall + floor)	Program not specified. 2D+1D	Program not specified.1D	Ground		No	Not addressed					
	Deru [39] USA (2003)	Ground-coupled heat and moisture transfer from buildings. Insulated concrete basement (wall and floor)	GAHMT (2D)	GHT2D (2D)	Ground		Yes	In air, in soil					20 days
Thermal performance of basements, see Chapter 4.4	Saaly et al. [40] Canada (2020)	Annual energy loss from a concrete basement (walls +floor). Including freezing of soil and change in thermal properties.		COMSOL (3D+2D)	Walls + ground	n.a.	No			Soil (frozen /not frozen)			No

(continued on next page)

Table 1 (*continued*)

		Main focus	Simulations				Validation/ verification	Measurements					
			Hygrothermal	Only thermal	Component included	Exterior boundary condition below grade		T	RH	Moisture content	Precipitation	Other	Duration
	Swinton et al. [41] Canada (2006)	Thermal performance of insulated concrete basement walls	Not addressed					Interior, exterior, in wall, soil		Soil	√		
	Zoras [42] Greece (2009)	Building Earth-Contact Heat Transfer.		Refers to the work of others				Not addressed					
Hygrothermal performance of slabs-on-grade, see Chapter 4.5	Rantala & Leivo [43] Finland (2009)	Heat, air, and moisture control in slab-on-ground structures	Only steady-state 1D		Slab	100 % RH	No	Fill layer below slab		Fill layer below slab		Micro-biological conditions	Long-/short term
	Dos Santos & Mendes [44] Brazil (2006)	Heat and moisture transfer in soils combined with building simulation	Program not specified 3D		Ground, slab and building		No	Not addressed					

RH, were considered as problematic areas in the simulations. The computation slowed considerably when the moisture content achieved full saturation. The complex computational models required long computational time, and often lead to unstable convergence. The numerical models, geometries, meshes and the ground size included in the models was not fully described. The precipitation and capillary transport in the soil were, according to the article, taken into account, but the initial conditions, moisture content, and material properties of the soil were not described. Other material properties, including those of gravel, were stated. Direct rain leakage and air convection values were omitted. A Finnish guideline (RIL 107–2012) and Jokioinen 2004 test year were employed for the interior and exterior conditions, respectively. The ground surface boundary conditions were not described. The snow cover, freezing or thawing of soil, solar shading, and net movement of ground water below the building were omitted. As the thermal resistance of a basement structure directly affects the ground temperature distribution, each numerical model (each refurbishment strategy) was simulated in two phases. First, the temperature distribution throughout the entire geometry was simulated. Second, the ground area was excluded, and thermal boundary conditions were represented by the results from the first simulation (walls split into 9–10 sections with 400 mm height). The results confirmed previous research showing that exterior thermal insulation is the most robust solution for basement walls. The results also showed that if only interior insulation is applicable, using capillary-active materials is efficient for enabling inward drying (if a limited thickness is applied). The study concluded that refurbishment of basement walls should be analysed in detail. Pallin [36] described a hygrothermal risk assessment procedure. To show the procedure in practice, hygrothermal simulations were performed for a concrete basement wall. The main objective was to investigate the effect (s) of the outward drying, and how it was affected by different types of soil and indoor climates. The basement wall represents the target of a common retrofit approach, where permeable drainage and insulation boards are positioned on the exterior surface below grade and covered with landscape fabric. The previously removed ground material is used as backfill. In Pallin's study, hygrothermal simulations of a wall were performed in WUFI®2D for 12 different classified soil textures. One consecutive year was assumed to be sufficient for the comparison analyses. The concrete and soil were assumed to be water vapor saturated (100% RH). The climate of Gothenburg (Sweden) and a south-west direction were used, as solar radiation, increases the soil temperatures and reduces the drying potential. The basement was set to a constant temperature of 18 °C. The heat and moisture fluxes were studied at three depths from the ground surface. Temperature variations at the same depths were studied for both sides of the drainage/insulation board. The results showed that the soil temperatures varied significantly on a yearly basis, depending on the distance to the ground surface. The temperature variations at the studied depths were applied to determine the variations in the water vapor contents at the wall surface and in the soil. When the temperature of the soil was higher than the surface temperature of the wall, the moisture flux was turned inward. The deviations between the different soil textures were small. The variations in the heat flux between the 12 soil textures were higher, and deviated by approximately 10% depending on the soil type. The largest heat flux deviation was observed between silty clay and sand. The simulations showed that only small amounts of precipitation can penetrate the insulation/drainage board if the drying potential is positive. If more water penetrates, the drying potential will be equalised or reversed.

4.3. *Heat and moisture transfer in the soil adjacent to basements*

Three studies were found concerning heat and moisture transfer in the soil domain. Two of them performed numerical simulations and investigated the influences of precipitation and different types of soil on the heat loss from buildings. The third study investigated the implementation of precipitation in hygrothermal simulations of basements.

Janssen et al. [38] performed hygrothermal simulations of an insulated basement and the surrounding soil to investigate the influence of soil moisture transfer on building heat loss via the ground. A parameter study was conducted with varying climates, precipitation, soil types, thermal resistances of basement walls and floor, basement widths, and shapes of the foundation (ground floor). Completely coupled simulations (coupled equations for soil heat and moisture transfer and the full formulations of the surface heat and moisture balances) were compared with linear thermal simulations (moisture contents kept at their respective yearly averages from the coupled simulation, i.e. no moisture transfer was included; only thermal conduction). The fully coupled simulations were initialised with the matric head field and temperatures from a steady-state initial simulation and run at intervals of 10–15 years. Loam was used as a typical soil, and a bare soil surface was assumed. Climate data were obtained from the designed reference years of Essen (Germany). A water table was assumed to be present at the bottom of the soil domain, and thus saturation was imposed as a hygric boundary condition. Owing to the low velocities of the ground water flow, an adiabatic thermal boundary condition was applied. As both radiation and evaporation contribute to the surface heat balance, the external surface temperature, and not the air temperature, was used in the definitions of the thermal permeances. A finite element spatial discretisation and fully implicit time-stepping scheme were used to solve the transfer equations and boundary conditions. The Newton–Raphson algorithm was employed to improve the convergence of the iterative procedure (because the boundary conditions were highly nonlinear). A 'variable time step' algorithm was also used. The daily average climate was used, and did not notably affect the transfers of heat and moisture in the soil as compared to hourly data. The linear simulations were also compared to linear calculations using current European standard for heat loss via the ground [21]. The comparison of the fully coupled and linear heat losses showed that the coupled simulation (moisture transfer in the soil included) yielded higher heat losses. Janssen et al. [38] showed that the increase in heat loss could mainly be attributed to (1) the greater amplitude of the soil surface temperature's amplitude, (2) the variation of the thermal conductivity with moisture content and (3), the advection of sensible heat by liquid moisture transfer. The parameter study showed that neither basement width nor soil type significantly affected the influence of the coupling. However, it was observed that, despite the soil type differences in regard to hygrothermal properties, the transfers of heat and moisture in the different soils were similar. Ultimately, the hygrothermal behaviour of the soils was governed by the climate. This deduction was also confirmed from the significant effects of climate and precipitation on the difference in the linear/coupled heat loss. Janssen et al. [38] concluded that the increased heat loss difference between coupled and linear simulations cannot be regarded as insignificant, and that soil moisture transfer has an indisputable influence on building heat loss via the ground. Janssen et al. [38] also showed, by comparing the two linear simulations, that using the conservative values provided by the European standard [21] introduces far greater deviations than those owing to coupling phenomena, and that an accurate assessment of the thermal conductivity of the soil is therefore not feasible.

Deru [39] performed 2D simulations of a basement and the surrounding ground, with and without a rain event. The objective was to investigate the moisture transfer in the ground and its impact on building heat loss. Deru [39] developed programs called 'GHAMT' (for 2D heat and moisture transfer) and 'GHT2D' (for 2D heat conduction). The basement was simulated for summer and winter conditions, with and without insulation, and with different types of soil. Vegetation was assumed on the ground surface boundary. The boundary at the bottom was 10 °C, and saturated. Along the sides of the model, the heat and moisture fluxes were set as zero. The groundwater was modelled as a saturated boundary. To determine the initial temperature and moisture fields for the simulations, detailed pre-simulations were performed with varying weather conditions. Deru [39] showed that when rain was added during the summer conditions, the heat loss showed a jump, and then converged towards the dry case as the soil dried out. For the cases with winter conditions, very little change was shown when rain was added to the surface. The contour plots of the soil volumetric moisture content in the ground for the uninsulated basement summer cases showed that the moisture distribution in the soil was affected very little by the presence of the basement, for all of the simulated summer cases. According to Deru [39] this demonstrated that it might be possible to approximate the change in the soil moisture content with depth around a building by using a 1D column of soil (which is much easier to simulate). Hence, a heat transfer program could be used, which is much faster (including only the variation in thermal conductivity with depth). A simple freezing model was used in the simulations; however, according to Deru [39] the soil thermal conductivity and moisture behaviour could be significantly affected by freezing. If cyclic freezing and thawing occurred, the various types of ice formation and complex soil moisture behaviours at the freezing front would require a more detailed model. A comparison of GHAMT and GHT2D showed that GHT2D should consider the variation of the soil thermal conductivity with depth, and accurately model the ground-surface boundary condition (including the effects of evapotranspiration). Deru [39] suggested a simple method for modelling the variation in the soil, with at least two values for the soil thermal conductivity with depth, to account for the higher soil moisture content below the top of the soil. According to Deru [39], the evapotranspiration at the ground surface could have a large impact on the calculated heat transfer from the basement walls, and the results should be bracketed between the potential value and zero (unless there is knowledge of the exact level of evapotranspiration). According to Deru [39] a soil thermal conductivity value is usually chosen with very little knowledge of the soil type and moisture content, despite its large impact on the hygrothermal properties of the soil (e.g., the thermal conductivity can change by a factor of ten with the moisture content).

Pallin and Kehrer [37] defined properties for 12 classified types of soil and aimed at evaluating the heat and moisture performance of different basement assembly types in several climate zones. However, they found that the applied assumptions typically used in hygrothermal tools for the implementation of precipitation are inadequate. The precipitation typically functions as a boundary condition; thus, the moisture load initially only affects the grid element closest to the border. If the element is saturated, the moisture buffering capacity (and hence, the surplus of moisture) is neglected. Although this assumption might be applicable for a vertical wall with drainage, it is not applicable at the soil surface, where most of the precipitation will be absorbed eventually. Pallin and Kehrer [37] investigated how the amount of precipitation neglected during the simulations could be decreased. A 20-m deep 1D soil column was simulated in WUFI®Pro and compared to soil temperatures measured hourly at two depths. The precipitation in this model was distributed directly into the first four elements as an impregnated source. A rather good agreement was shown when comparing the simulated and measured temperatures at a depth of 1 m. According to Pallin and Kehrer [37] the simulations required the following improvements: (1) better account for the liquid uptake of precipitation on the soil surface, (2) address the moisture transfer at the lower boundary (the infinite ground), (3) provide a better heat-transfer coefficient at the soil surface (which varies with a number of factors), and (4) address snow cover (and its effect on the surface thermal resistance and long- and short-wave radiation).

4.4. *Thermal performance of basements*

Three studies mainly focused on the heat loss from basements. The first study investigated how including freeze-thaw cycles in the soil affected the heat loss. The second investigated the in situ thermal performance of basement walls and effects from weather extremes. The third reviewed different methods for predicting heat transfer in the ground adjacent to buildings.

Saaly et al. [40] performed thermal simulations (2D + 3D) to investigate the effects of freeze-thaw cycles (pore water phase changes) on the heat transfer of a concrete basement in a severely cold climate (frost depth of approximately 2.5 m). Both frozen and unfrozen soil samples, from several depths and locations on site, were analysed to determine the variability and soil thermal properties. Different thermal insulation scenarios and the use of draining backfilling materials were investigated. COMSOL Multiphysics was used; the simulation models included a large part of the adjacent soil and the simulations were run for one year. Constant average soil thermal properties was compared to variable thermal properties (soil assumed to be homogeneous, isotropic, and incompressible). The initial temperatures were all uniform. The thermal properties of the concrete and insulation were considered as constant. The soil thermal properties varied as the temperature dropped below the freezing temperature; hence, the thermal soil properties depended on the latent heat of fusion and the fractions of water and ice in the soil pores. To include this numerically, the soil was assumed to be fully saturated. The frost heave was assumed to be negligible, and only heat transfer by conduction was included in the soil. The uninsulated basement showed an approximately 34% higher energy loss when phase change in the soil was included. Without including freezing, the overall energy efficiency of the basement increased by approximately 51% as insulation were applied. This enhancement increased to 60% once freezing in the soil was included. The results also showed an approximately 22% higher heat flux as predicted by the 2D model relative to that predicted by the 3D model. The layer of backfill materials surrounding the basement walls decreased the basement heat loss by 16.5%.

Swinton et al. [41] investigated the in situ thermal performance of two concrete basement walls, insulated with exterior spray polyurethane foam (SPF) over the full height and exposed to the climate of Ottawa (Canada) for 2.5 years. Specimens with horizontal z-bars (soil sloped towards the wall) were compared to specimens with z-bars fastened vertically (soil sloped away from the wall). Both specimens were in direct contact with the soil below grade. The boundary conditions were recorded, including observations of weather extremes. Measurements were performed in the soil and on the surface. The soil temperatures and moisture content were recorded, and four separate soil analyses were performed to characterise the soil environment; however, the results were not further described in the study. The differences in the observed thermal performances of the specimens were qualified with information from monitoring. The results showed that the thermal performance was relatively steady, with an equal or improved performance during the second heating season. The thermal performance did not appear to be significantly affected by major rain and thaw periods. The system with horizontal z-bars yielded consistently superior thermal performance compared to the system with vertical z-bars. The results also showed that periodic temperature deflection ‘spikes’ occur, corresponding to periods with heavy precipitation or winter thaw events. In summer, the temperature profile at the insulation/soil interface deflected upwards, owing to warm rainwater moving down. In winter, the deflections were downward, because the melt water temperature was initially 0 °C, and thus cooled the soil and insulation at the interface.

Zoras [42] reviewed methods for predicting heat transfer in earth-coupled structures and divided them into four categories: analytical/semi-analytical methods, numerical methods, manual methods, and design guides. According to Zoras [42], analytical methods provide far more accurate results; however, solutions are restricted to linear heat conduction (e.g. dry soil) and simple geometries. Manual methods and design guides, in contrast, suffer from simplicity and empirical inefficiencies. Numerical simulations can be performed using robust coupled tools, however, the lack of initial conditions for the underground domain causes inefficiencies, owing to the inevitable multi-year simulations needed to approximate realistic soil temperature fields. Zoras [42] briefly addressed an idea for future work. It involved being able combine an unconditionally stable implicit scheme, generally fast explicit scheme, and flexible variable time-stepping scheme. This combination could be implemented for all finite volume-based numerical models. For most of the above-mentioned methods to be implemented, the unique entities defined therein must be described by linear equations. In particular, the variation in conductivity owing to temperature changes is a very important issue, as it is a non-linear phenomenon. During numerical simulations, this can only be handled with iterative processes (extremely time consuming, especially for simulations over long periods). According to Zoras [42], it is possible, through the application of Kirchhoff’s transform, to remove the non-linearity of the variable conductivity owing to temperature fluctuations, i.e. to convert the non-linear effects into linear effects. The actual solution had previously been integrated into a finite element formulation for non-linear heat conduction. Combined with superposition methods, this particular transformation could be advantageous, e.g. it could lead to fast simulations where non-linear phenomena would be considered. The study concludes that a future fully complete tool must consider the variable conductivity, heat and moisture coupling, changes of phase, snow cover, convection, and evaporation at the earth’s surface. The study refers specifically to the very comprehensive review concerning the handling of soil water content by Rees et al. [45], and Krarti’s method [46] for addressing convection and evaporation at the earth’s surface.

4.5. Hygrothermal performance of slabs-on-grade

Two studies concerned the hygrothermal performance or simulation of slabs-on-grade. The first investigated the relative humidity in the drainage layers below slabs and the second integrated a coupled three-dimensional heat and moisture transfer model of the ground beneath a slab to a single-zone building model.

Rantala & Leivo [43] measured the moisture content, the thermal conditions and the microbiological conditions in the coarse-grained fill or drainage layers beneath slabs. Long-term field tests were performed on new buildings and a series of short-term in situ surveys were performed on already established buildings. The water content of fill layers (samples from 33 different buildings) was determined at the fill/slab interface using the weighing–drying–weighing method. Different types of slabs, both with and without insulation, were included. 49 soil samples, taken beneath the ground slabs, were cultured in the laboratory so the microbe content could be studied. The objective of the study was to increase the knowledge of the boundary conditions at the slab-fill interface and to determine the conditions during the lifespan of seasonally heated buildings. Results showed that the measured water contents were, in almost every single case, higher than the hygroscopic equilibrium moisture content of the material in high RH (RH $\approx$ 100% $\leftrightarrow$ w$<$0.5% by weight). The samples were considered to be at the annual minimum because they were taken in late winter/early spring (while there is still heavy frost on ground surface and the groundwater table is at its lowest). Temperature measurements showed that, despite the significant variation in the outdoor air temperature, the temperature in fill layers at the central part of the slabs was relatively warm throughout the year. Fungal or bacterial growth was detected in 98% of the test specimens. Bacteria were detected in all age groups of the buildings and in the oldest structures. Some of the concentrations were extremely high. According to Rantala & Leivo [43], the high microbe concentration in the fill layer is a normal boundary condition related to the existing thermal and moisture conditions of the layers, and is not a sign of moisture damage. Rantala & Leivo [43] also investigated the hygrothermal performance of slab-on-ground structures theoretically under steady-state conditions. Two different floor structures of in situ cast concrete were investigated with varying combinations of thermal and moisture parameters of the structural materials and changing surrounding conditions. Humidity values at the slab/floor-covering interface was compared as the RH of the lower surface of the floor covering is usually critical for the behaviour of the structure. Results showed that the importance of the water vapor resistance properties of the floor covering material was significant to the overall hygrothermal performance of the structure and that the thermal insulation should be placed mainly or entirely underneath the slab.

Dos Santos & Mendes [44] present a coupled three-dimensional heat and moisture transfer model of the ground beneath a slab which is integrated to a single-zone building model. One objective of the study was to investigate how important moisture in soil can be in different scenarios, taking a coupled three-dimensional effect in to account. A concrete floor was considered, but no moisture barrier or insulation were included in the floor. Solar radiation and rain were considered. The exterior climate was represented by sinusoidal functions from Curitiba in Brazil and the annual average temperature was set to 20 °C. The governing equations used for the heat and moisture transfer in the soil was based on the theory of Philip and De Vries. Sandy silt soil and sand with properties strongly affected by temperature and moisture content were used in the study. According to Dos Santos & Mendes [44], the simulation time step, the grid refinement, the pre-simulation time period, the size of the physical domain, the boundary conditions, the convergence errors and the required computer run time, have to be chosen carefully in order to accurately predict temperature and moisture content profiles in soils under different weather data. A sensitivity analysis showed that the grid size had to be refined at the upper surface which is in contact with the air. It also showed that the results were less sensitive to the time step due to the robust algorithm used and due to the linearization of vapor concentration difference at soil top surface.

5. Discussion

This article has examined three research questions, the answers to which will be discussed in the following sections:

5.1. *Hygrothermal simulations of thermally insulated basement envelopes in existing literature*

Only four individual studies identified in this review —Goldberg and Harmon [33], Straube [34], Fedorik et al. [35] and Pallin [36]—actually addressed hygrothermal simulations of basement envelopes. Different approaches were used by these authors to define the boundary conditions below grade. Pallin [36] simplified the soil domain by assuming fully saturated soil, and used a corresponding constant thermal conductivity for the entire ground. The walls and soil were simulated first to determine the annual temperature variations on the exterior sides of the walls; this information was used to investigate the hygrothermal performance of the walls. This was the same two-step approach used in Ref. [22]. Using an average 'conservative' thermal conductivity for soil are also proposed in the current European standard for modelling heat loss from buildings through the ground [21]. Although this simplification might be sufficient to appropriately estimate heat loss, it might not be sufficient for investigations of hygrothermal performance. Fedorik et al. [35] used the same two-step approach, but additionally included the effects of rain and capillary transport in the soil. According to Fedorik et al. [35] they illustrated that hygrothermal simulations of fully saturated underground structures and soil can be performed using the commercially available program DELPHIN 5.8, however, the complex computational models required long computational time, and often lead to unstable convergence. The study also lacked a thorough description of the numerical method(s) and inputs used. Straube [34] performed 1D hygrothermal simulations of basement walls at three different height locations, using measured temperature variations and assuming 100% RH for the wall's exterior boundary conditions below grade. However, the simulations were not successful for parts of the walls near the ground surface. Goldberg and Harmon [33] attempted to perform 2D hygrothermal simulations for basement walls and the surrounding soil. They divided the soil into three domains with different thermal properties to account for the different soil types and measured moisture contents. Unfortunately, they found that WUFI®2D failed to yield a solution to the moisture transport equation.

The remaining studies mainly focused on the thermal performances of basements; nevertheless, the methods used are highly relevant, because they address the soil moisture content and/or moisture transfer. Deru [39] and Janssen et al. [38] investigated the impact from soil moisture transfer on the heat loss from basements. According to Deru [39], the thermal conductivity of the soil can change by a factor of ten with the moisture content, and is the most important parameter in determining the ground-coupled heat transfer. Deru [39] proposed that a 1D column of soil (which is much easier to simulate) might be used to approximate/pre-simulate the changes in the soil moisture content, and thus the thermal conductivity with depth around a building. Janssen et al. [38] further investigated the differences between completely coupled heat and moisture simulations with linear thermal simulations and found that soil moisture transfer has an indisputable influence on heat loss. Janssen et al. [38] showed that, despite the soil type differences in regards to hygrothermal properties, the transfers of heat and moisture in the different soils were similar and ultimately governed by the different climates. The foundation width was shown to be of lesser importance. Due to the inaccuracy of determining actual soil properties, however, Janssen et al. [38] concluded that using the conservative values provided by the European standard [21] introduces far greater deviations than those introduced owing to coupling phenomena. The basement in the study of Janssen et al. [38] had a thermal transmittance of 0,7 W/m^2. Janssen [47] investigated the difference between coupled and linear simulations for basements with different thermal transmittances (0.35, 0.7 and 5.4 W/m^2) and showed that the difference increased with less insulation, i.e. the difference in heating season heat losses were 8.9, 10.1 and 13.6% respectively.

The experiences from Goldberg and Harmon [35], Fedorik et al. [35], and Pallin and Kehrer [37], show that WUFI®2D and DELPHIN 5.8 might not be optimal to use for the coupled heat and moisture transfer in the soil. These tools are tailored for porous building materials, assemblies and building envelopes. In WUFI® precipitation (in the form of driving rain) can be included as a boundary condition inflicting a source of moisture for the exterior surface to draw from during rain events and then further redistributed in the component. The liquid transfer by gravity (and transfer of sensible heat) is not included. For both DELPHIN 5.8 and WUFI®, the high moisture contents in the soil and the fine mesh refinement required was challenging numerically, i.e. required long computational time, often leading to unstable convergence or failing to yield a solution to the moisture transport equation. According to Zoras [42], future fully completed tool should address variable conductivity, heat and moisture coupling, changes of phase, snow cover, convection, and evaporation at the earth's surface. Zoras [42] points out that numerical simulations of earth-coupled structures suffers from inefficiencies, owing to the inevitable multi-year simulations needed to approximate realistic soil temperature fields as initial conditions for the soil/ground domain. This is also experienced by Janssen et al. [38], when performing two-dimensional fully coupled simulations of the soil adjacent to a basement, using the equations derived in Milly [48]. They experienced that very small time steps were necessary, at the onset of a rain event, to adequately simulate the absorption and the drainage of the precipitation. The large simulation domains, the rather difficult transfer equations and boundary conditions, and the long simulation intervals needed to reach the steady-periodical solution, made computational efficiency an essential concern. To considerably accelerate the convergence towards a steady-periodical solution, the two-dimensional simulations were initialised with temperature and matric head fields, from a steady-state initialisation run. From there, a 10–15 year of simulation was needed to attain a steady-periodical state. The effect of including freeze-thaw cycles in the soil were not addressed by Janssen [38], but might be important to consider in colder climates. Saaly et al. [38] performed thermal simulations in COMSOL Multiphysics and included freeze–thaw cycles in the soil by using a thermal conductivity which varied as temperature dropped below zero. Although the freezing model used was simplified, the study illustrates how a basement wall and floor and the large part of the adjacent ground, can be simulated, in both two and three dimensions, including a varying thermal conductivity for the soil domain.

5.2. Verification with measurements

Goldberg and Harmon [38] and Straube [34] are the only two studies that have attempted to verify hygrothermal simulations of basement walls using measurements. Pallin and Kehrer [37] and Deru [39] verified the heat and moisture transfer in soil by comparing hygrothermal simulations with measured temperatures only.

In Goldberg and Harmon [38] the agreements between the measured and simulated wall and soil temperatures were better in the heating season than in the cooling season, and the wall temperature discrepancies decreased with the height above the slab. The likely causes for the discrepancies recognised by the authors were the inability of BUFETS to model the buoyant cavity flow loops in the hollow masonry block walls, and its inability to model a water table with a seasonally varying height and temperature. They also recognised the absence of a soil moisture transport model (enabling the calculation of seasonally varying thermal conductivities as a function of soil moisture content) as a possible cause. Perhaps a better correspondence between measurements and simulations could have been achieved if concrete had been used in the experiment instead of the hollow masonry block walls, or if the soil had been simulated separately using the methodology adapted in Janssen [38].

For Straube [34] the simulation at the near-grade location yielded a lack of correspondence with the measurements. It was considered likely that heat flow to/from the soil affects the above-grade part of the wall, and that a 1D simulation simplification is not favourable when considering basement walls. In contrast, 2D hygrothermal simulations of the concrete basement walls, such as those performed by Fedorik et al. [35], might have yielded a better correspondence with the measurements.

Pallin and Kehrer [37] simulated a 1D soil column using WUFI®Pro and compared the results with soil temperatures measured hourly at two depths. The results showed a rather good agreement when comparing the ground temperatures from measurements and those from simulation at a depth of 1 m, but improvements to the simulation model were required.

Deru [39] compared the simulations of a soil column to measured soil temperatures. Unfortunately, moisture data that would have provided a more decisive validation were not measured. The comparison showed the sensitivity of the results at the surface to atmospheric conditions. Short-term variations in the atmospheric conditions were shown to have little effect on the predicted soil temperatures below 0.2 m, but small inaccuracies at the surface were shown to potentially cause the predictions to slowly diverge from the actual behaviour for simulations longer than a few weeks. For simulations without precipitation, the results at all depths slowly diverged from the measured data, owing to the slow drying of the soil. Deru [39] also noted that the presence of persistent snow cover and ground shading could also substantially affect the results.

5.3. Exterior boundary conditions below grade for thermally insulated basement envelopes

This review has provided an overview of the state-of-the-art hygrothermal simulation methods applied to basement envelopes. The following valuable experiences have been identified:

1. 1D simulations of basement walls, at three different wall heights, showed a lack of correspondence with measurements. The near grade location exhibited the largest deviations (Straube [34]).
2. Including the soil moisture transfer in the ground (fully coupled 2D simulations) increases the heat loss (Janssen et al. [38] and Deru [39]).
3. The difference between coupled and linear simulations of heat loss were mainly attributed to (1) the greater amplitude of the soil surface temperature's amplitude, (2) the variation of the thermal conductivity with moisture content and (3), the advection of sensible heat by liquid moisture transfer (Janssen et al. [38]). The difference increases with less insulation (Janssen [47]).
4. The high moisture content in the soil domain is considered problematic using the 2D hygrothermal simulation tool WUFI®2D (Goldberg & Harmon [33]), and often leads to unstable convergence using DELPHIN 5.8 (Fedorik et al. [35]).
5. Using daily average climate data did not notably affect the transfers of heat and moisture in the soil compared to hourly data (Janssen et al. [38]).
6. Hygrothermal boundary conditions for basement envelopes below grade should account for the following:
   - advection of sensible heat by liquid moisture transfer (Janssen et al. [49]), Straube [34];
   - liquid uptake of precipitation on the soil surface (Pallin & Kehrer [38]);
   - moisture transfer at the lower boundary (infinite ground) (Pallin & Kehrer [38]);
   - heat and moisture coupling (Janssen et al. [38] and Deru [39]);
   - convection and evaporation at the earth's surface (Pallin & Kehrer [38]) (Zoras et al. [42]);
   - changes of phase owing to freezing (Zoras et al. [42]) Deru [39] (Saaly et al. [40]);
   - snow cover (Pallin & Kehrer [38]; Zoras et al. [42]).
   - address the inefficiencies associated with the inevitable multi-year simulations needed to approximate realistic initial conditions (soil temperature and moisture fields) (Zoras et al. [42], Dos Santo & Mendes [44]).
7. High RH (RH ≈ 100% ↔ w<0.5% by weight) has been measured in drainage layers below slabs (Rantala & Leivo [43])
8. Solar radiation should not be neglected when considering the drying-out capacity of the basement walls, as solar radiation can cause inwards moisture transfer (Pallin [36]).
9. COMSOL Multiphysics can be used for three dimensional simulations of heat transfer from a basement including a variable thermal conductivity for the soil (Saaly et al. [40]).
10. The hygrothermal properties for 12 different soil textures were defined (Pallin & Kehrer [38]).

Adequately determining the exterior boundary conditions below grade for basement envelopes is challenging because the conditions vary along with the height below grade and depends on several varying factors (e.g. the soils' composition, varying moisture content and hygrothermal properties, the thermal resistance of the envelope, the indoor temperature and exterior climate factors). The boundary conditions may be determined from simulations of the adjacent ground together with the basement envelope (or its thermal resistance). This can be done in several ways: (1) the approach used by Janssen et al. [38] including fully coupled heat and moisture transfer simulations for the soil, (2) using only thermal simulations but accounting for varying moisture content or freezing etc. through a variable thermal conductivity like Sally et al. [40], or (3) using only thermal simulations and simplifying the soil domain by assuming a constant thermal conductivity for the soil like Geving et al. [22].

Using the approach by Janssen et al. [38] requires much knowledge from the user, numerous parameters (sometimes unknown), and is considered time consuming due to the inevitable multi-year simulations needed to approximate realistic initial conditions (soil temperature and moisture fields). Using the approach by Saaly et al. [40] or Geving et al. [22] constitutes a more manageable approach in terms of computational costs. However, Janssen et al. [38] showed that the coupled simulations resulted in an increase in heat loss compared to the linear simulations, and that this difference increased as the thermal resistance of the envelope decreased (with less insulation). Janssen et al. [38] also showed that, despite the soil type differences in regards to hygrothermal properties, the transfers of heat and moisture in the different soils were similar and ultimately governed by the different climates. Specifically, the increase in heat loss could mainly be attributed to (1) the greater amplitude of the soil surface temperature's amplitude, (2) the variation of the thermal conductivity with moisture content, and (3) the advection of sensible heat by liquid moisture transfer. However, based on current literature, it is not possible to determine the importance of the coupled simulation for the hygrothermal performance of thermally insulated basement envelopes and whether this effect should be accounted for in the determination of below grade boundary conditions. Hence, further research should focus the impact of including coupled simulations and other varying influencing factors on the hygrothermal performance of thermally insulated basement envelopes, to investigate how the boundary conditions below grade should be determined. Finally, experiences from this review indicate that DELPHIN or a more advanced multiphysics tools (e.g. COMSOL Multiphysics), might be favoured for future research on boundary conditions below grade. Advanced tools provide powerful solvers to reduce computational costs and more flexibility to implement the required physics (e.g. liquid transfer of precipitation by gravity), but require more knowledge and resources from the user for the implementation.

6. Concluding remarks

In cold climate countries, basements are often used as a habitable part of dwellings, representing a major challenge concerning moisture safety design. Assessing the suitability of a basement envelope design or a refurbishment strategy (e.g. ability to dry out), therefore requires an understanding of the heat and moisture transfer within the structures and how it is affected by the exterior boundary conditions and their seasonal variation, both above and below grade. This literature review illustrates the inadequacy of existing hygrothermal simulation tools to replicate actual hygrothermal conditions in basement envelopes and shows the lack of thorough validation of hygrothermal simulations using full-scale measurements. A range of factors seems to affect the exterior boundary conditions, however, no research seems to have been focusing on the relative impact of these various factors on the hygrothermal performance of thermally insulated basement envelopes.

Predefined climate data (e.g., moisture design reference years) can be chosen for the exterior boundary conditions above grade, in the dedicated commercial hygrothermal tools commonly used by consultants and researchers (e.g., WUFI®2D or DELPHIN 5.8). Such predefined boundary conditions should also be made available for the below grade part of buildings, and applicable for different thermal resistances, height below grade, soil types, and climates. The review shows that there is a need for a recognised method/procedure to determine the exterior hygrothermal boundary conditions below grade for basement envelopes without extensive computational effort. Future work aims at improving the hygrothermal simulations for thermally insulated basements by addressing this general deficiency.

Increased knowledge and improved hygrothermal prediction tools can contribute to further improving the durability and energy efficiency of basement envelopes. Moreover, there are significant potential economical savings related to avoiding or delaying expensive repairs on building parts below grade.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Identification and selection of studies for detailed review

A scoping literature study, focusing hygrothermal simulations or measurements of thermally insulated basement envelopes, was performed between January and February 2020. The large number of results provided by the search engines required the development of a manageable strategy for the selection of relevant studies. The selection process was conducted in three steps, as shown in Table A.1. First, a large number of results were sorted by relevance in the search engines. Second, the displayed results were reviewed, and articles were judged by the title alone. Articles clearly not concerning basements were excluded, and articles that might concern basements were selected. In most of the searches, the selected articles were found within the first 30–50 displayed results. Based on a judgment made by the author, reviewing the first 100 displayed results was sufficient, if the last 30 results were not relevant. In one of the searches, articles were still relevant for selection after the first 100 displayed results. In this case, reading through the first 200 displayed results was considered sufficient. Third, the selected articles were more thoroughly examined, and studies not concerning basements were excluded. In total, 85 studies were identified from a review of the titles and 39 of them were relevant to the hygrothermal performances of basement envelopes. Of these, 22 studies of particular interest were selected according to the following criteria: (1) they concerned hygrothermal simulations of walls and/or floors in basements and/or the adjacent ground/soil, or (2) they included measurements of temperatures, RH, or moisture content in basement walls and/or floors and/or adjacent ground that could be used for validation purposes.

Table A.1
Identification of relevant studies and selection of studies for detailed review.

Search engine/ date of search	Search terms:	Limitations in Search engine	Selecting relevant studies (3 steps)			Particularly interesting	Selected for review
			Results (sorted by relevance)	From review of the title	Actually concerning basements		
Science Direct	building AND moisture AND hygrothermal AND simulation AND (basement OR foundation	Limited to research and review articles	183	13	5	Includes hygrothermal simulations or	Of the 22 identified studies, several were related to the same research or written by

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Table A.1 (*continued*)

Search engine/ date of search	Search terms:	Limitations in Search engine	Selecting relevant studies (3 steps)			Particularly interesting	Selected for review
			Results (sorted by relevance)	From review of the title	Actually concerning basements		
(January 2020)	OR below grade) Should have been: 'below grade' (138)					measurements of basements.	the same author, se Table B.2.
Google scholar (January 2020)	building AND moisture AND hygrothermal AND simulation AND (basement OR foundation OR 'below grade')	Patents and quotes not included	3150	1 (to wide)	1	From Science Direct: 5 (+2 unavailable) From Google Scholar: 15 (+6 unavailable)	Only the 10 newest and most comprehensive were selected for a detailed review and referred to under results.
	hygrothermal AND simulation AND (basement OR below grade)	Patents and quotes not included	1890	1 (to wide)	1		
	building AND hygrothermal AND simulation AND basement	Patents and quotes not included	841	24 (review of the first 100 results.)	15 relevant (+3 already referred to in previous search)		
Science Direct (February 2020)	building AND moisture AND measurement AND basement	Limited to research and review articles	1293	9 (review of the first 100 results.)	5 (+4 already referred to in previous search)		
Google scholar (February 2020)	building AND moisture AND measurement AND basement	Patents and quotes not included	32 700	37 (review of the first 200 results.)	12 relevant (+8 already referred to, 6 unavailable, 9 less relevant, 2 not relevant)		
Total:			40 057	85	**39**	**22**	**10**

Majority of the 22 studies were from the USA (9) and Canada (7) (see Figure A.1). The study publication dates ranged from 1999 to 2020. The main purposes of the studies varied, e.g. some investigated hygrothermal performances of different designs, some mainly concerned the numerical simulations of heat and moisture transfer, some focused on hygrothermal properties of the ground, whereas others mainly concerned the thermal performances of the walls or energy loss of the basement. A detailed examination of the 22 particularly interesting studies revealed that several of them were related, either to the same research or to the same authors. Through a sorting process, involving a detailed examination of the studies, 10 of the newest or most comprehensive studies were selected for further review and subjected to scrutiny. A complete overview of the 22 interesting studies and the 10 selected for review is shown in Table A.2. The overall scientific legitimacy of each article and its origin were considered continuously throughout the selection process.

Table A.2
Overview of particular interesting studies identified and selection of the 10 included in results.

Country	Organisation/ University	Year	Author(s) &Title	Included in results	
Finland	University of Oulu and Tampere University	2019	**Fedorik, Heiskanen, Laukkarinen & Vinha** [35] *Impacts of multiple refurbishment strategies on hygrothermal behaviour of basement walls*	X	
Canada	University of Manitoba	2020	**Saaly, Bobko, Maghoul, Kavgic & Holländer** [38] *Energy performance of below-grade envelope of an institutional building in cold regions*	X	
	NRC	2011	**Saber, Maref & Swinton** [50] *Thermal response of basement wall systems with low emissivity material and furred airspace*		**Related**
		2010	**Saber & Swinton** [51] *Determining through numerical modeling the effective thermal resistance of a foundation wall system with low emissivity materials and furred - airspace* (much the same as Saber, Maref & Swinton 2011)		
		2006	**Swinton, Maref, Bomberg, Kumaran & Normandin** [41] *In situ performance evaluation of spray polyurethane foam in the exterior insulation basement system (EIBS)*	X	**Related**
		2001	**Maref, Swinton, Kumaran, Bomberg** [52] *Three-dimensional analysis of thermal resistance of exterior basement insulation systems (EIBS)*		
		1999	**Swinton, Bomberg, Kumaran, Normandin & Maref** [53] *Performance of Thermal Insulation on the Exterior of Basement Walls*		
	University of Waterloo	2007	**Uneo** [54] *Hygrothermal Behavior of Interior Basement Insulation*		**Related**
USA	Building Science Cooperation	2009	**Straube** [34] *Field Monitoring and Hygrothermal Modeling of Interior Basement Insulation Systems* (Measurements performed in Kitchener, Ontario, Canada.)	X	
		2010	**Smegal & Straube** [55] *Building America Special Research Project: High-R Foundations Case Study Analysis*		
Sweden /USA	Chalmers University of Technology & USA, Oak Ridge National Laboratory	2012	**Pallin & Kehrer** [38] *Hygrothermal simulations of foundations: Part 1: Soil material properties*	X	**Related**
USA	Minnesota	2012	**Kehrer, Pallin**, Harmon & Goldberg [56] *Hygrothermal simulation of foundations part 1, Soil Material Properties*		
		2015	**Goldberg & Harmon** [33] *Cold Climate Foundation Retrofit Experimental Hygrothermal Performance: Cloquet Residential Research Facility Laboratory Results*	X	
		2013	**Goldberg & Steigauf** [57] *Cold Climate Foundation Retrofit Energy Savings: The Simulated Energy and Experimental Hygrothermal Performance of Cold Climate Foundation Wall Insulation Retrofit Measures— Phase I, Energy Simulation*		**Related**
		2015			

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Table A.2 (*continued*)

Country	Organisation/ University	Year	Author(s) &Title	Included in results
			Harmon (Advisor: Goldberg & Huelman) [58] *The Hygrothermal Performance of Cold Climate Basement Walls Retrofitted with Insulation and a Water Separation Plane* (Much of the same as in (Goldberg & Harmon 2015)	
	Colorado	2003	**Deru** [39] *Model for Ground-Coupled Heat and Moisture Transfer from Buildings*	X
	University of Washington	2007	**Emry, Heerwagen, Klippenhan & Steel** [59] *Measured and Predicted Thermal Performance of a Residential Basement*	
Sweden	Chalmers	2013	**Pallin** [36] *Risk Assessment of Hygrothermal Performance - Building Envelope Retrofit* (Pallin has cooperated with USA, Kehrer)	X
Belgium	Catholic University of Leuven	2004	**Janssen, Charmeliet & Hens** [38] *The influence of soil moisture transfer on building heat loss via the ground*	X **Related**
		2002	**Janssen, Charmeliet & Hens** [49] *The Influence of Soil Moisture in the Unsaturated Zone on the Heat Loss from Buildings via the Ground*	
Greece	Democritus University of Thrace	2009	**Zoras** [42] *A Review of Building Earth-Contact Heat Transfer*	X

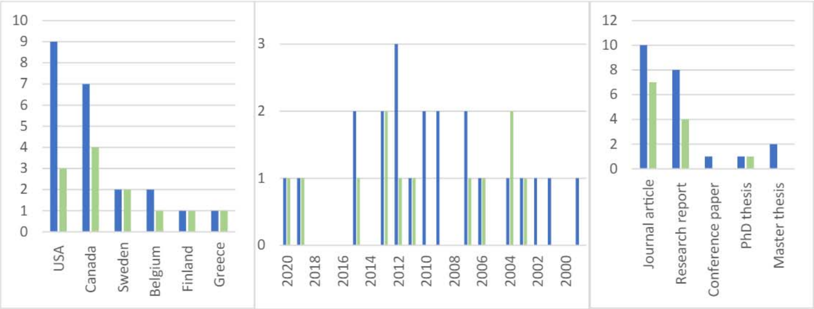

Fig. A.1. The 22 identified studies (blue) and 12 selected for further review (green) divided by country (left), year of publication (middle) and type of study (right).

Several limitations to the analysis have to be acknowledged:

- Including other search terms and additional search engines might have resulted in additional studies relevant to the scope of the study.
- The selection of relevant studies and identification of studies of particular interest are based on the main authors' subjective judgment.
- Several relevant studies might have been identified by performing citation chaining.
- The search was limited to research and review articles available online.

Although these limitations might have some bearing on the main outcome, their influence does not seem sufficient to significantly undermine the main conclusions presented in this article.

Appendix B. Identification and selection of studies focusing slabs-on-grade

An additional scoping literature study, focusing hygrothermal simulations of slabs-on-grade, was performed April 2021. The strategy for the selection of relevant studies was the same as for the initial search described in Appendix A, see Table B.1. First, 30 studies were selected from the review of the titles. Secondly, the studies were reviewed, and 17 particularly interesting studies were selected according to the following criteria: (1) they addressed hygrothermal simulations of slabs-on-grade, or (2) they covered three-dimensional effects related to heat loss from slabs to the ground. The 15 studies were reviewed and the two most relevant studies were selected for further review and subjected to scrutiny.

Table B.1
Identification of relevant studies and selection for review

Search engine/date	Search terms/ Limitations in the search engine	Selecting relevant studies			
		Results (sorted by relevance)	From review of titles	Particularly interesting studies concerning slabs-on-grade (References are not selected repeatedly)	Included in results
Science Direct (March 2021)	building AND moisture AND simulation AND ground AND (floor OR slab OR slab-on-ground) building AND moisture AND simulation AND ground AND soil AND (floor OR slab OR slab-on-ground) building AND moisture AND (slab OR floor) AND hygrothermal AND (ground OR soil)	3247 2706 375	17 new (review of first 200 results) 0 new 0 new (review of first 50)	Dos Santo & Mendes (2006) [44] Simultaneous heat and moisture transfer in soils combined with building simulation Rees, Zhou & Thomas (2001) [45] The influence of soil moisture content variations on heat losses from earth-contact structures: an initial assessment. Rees, Zhou & Thomas (2007) [60] Ground heat transfer: A numerical simulation of a full-scale experiment	Yes No, not as comprehensive as Janssen et al. (2004) [38] No, focus heat loss from a basement No, only heat transfer

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Table B.1 (*continued*)

Search engine/date	Search terms/ Limitations in the search engine	Selecting relevant studies			
		Results (sorted by relevance)	From review of titles	Particularly interesting studies concerning slabs-on-grade (References are not selected repeatedly)	Included in results
	/ Limited to research articles and review articles			Zhou, Rees & Thomas (2002) [61] A numerical and experimental investigation of ground heat transfer including edge insulation effects.	
				Adjali, Davis & Rees (2004) [62] A comparative study of design guide calculations and measured heat loss through the ground.	No, only heat loss
				Adjali, Davies, Rees & Litter (2000) [63] Temperatures in and under a slab-on-ground floor: two- and three-dimensional numerical simulations and comparison with experimental data.	No, only heat loss
				Rees, Thomas & Zhou (2000) [64] Ground heat transfer: Some further insights into the influence of three-dimensional effects.	No, only heat loss
				Rees, Adjali, Zhou, Davis & Thomas (2000) [65] Ground heat transfer effects on the thermal performance of earth-contact structures.	No, only heat loss
				Thomas & Rees (1998) [66] The thermal performance of ground floor slabs—a full scale in-situ experiment.	No, only heat loss
				Yu, Kang & Zhai (2020) [67] Comparison of ground coupled heat transfer models for predicting underground building energy consumption.	No, only heat loss
				Weitzmann, Kragh, Roots & Svendsen [68] Modelling floor heating systems using a validated two-dimensional ground-coupled numerical model.	No, only heat transfer
Google scholar (January 2020)	building AND moisture AND simulation AND ground AND (floor OR slab) building AND moisture AND simulation AND coupled AND ground AND (slab OR floor) building AND moisture AND hygrothermal AND (slab OR floor) AND (ground OR soil) / Patents and quotes not included	42000 25700 4090	9 new (review of first 100 results) 0 new 1 new	Rantala & Leivo (2009) [43] Heat, Air, and Moisture Control in Slab-on-ground Structures	Yes
				Leivo & Rantala (2005) [69] Moisture behaviour of a massive concrete slab with a low temperature floor heating system during the initial drying period	No, Rantala & Leivo (2009) is included
				Wang et al (2018) [70] The effect of heat and moisture coupling migration of ground structure without damp-proof course on the indoor floor surface temperature and humidity: Experimental study	No, only experimental
Citing/related to	Dos Santos & Mendes (2006)		2 new	Libralato, Angelis & Saro (2019) [71] Evaluation of the ground-coupled quasi-stationary heat transfer in buildings by means of an accurate and computationally efficient numerical approach and comparison with the ISO 13370 procedure	No, quasi stationary
				Spiga & Vocale (2014) [72] Effect of Floor Geometry on Building Heat Loss Via the Ground	No, focus steady-state heat loss
Citing/ related to	Rantala & Leivo (2009) [43]		1 new	Leivo & Ralanta (2006) [73] Seasonal Changes in Water Content of Subsoil Beneath Old Slab-on-ground Structures in Finland	No – Rantala & Leivo (2009) is more comprehensive
Citing/ related to	Janssen et al. (2004) [38]		0 new		
			30	**17**	**2**

Several limitations to the analysis have to be acknowledged:

- Including different search terms or additional search engines might have increased the number of selected studies.
- The identification of relevant studies and selection of studies of particular interest are based on the main authors' subjective judgment.
- The search was limited to research and review articles available online.

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Paper 3

Monitoring outward drying of externally insulated basement walls: A laboratory experiment

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Monitoring outward drying of externally insulated basement walls: A laboratory experiment

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ABSTRACT

Basements used for habitation represent a major challenge in terms of moisture safety design; they are prone to high moisture strain and have a limited ability for outward drying compared to structures above grade. Exterior vapour-permeable thermal insulation is used in countries with cold climates to enable outward drying. However, its effect is not well documented when combined with a dimpled membrane. A laboratory experiment was performed to investigate the outward drying of concrete walls and to generate data for the validation of hygrothermal simulations. Two wall segments with vapour-permeable insulation and exterior dimpled membranes were compared with a segment having a dimpled membrane positioned between the concrete and exterior insulation. The segments were subjected to a steady warm interior and a cold exterior climate in a climate simulator. Weight change, precipitated condensation, and temperature data were monitored for six months. Although the weights varied nonuniformly at the start, they decreased uniformly during the last four months; they exhibited the same rate and variations of weight change. No precipitated condensation occurred in the air gaps, although the moisture content of the concrete was high and the driving potential for diffusion (temperature gradient) was large. Results indicate that the concrete's ability to transfer moisture to the drying surface limits outward drying. Hence, the vapour permeability of the insulation and the membrane position were less influential. The moisture transfer properties of concrete currently used in basements should be investigated to better predict the long-term moisture performance of products and solutions for basements.

1. Introduction

Over time, the use of basements in countries with cold climates has changed considerably. Traditionally, basements have been utilized for food storage because of the stable climatic conditions provided by the thermal storage capacity of the soil. However, recent population growth, increasing house prices, and housing shortages have caused people to use basements for habitation. Regulatory requirements concerning indoor climate control, moisture control, and energy efficiency of inhabitable spaces are becoming stricter. This has resulted in increased thicknesses of thermal insulation as well as changes in the use of membranes/barriers to prevent moisture, air, and radon infiltration through the basement envelope [1,2].

Proper moisture control of the basement envelope is essential, because this part of the building is prone to substantial moisture strain in the form of high relative humidity (RH) in the soil/backfill, precipitation, and snowmelt. These loads are also likely to increase in the near future, because climate change entails more frequent and intense events of heavy rainfall and rain-induced floods [3,4]. The moisture strain on a basement envelope may also increase when the stormwater management strategy involves infiltration of surface runoff into the ground surrounding the building [5]. In addition, newly constructed site-cast or concrete-block basement walls contain a significant amount of built-in moisture, and thus require structural drying [6]. Even after renovation, older structures may be prone to moisture uptake from the ground owing to poor drainage underneath the foundations.

A host of different products have been designed to ensure the moisture performance of basements, for example, dimpled membranes, matrix panels, insulation drainage panels, drainage mats and spray-on waterproofing membranes. Some products provide several functions, whereas others are used in combination with other products. Some products are designed to eliminate the need for a granular backfill, whereas others have been proposed to enable outwards drying [7].

Asphaug et al. [1] investigated the national recommendations for

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thermally insulated basement envelopes in cold climates. Asphaug et al. [1] identified 10 main challenges in moisture safety design in basements and compared recommendations from five different countries. According to Asphaug et al. [1], countries with cold climates emphasize the ten key challenges differently. The recommendations have many similarities; however, the weighing of the ten challenges (or prioritising) distinguishes the moisture control strategies of the five countries. The results showed interesting differences regarding the use and position of dimpled membranes, moisture/vapour barriers/membranes, and the type, thickness, and vapour permeability of thermal insulation in walls and floors.

Vapour-permeable thermal insulation on the exterior side of basement walls is practised in many countries with a cold climate to enable outward drying below grade, e.g. Sweden [8], Denmark [9] and Norway [10]. This differs from commonly applied traditional strategies (e.g. Canada [11,12], Estonia [13], USA [2] and Finland [14]) where the exterior side of the walls is protected by a waterproofing membrane, treated with sprays or roll-on compounds, or a dimpled membrane is positioned between the wall and exterior thermal insulation. Outwards drying may be particularly beneficial in cases where: 1) poor drainage below foundations dampens the rehabilitated walls, 2) a bathroom/laundry room inhibits inward drying or 3) one seeks to increase the use of organic materials such as wood on the inside to reduce the carbon footprint of the building.

The principal theory behind the use of vapour-permeable thermal insulation below grade, is that in heated buildings in cold climates, the temperature across the basement wall decreases from the warm interior side to the cold exterior side. Vapour from the structure may therefore diffuse through the vapour-permeable thermal insulation, owing to the difference in vapour pressure induced by the temperature differences, condense at the exterior cold side of the exterior insulation/exterior membrane/geotextile and be drained down to the ground below the building [15]. Mineral wool boards or special qualities of expanded polystyrene (EPS) can be used. Different products are used either with or without draining backfill, and with or without a protective exterior membrane or geotextile. Either way, the use of vapour-permeable thermal insulations requires sufficient stormwater management and on-site drainage because the exterior side of the structure quickly dampens when exposed to liquid water [7].

In Norway, vapour-permeable thermal insulation with a water vapour diffusion resistance factor less than 10 is recommended below grade to increase outward drying of basement walls [10]. When this recommendation was introduced in 2015, the recommended position of the dimpled membrane also changed. The dimpled membrane, traditionally positioned directly on the basement wall, is now recommended to be positioned on the outer side of the exterior insulation. According to Ref. [10] the traditional position is not wrong and does not necessarily lead to damage; however, the change was aimed at further reducing the risk of moisture related damage by enabling outward drying. The changes were mainly based on unpublished calculations and assessments, and were implemented although the additional drying effects had not been sufficiently substantiated or quantified through measurements [15,16]. Those in favour of the new recommendations argue that both solutions represent robust structures. According to others, the effect of outward drying is minimal, inadequately documented, and the air gap behind the dimpled membrane when positioned directly on the wall can likely provide sufficient drying [17].

The main objectives of this study were to 1) investigate the potential for outward drying of concrete walls below grade and 2) generate data for the validation of hygrothermal simulations. Specifically, we investigated the effect of the permeability of the thermal insulation and the position of the dimpled membrane on the outward drying of basement walls. The following research questions were formulated to address this objective:

- How does the vapour permeability of exterior thermal insulation influence the drying behaviour of concrete walls?
- How does the position of the dimpled membrane influence the drying behaviour of concrete walls?

A parallel study is currently underway by the authors to investigate the outward drying of different basement walls and its impact on the long-term heat and moisture performance using hygrothermal simulations. A two-dimensional coupled heat-, air- and moisture transfer model developed in COSMOL Multiphysics was used to investigate the airflow in the air gaps behind the dimpled membrane. Therefore, an important outcome of the current study was to determine the data and material properties to validate hygrothermal simulations.

Some limitations of this study are acknowledged. The study did not address the following topics: 1) floor assemblies, 2) soil moisture content, 3) air convection in the ground, 4) air leakage through the building envelope, 5) drying behaviour of interior thermal insulation systems, 6) condensation risk at interior surfaces, 7) load-bearing capacity of structures, 8) durability of thermal insulation materials, 9) constructions below groundwater level or exposed to permanent water pressure, or 10) constructions subjected to freeze-thaw cycles.

2. Theoretical framework

2.1. Outward drying of thermally insulated basement walls in cold climates

Efficient drainage, airtightness, capillary breaking layers, and indoor ventilation are some of the most important measures to reduce the risk of moisture-related defects in basement envelopes. Thermal insulation should also be positioned on the exterior side of the load-bearing structures to reduce the risk of interstitial condensation [1]. In addition, increasing the drying capacity of basement walls may be advantageous, because high RH/moisture contents in the structures may lead to the growth of mould and rot fungi, structural decay, and reduced thermal performance of the basement envelope [18–21].

Based on two-dimensional hygrothermal simulations, using vapour-permeable thermal insulation ($\mu \sim 4.2$) on the exterior side of rehabilitated basement walls may increase the drying rate and lead to a lower moisture content at equilibrium, compared to using standard qualities of EPS ($\mu \sim 50$) or extruded polystyrene insulation ($\mu \sim 150$) [16]. However, in these simulations, a geotextile was assumed on the exterior side of the thermal insulation and not a dimpled membrane. Theoretically, in cold climates, the difference in temperature and hence vapour pressure across the exterior thermal insulation layer enables the moisture within the structures to dry outwards through the insulation by vapour diffusion, condense at the cold side, and be drained to the ground below. Outward drying is largest when all the insulation is positioned on the exterior side of the load-bearing structure – interior insulation/cladding reduces the difference in temperature and thus vapour pressure across the exterior insulation layer (the driving potential for outward diffusion), thus reducing outward drying. Factors such as the thickness, permeability and thermal conductivity of the exterior insulation and structure, amount of interior insulation and interior vapour barriers (if applied), interior and exterior climate conditions, and use of exterior dimpled membranes or geotextiles will also influence the drying of the wall [22].

Dimpled membranes/sheets were designed to provide capillary breaks and vertical drainage. A dimpled membrane typically consists of polypropylene sheets of 1 mm with dimples extruded at approximately 7–10 mm on one side, creating an air gap. When positioned on the exterior side of uninsulated basement walls or exterior side of exterior insulation, moisture that penetrates the membrane from the exterior or condenses in the air gap may be drained down to the ground below the building. It is, however, uncertain how a dimpled membrane placed on the exterior of the vapour-permeable thermal insulation will influence the outward drying through the insulation. It is difficult to predict the air change rates through the air gap of the dimpled membrane owing to the varying but limited openings at the top and bottom. It is also uncertain whether and when moisture will condense in the air gap and whether it will be drained out of the wall. If small air exchanges through the air gap are sufficient to enable drying when positioned on the exterior side of the insulation, it may also be sufficient to enable drying when positioned directly on the wall (between the insulation and structure). At this position, condensate drainage may be limited because the air in the air gap is as warm as the wall, however, the larger temperature difference between the air in the air gap and the air in the backfill might increase the air exchange. Fig. 1 illustrates a basement wall and dimpled membrane positioned either on the exterior side of exterior vapour-permeable thermal insulation or directly on the wall structure.

Both positions of the dimpled membrane are currently applied in present-day practice, as they both entail a low risk of moisture failure [10]. However, the expected performance is affected by the local climate, boundary conditions, and materials used. In particular, many basement envelopes experience extensive failure due to flawed construction, and knowledge targeting robust structures is necessary [24–26]. The building industry is reluctant to fully adopt the contemporary recommendations owing to the positive experiences and sufficient effects obtained using the traditional recommendations. Contradictory and obscure results from research investigating the effects of vapour-permeable thermal insulation and positions of the dimpled membrane should be addressed and examined to evaluate and target the best design solutions.

2.2. *Outward drying of basement walls in existing studies*

Relatively few studies considered the outward drying achieved by different thermal insulation permeabilities and positions of the dimpled membrane in basement walls below grade. However, some existing studies have dealt with this topic, such as Geving et al., Blom, Pallin, and Asphaug et al. [1,7,16,27]. Hygrothermal simulations performed by Geving et al. [16] demonstrated faster drying and lower moisture content at equilibrium for walls fitted with vapour-permeable thermal insulation compared ($\mu = 4.4$) with standard EPS ($\mu = 50$). In contrast, the field measurements did not report any signs of drying over a period of 19 months. Blom [27] conducted field measurements of the outward drying behaviour of six concrete basement test walls, measuring the temperature, RH, and moisture content in the wall assemblies. The study did not detect any increased drying effect for the wall with exterior vapour-permeable thermal insulation and exterior dimpled membrane compared to the walls with the dimpled membrane positioned directly on the wall (between the wall and insulation).

The use of vapour-permeable thermal insulation combined with landscape fabric (geotextile) instead of a dimpled membrane, and backfill of existing soil is a common approach in Sweden [7]. Pallin [7] used hygrothermal simulations to investigate the effects of outward drying of concrete basement walls retrofitted with exterior vapour-permeable thermal insulation in the climate of Gothenburg, Sweden. Based on results, outward drying was slow and only approximately 6–8 (kg/m^2) of the moisture in the wall could be dried annually, at maximum. If any of the rain loads directly hitting the ground or drained from the upper wall surfaces accidently penetrates the drainage/insulation board, the expected drying potential would be equalised or reversed. To ensure a positive drying potential, Pallin [7] suggested replacing the landscape fabric with a water vapour barrier.

Several noteworthy studies have focused on the moisture performance of thermally insulated basements. Goldberg and Harmon [24] conducted a comprehensive large-scale experiment to investigate the moisture durability of basement walls retrofitted with interior insulation solutions in cold climates. Straube [6] investigated interior insulation systems by performing both in situ measurements and hygrothermal simulations. Fedorik et al. [28] investigated various refurbishment strategies for basement walls through hygrothermal simulations, and Blom and Holøs [29] measured the drying behaviour of internally insulated basement walls. However, as these studies mainly focused on the performance of interior insulation systems, they did not address the drying behaviour achieved using exterior vapour-permeable thermal insulation or the position of the dimpled membrane.

Hence, the identified knowledge gap regarding the effect of using vapour-permeable thermal insulation and the recommended dimpled membrane position should be addressed.

2.3. *Effect of the exterior air gap on outward drying*

The air gap of a dimpled membrane, positioned on the exterior side of the basement walls, enables penetrated or condensed moisture to be

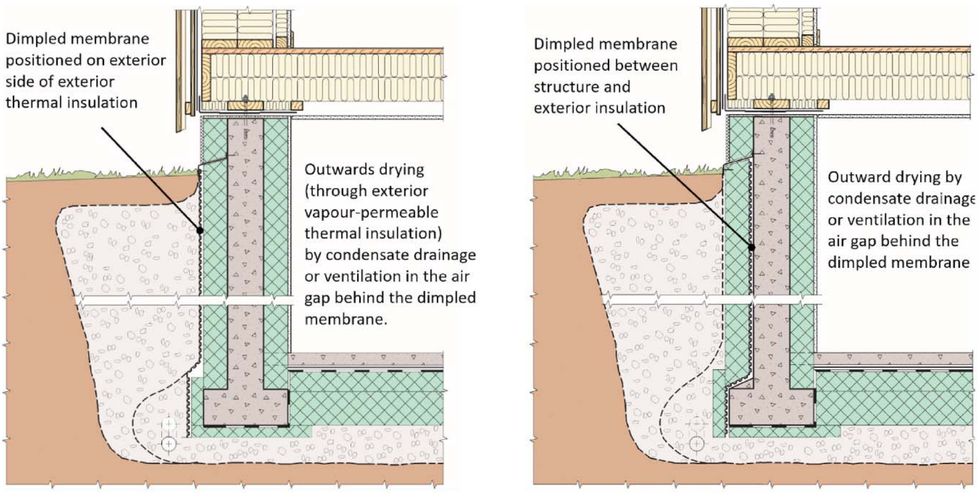

Fig. 1. Dimpled membrane positioned on the exterior side of the vapour-permeable thermal insulation (left). Dimpled membrane positioned directly on the concrete wall (right).

drained down to the ground below the building (see Fig. 1). Based on research, the air gap might be utilized to improve the thermal performance of the basement walls (e.g. Ref. [30]); however, fewer studies seem to have focused on ventilation and outward drying. Some important research aspects focusing on exterior air gaps in walls above grade level need to be highlighted.

Straube [31] developed a test method using full-scale wall systems to investigate the role of small gaps in ventilation drying and the gap size required to ensure drainage. According to results, ventilation drying could play a role in small gaps of approximately 1 mm, at a pressure difference of only 1 Pa. Based on observations, even tiny gaps (less than 1 mm) could drain more water than would normally be found in a drainage gap, and in some special cases, small gaps stored less water than a large drainage gap. Straube and Smegal [32] continued this study and investigated the use of one-dimensional simulation models with source and sink enhancements to simulate the hygrothermal performance of wall systems with drained and ventilated air gaps. This study illustrated the challenges of modelling the real moisture storage of the air in the air gap and the moisture retained on drainage gap surfaces, highlighting the importance of laboratory investigations and field studies.

Finch and Straube [33] investigated the drying of ventilated claddings in exterior walls above grade. According to Finch and Straube [33], the probable range of ventilation rates depends on the cladding type, cavity dimensions, and venting arrangement and is determined by the thermal and moisture buoyancy and wind pressures. The vent openings are critical details and should be as large and unobstructed as possible. Straube et al. [34] performed field studies on wooden-framed wall systems clad with brick or vinyl siding. They observed that the drying rates varied significantly under different weather conditions and that ventilation increased the drying potential of some walls. Further, solar-driven vapour diffusion redistributed vapour from within the wall to the interior (where caused damage). Ventilation was found to reduce the magnitude of this flow. Rahiminejad and Khovalyg [35] reviewed ventilation rates in air gaps behind the cladding of walls above grade and indicated that the stack effect and wind effect are two major mechanisms driving the airflow in ventilated air spaces. For basement walls, the wind effect may be less significant than in walls above grade; however, the stack effect may be more important because of the temperature difference between the top and bottom of the walls.

In general, existing studies illustrate the importance of exterior air gaps in drainage and ventilation drying. These effects are difficult to numerically simulate, illustrating the importance of laboratory investigations and field studies.

2.4. Measuring the outward drying of basement walls

Field measurements can be conducted to investigate outwards drying, such as those performed by Blom [27], Geving et al. [16], Goldberg and Harmon [24] and Straube [6]. However, conducting field measurements to investigate the outwards drying rates may not be straightforward. First, field measurements may be time-consuming because the conditions are primarily favourable for outward drying during sufficiently cold periods. Geving et al. [16] reported that the RH measured in a renovated concrete wall increased during summer, decreased during winter, and then increased again in spring. Therefore, sufficient results may require several years. Second, RH-sensors and moisture content measurement devices (e.g. moisture content electrical readings used in wood plugs in the concrete) have a limited accuracy above the hygroscopic moisture range of 95–98% RH. The moisture content in the masonry wall measured by Geving et al. [16] may initially have been too high to be detected by the Vaisala RH-sensors (above the hygroscopic moisture range of 95–98%); thus, no drying could be detected during the 19-month period. Third, even if the sensors accurately measure high RH values, they may not endure a humid climate below grade level for long durations. Goldberg and Harmon [24] reported that the RH-sensors they used (which were developed to be more accurate at high moisture contents (>95%) than the Honeywell RH-sensors) failed consecutively, likely because of the failure of the electrode conductive epoxy sealant under prolonged wetting. Fourth, the measurements should preferably be conducted on newly built basement walls to avoid uncertainties related to the initial moisture content, insufficient drainage, air leakages, or capillary transfer of moisture through the foundations.

Because the present study aims to gain more knowledge of outward drying and to generate data for the validation of hygrothermal simulations, a laboratory experiment may provide useful information upon initiating long-term field measurements. Johansson et al. [36] investigated the hygrothermal performance of brick walls using a large-scale building envelope climate simulator. Knarud et al. [37] used the same climate simulator to study insulated brick wall segments subjected to wetting and drying. The use of a climate simulator to study the outward drying of basement walls is advantageous in that the interior and exterior climates may be controlled. Thus, the samples may be subjected to the same conditions and the experiment may be conducted within a reasonable time. Further, investigating the drying behaviour in a climate simulator is advantageous in that the moisture precipitating in the air gap behind the dimpled membrane may be collected and measured simultaneously. Conducting a laboratory experiment instead of field measurements also enables us to thoroughly consider how outward drying should be investigated in future long-term field measurements. However, both Johansson et al. [36] and Knarud et al. [37] experienced vulnerabilities using RH sensors at high RH values and inhomogeneity of the masonry specimens. Straube [31] used a load cell to investigate the drainage and ventilation drying of full-scale wall systems. By using load cells as a measuring device, rather than RH-sensors, a more accurate monitoring of the drying behaviour may be achieved with a better basis for comparing different wall designs.

3. Method

3.1. General overview of the experimental setup

This study investigates the influence of the permeability of the exterior thermal insulation and the position of the dimpled membrane on the drying behaviour of basement walls. Three concrete wall segments were fitted with different configurations of thermal insulation and dimpled membranes at different positions. The three wall segments were hung in load cells in an insulated wooden frame and subjected to warm interior and cold exterior climates in a climate simulator for 6 months (26 weeks, 20.03.2021–18.09.2021). The variation in the total weight of the wall segment, weight of the condensed/drained water, and temperature data were collected continuously. A general overview of the experimental setup is shown in Fig. 2. The material configuration and dimensions of the wall segments are shown in Fig. 3, and the details of the experimental setup are shown in Figs. 4 and 5. Further details and photographs are provided in Ref. [38].

3.2. Three wall segments

The compositions and dimensions of the three wall segments are shown in Fig. 3. Fig. 3 also shows how the wall segments relate to the basement envelopes and the dimensions of one weighed wall segment positioned in the wooden frame. The dimensions of the wall segments were 600 × 1500 mm, and the thicknesses of the concrete segments, exterior thermal insulation, and dimpled membranes were 60, 100, and 7.5 mm, respectively. The wall segments were insulated around the perimeters using a 100 mm EPS.

Wall segment 1 had a dimpled membrane mounted on the exterior side of the exterior permeable thermal insulation. Wall segment 2 had a dimpled membrane mounted on the exterior side of the exterior semi-permeable thermal insulation. Wall segment 3 had an exterior semi-

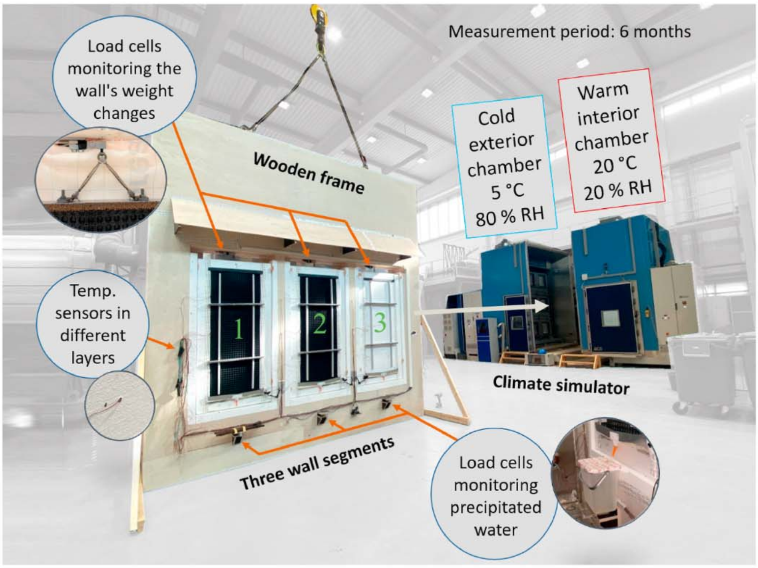

Fig. 2. General overview of the experimental setup. The three wall segments were hung in load cells in an insulated wooden frame and subjected to warm interior and cold exterior climates in a climate simulator for 6 months.

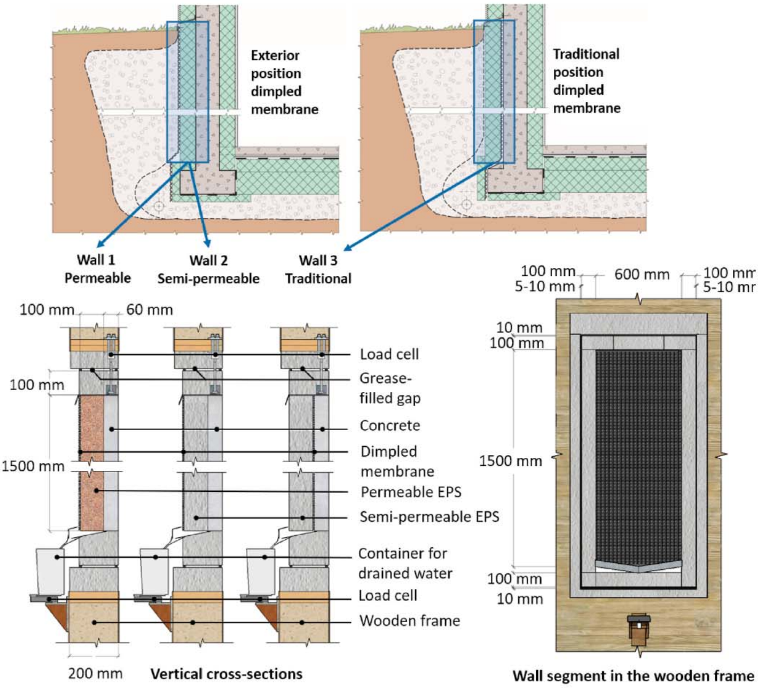

Fig. 3. Diagrams of the wall segments showing dimensions and material configurations (left) and one wall segment positioned in the wooden frame (right).

permeable thermal insulation mounted on the exterior side of the dimpled membrane. In the text, wall segments 1, 2, and 3 are referred to as the permeable, semi-permeable, and traditional wall, respectively.

3.3. Edge insulation and frame insulation

To obtain an accurate weighing of the dried-out moisture, the wall segments were required to freely hang in the suspended load cells. To

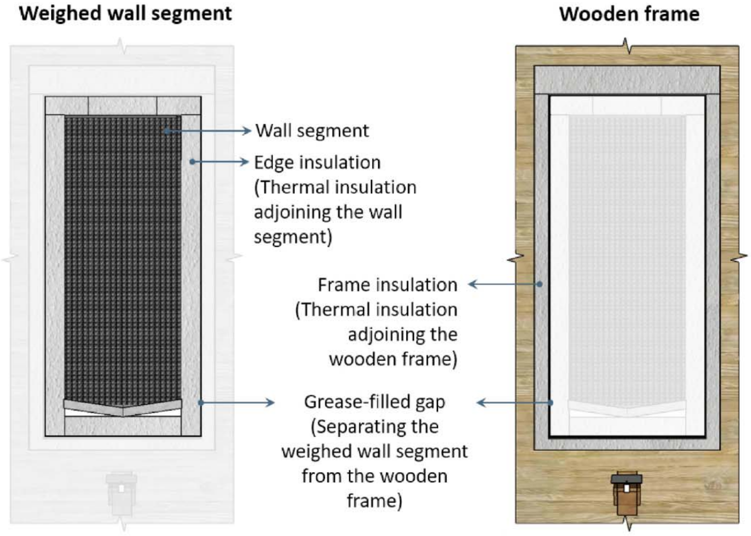

Fig. 4. Diagram of a weighed wall segment consisting of a wall segment and edge insulation (left), wooden frame with frame insulation (right), and a grease-filled gap (left and right). The front view of the weighed wall segment and wooden frame are shown from the exterior side (cold chamber).

Fig. 5. Details of the weighed wall segments and wooden frame. Enlarged versions of the photographs and a detailed explanation of the compositions are presented in Ref. [38].

reduce the impact of thermal bridges on the transition between the wall segment and wooden frame, the edges around the wall segments were insulated using EPS. This EPS is referred to as edge insulation. Wall segments and edge insulation were included in the weighing. EPS was also applied around the openings in the wooden frame. This EPS is referred to as frame insulation. A string of grease was applied on the exterior side of the gap between the edge and frame insulation to prevent moisture and heat transfer by air convection. The grease was applied after the wooden frame was moved to the climate simulator. Fig. 4 shows the terms assigned to the different elements. More details of the grease-filled gap and preparation of the edge and frame insulation are presented in Ref. [38].

3.4. Material qualities

The EPS with a compressive strength of 150 kPa is, according to SINTEF, commonly used in basement walls and was therefore selected as the standard thermal insulation in the semi-permeable and traditional wall. The thermal conductivity of the semi-permeable EPS was 0.035 W/mK. When lower water vapour resistance is desired, rigid mineral wool boards or special qualities of EPS are commonly used. To enable the most equal comparison, a special quality EPS with the most similar thermal conductivity to that of the semi-permeable EPS was selected for the permeable wall. These two qualities are referred to as semi-permeable EPS (standard) and permeable EPS (special quality). The water vapour resistance factors of the permeable and semi-permeable EPS qualities were not documented by the producers/manufacturers;

however, they were measured in this project as 8.2 and 27.9 respectively. According to the manufacturer Isola, Platon Extra is the dimpled membrane that is sold the most for use on basement walls and is therefore used in this project. The permeable and semi-permeable EPS, and the dimpled membrane are shown in Fig. 5. Fig. 5 also shows photographs of the load cells, attachments, web cameras, and metal fittings discussed in the following sections.

A concrete quality commonly used in basement walls nowadays was selected for the wall segments in the study. With respect to the overall experimental setup, a relatively permeable concrete with a high initial moisture content was desirable to enable comparison of the walls. It was not desirable to use concrete with an unrealistically high w/c-ratio. According to Ref. [39], a w/c-ratio of above approximately 0.4 results in full hydration and formation of capillary pores that store excess water and increase the permeability of the concrete. Above approximately 0.6, the permeability of concrete increases rapidly as the capillary pores become continuous. Based on the advice from SINTEF, the B30M60 concrete quality with a w/c-ratio of 0.54 and a low amount of plasticising or water-reducing additives was selected. The material properties measured for the thermal insulation and concrete in question, list of specific materials used in the laboratory experiment, and the preparation of the thermal insulation and dimpled membranes are presented in Ref. [38].

3.5. *Wooden frame*

A wooden frame with dimensions of 3830 mm × 3800 mm × 206 mm was constructed, as shown in Fig. 5, and insulated with 200 mm mineral wool. A vapour barrier covering the entire interior side prevented air leakage between the climate chambers. The joints between the vapour barrier and construction timber were sealed with vapour barrier tape. Plywood sheets were mounted on the exterior and interior sides and sealed with a wind barrier tape on the exterior side. A roof overhang was mounted on a wooden frame to protect the wall segments from condensed water that could drip from the roof in the exterior climatic chamber. Further details on the construction of the wooden frame are presented in Ref. [38].

3.6. *Climate simulator setup*

The wooden frame was installed in a climate simulator, as shown in Fig. 2, which consisted of cold exterior and warm interior climate chambers. The wall segments were exposed to 5 °C/80% RH and 20 °C/20% RH in the exterior and interior chambers, respectively. The climatic exposure was chosen to represent average exterior and interior climates of heated basements in countries with cold climates. Ideally, the RH in the exterior chamber should have been maintained at a higher level, closer to 100% [40]. Several test runs were conducted to achieve a higher RH; however, this was not possible owing to equipment limitations. To avoid freezing of the cooling pipes in the exterior climatic chamber, intermittent defrosting was performed automatically for 30 min per day.

3.7. *Preparation and mounting of the wall segments*

The concrete segments were casted horizontally in the formwork and cured in water before they were retrieved and prepared for the experiment after 28 days. Primer and epoxy paint were applied to all sides, except the drying surface. Two coats of epoxy were applied along the side edges of the drying surface with a width of 50 mm. In this manner, the drying area of the concrete surface was 500 × 1400 mm, and the impact of unfavourable edge effects was limited. To maintain a high moisture content in the concrete before the onset of the measurements, the drying surface was wetted and covered with soaked shoddy overnight. The shoddy was removed when the concrete segments were mounted in the timber frame, and a vapour barrier was applied to the drying area to retain moisture. The concrete segments, thermal insulation, dimpled membranes, and thermocouples were successively mounted. To avoid screws penetrating the wall segments, the thermal insulation and dimpled membranes were gently pressed against the concrete segments and held in place by means of frames and band-hose clamps. More details concerning the casting and surface treatment of the concrete and mounting of the wall segment in the wooden frame are presented in Ref. [38].

Along the sides of the wall segments, the gaps between the concrete, dimpled membrane, and thermal insulation were sealed using a wind barrier tape. An epoxy adhesive for air and moisture sealing was applied along the sides of the thermal insulation and dimpled membrane (not at the top and bottom) to prevent moisture diffusion through the sides of the wall segments and into the edge insulation. A plastic flashing was placed (not glued) at the top of each wall segment to resemble a real basement wall. The flashings were taped to the upper side of the concrete segments, as shown in Fig. 5. Photographs are provided in Ref. [38].

3.8. *Monitoring*

Each weight wall segment was provided with two load cells: one for weighing the suspended load (weighing of the wall segments and edge insulation) and one for weighing the standing load (weighing condensed water), as shown in Fig. 5. The suspended load cells had a load capacity of 220 kg and accuracy of 20 g, and the standing-load cells had a load capacity of 10 kg and accuracy of 1 g. To transfer condensed water from the wall segments to the water tanks, metal fittings with plastic funnels and plastic tubes were mounted underneath the wall segments, as shown in Fig. 5. Additional details regarding the mounting and adjustments of the load cells, their accuracy, and the collection of condensed water are presented in Ref. [38].

Web cameras were installed to film and take images of potential water runoff underneath the wall segments, as shown in Fig. 5. The tripods were mounted on the wooden frame, and a hole of approximately 10 mm in diameter was drilled through the corner of each metal fitting to enable the lens to film the bottom side of the dimpled membrane, and thermal insulation.

Each wall segment was instrumented with 13 thermocouples to measure the temperature. An orchestrator was used for the temperature-control setup. The orchestrator logged sampling data every 10 s and averaged six sampling points over 1 min to a log file. Each wall segment was instrumented with 13 thermocouples to measure the temperature. The positions of the thermocouples in the three wall segments is shown in Ref. [38].

4. Results

4.1. *Weight changes*

The weight changes of the three wall segments during the measuring period of 6 months are depicted in Fig. 6 and summarized in Table 1. As can be observed from Fig. 6, the weights of the walls vary somewhat differently in the first two months, but decrease quite uniformly during the last four months. By observing only the last four months and shifting the graphs to the same initial weight at that time, a close correlation between the three walls can be observed (see Fig. 7). During these months, the walls have approximately the same average drying rates, the same total weight changes, and portray the same fluctuations in the measured weights.

The recurring oscillations in the weight-change data are mainly caused by the sensitivity of the load cells to fluctuations in temperature. On several occasions, the measured weights of the walls were affected by technical errors in the climate simulator and subsequent large changes in temperature. The reduction in weight changes in the last weeks of the measuring period is likely caused by the difficulty in maintaining the

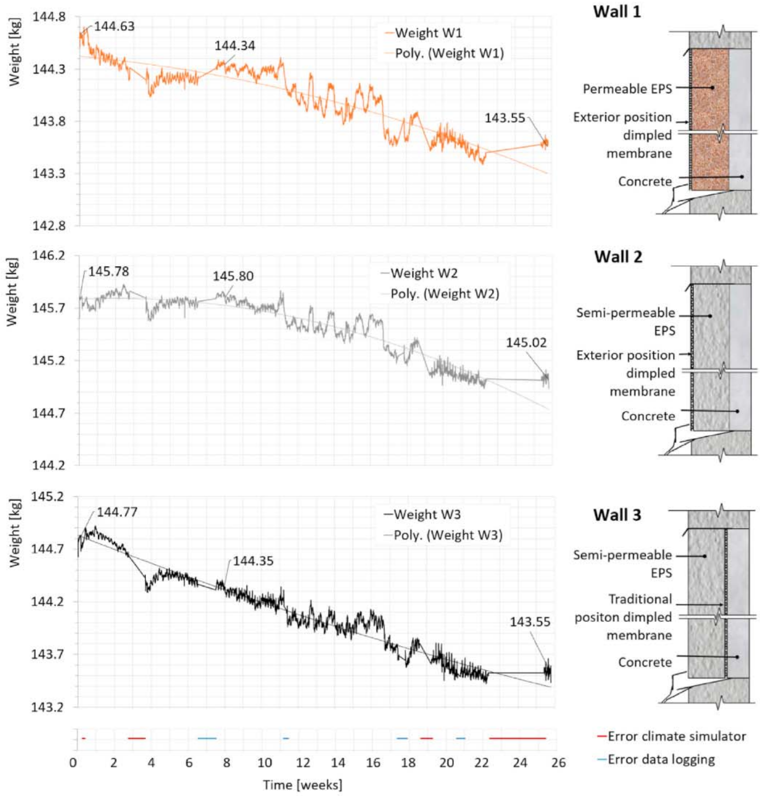

Fig. 6. Weight changes of the three wall segments during the measuring period of 6 months. The flattening portrayed by the three wall segments at the end of the period is due to the difficulties in maintaining the exterior chamber cold (5 °C), see Appendix A.

Table 1
Weights of the three wall segments at different stages.

Wall segment	Initial weight [kg]	Weight after 8 weeks [kg]	Final weight (after 26 weeks) [kg]	Difference between initial weight and weight after 8 weeks [kg]	Difference between initial weight and final weight [kg]	Difference between weight after 8 weeks and final weight [kg]
1	144.63	144.34	143.55	0.29	1.08	0.79
2	145.78	145.80	145.02	0.02	0.76	0.78
3	144.77	144.35	143.55	0.44	1.24	0.80

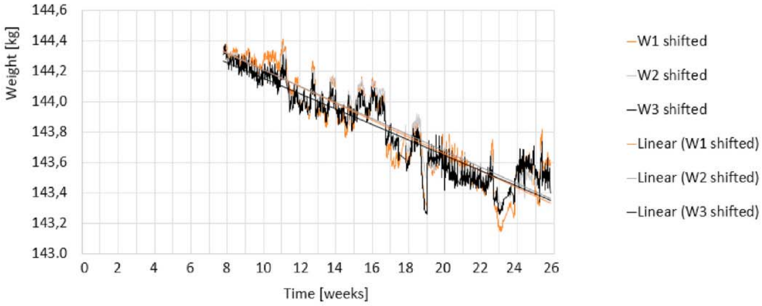

Fig. 7. Weight changes of the three wall segments during the last four months of the measuring period. The graphs have been superimposed for the purpose of comparison.

exterior climate chamber cold (5 °C). More information regarding the sensitivity of the load cells to fluctuations in temperature and technical errors can be found in Appendix A.

4.2. Temperature measurements

The temperatures measured in the wall segments were relatively stable in the interior and middle positions of the walls, with some large fluctuations caused by errors in the regulation of the climate simulator. The exterior temperatures exhibited small daily fluctuations caused by the daily defrosting of the cooling pipes in the cold chamber. The temperatures measured in the different layers of the wall segments and within the air gaps behind the dimpled membrane are displayed in Appendix A.

4.3. Precipitated condensate

The load cells below the walls did not collect any precipitated water during the measurement period. This was also confirmed by photographs taken regularly in the air gaps below the walls [38].

5. Discussion

5.1. Vapour permeability of the exterior thermal insulation

Vapour-permeable thermal insulation on the exterior side of basement walls is practised in many countries with cold climates to enable outward drying below grade, for example, Sweden [8], Denmark [9] and Norway [10]. However, is not well documented, especially when used in combination with an exterior dimpled membrane. In this experiment, the drying behaviour of a wall configuration with vapour-permeable EPS ($\mu = 8.2$) was compared with that of a wall with semi-permeable (standard) EPS ($\mu = 27.9$). The semi-permeable EPS and the vapour-permeable EPS was selected because they had approximately the same thermal conductivity (0.034 W/mK), and this affects the outward drying [38]. The water vapour resistance factor of the two EPS types were unknown prior to the experiment, but was measured during the project. The two walls had dimpled membranes positioned on the exterior side of the thermal insulation. The two walls were further compared to a wall configuration with a dimpled membrane positioned between the concrete and semi-permeable EPS.

Prior to the experiment, it was predicted that the permeable wall would portray the greatest weight change, the traditional wall would portray a low weight change, and the semi-permeable wall would portray a very limited weight change. However, the weights of the three walls decreased quite uniformly during the last four months; that is, they have approximately the same average drying rates and the same total weight changes and portray the same fluctuations in the measured weights. The similarity in drying rates is rather unexpected, as the experiment represents a ‘best case scenario’ in terms of outward drying; the imbedded moisture content in the concrete is at a maximum, the temperature difference across the insulation is large (no insulation on the interior side), the exterior climate is air with 80% RH rather than 100% RH, and the air gap opening at the bottom of the dimpled membrane is not covered by granular backfill. The similar drying rates indicate that outward drying in this experiment, to a large extent, was limited by the properties of the concrete and the ability of the concrete to transfer imbedded moisture outwards to the drying surface. Knowledge regarding the hygrothermal properties of the concrete in question is essential to more accurately predict the outward drying of building components [41].

The concrete was selected to resemble the quality typically used in basements nowadays. According to Geving et al. [16], basement walls can achieve faster drying and lower moisture content at equilibrium using exterior vapour-permeable thermal insulation compared to standard quality EPS. However, the simulations performed by Geving et al. [16] compared vapour-permeable EPS with a water vapour resistance factor $\mu = 4.4$ and a standard quality EPS with $\mu = 50$. Hence, the relative difference in μ-value between the two EPS qualities is considerably larger in the simulation by Geving et al. [16] than in this experiment. Furthermore, the concrete adopted by Geving et al. [16] had a high liquid conductivity to resemble the quality of an old concrete basement wall.

The concrete used in the experiment had a high initial moisture content. Using concrete with a higher liquid conductivity could therefore have resulted in more drying and greater differences between the walls during the measurement period. As concrete dries, the moisture content decreases, and thus the drying rate decreases as well. At some point, the concrete’s liquid conductivity becomes less influential, and the drying will mainly be limited by be the concrete’s vapour permeability. If the measurements had continued over several years, a greater difference between the three wall segments might have been achieved. Considering the concrete quality, it is therefore unlikely that using a thermal insulation with lower vapour-permeability than 8.2, in the vapour-permeable wall, would have resulted in more drying. A thermal insulation with lower vapour permeability may, however, contribute to increase the outward drying of basement walls on a long-term basis.

During the first two months, the weights of the walls varied somewhat differently. Uncertainties related to the different behaviours are discussed in Appendix A. Although some uncertainties are linked to the drying behaviour in the start-up phase, the similar drying rates portrayed by the three concrete walls during the last four months indicate that the vapour permeability of the exterior insulation plays a minor role in the drying behaviour when the concrete quality is good (low liquid permeability). The concrete used in the experiment was selected to resemble the typical concrete used in basement walls nowadays. Older basement structures with poor concrete quality (high liquid permeability) may benefit more from using the special qualities of EPS with a low vapour resistance.

5.2. Position of the dimpled membrane

In many countries with cold climates, dimpled membranes are positioned directly onto concrete or masonry structures in basement walls to serve as a capillary break and ensure vertical drainage [2,12,13,23]. However, to enable and potentially increase outward drying, the dimpled membrane may be positioned on the exterior side of the exterior vapour-permeable thermal insulation [7,10]. In theory, moisture in the wall may be transferred outwards through vapour-permeable insulation by diffusion, condense at the cold side of the insulation or at the dimpled membrane, and be drained down through the air gap to the ground underneath the building. How this works in practice is however uncertain, and little research has been conducted to investigate how condensate water and air gap ventilation impact the outward drying of walls below grade.

The magnitude of the air exchange in air gaps behind dimpled membranes in basement walls is difficult to predict as it may be affected by many varying factors such as e.g., air gap openings, wall height, and wind- and stack effects [33–35]. Comparing the two positions of the dimpled membrane is therefore not straightforward. Moisture condensation on the drainage gap surfaces and the real moisture storage of the air gap makes it challenging to simulate the outward drying numerically [32]. The traditional position of the dimpled membrane requires some ventilation of the air gap for outward drying to occur. Research has showed that ventilation drying in walls above grade can play a role even in very small gaps of approximately 1 mm, at a pressure difference of only 1 Pa [31]. The position directly on the concrete wall might increase the air exchange, compared to the exterior position, because the temperature difference between the air gap and the backfilling is larger. When positioned on the exterior side, on the other hand, moisture may additionally condensate within the air gap and be drained down to the ground below. Whether this contributes to increase the outward drying is uncertain, however, as it has not been substantiated by measurements. Nevertheless, one may assume that also for this position there will be a need for some ventilation of the air gap to achieve outwards drying.

In this experiment, a wall segment with the dimpled membrane positioned between exterior insulation and concrete (traditional) was compared to two wall segments with the dimpled membrane positioned at the exterior side of exterior insulation (permeable and semi-permeable). The experiment does not take in to account all the various factors affecting the air exchange within the air gaps, however, the two walls are subjected to the same conditions. As discussed in Section 5.1, results show that the drying behaviour is similar for the three walls and considerably smaller than predicted by simulations, even under favourable conditions for drying. Moreover, no condensed water was detected during the period of 6 months. This indicates that the drying exhibited by the walls in this experiment may be limited by the concrete quality; thus, the position of the dimpled membrane might be of minor importance in contemporary basements.

When interpreting the results, some caution should be exercised, as the experiment does not consider the effects of wind pressure, the full height of the walls, temperature differences between the top and bottom of the walls owing to the presence of the exterior ground, and various foundation designs. Further, the bottom opening of the air gap behind the dimpled membranes influences the results of this experiment. Although the openings in the experiment are equal for the three walls, and thus comparable, they may be more restricted in real structures depending on the design of the foundation and backfill. Prior to the experiment, moisture was expected to condense in the gap in the permeable wall. However, because of the low drying rates exhibited by the concrete in this case, the moisture in the air gaps behind the dimpled membranes evaporated to the exterior air before condensation occurred. The impact of the size of the air gap opening on the moisture conditions in the air gaps and thus the overall drying behaviour of the walls is unknown. Although there is little indication that using smaller openings would have contributed to increasing the drying rates of the three walls, the following questions remain: Does the moisture in the air gaps ever condense, and what climatic conditions does this require?

Factors other than the drying behaviour of the walls should be considered when changing the recommended position of the dimpled membrane. Primarily, the dimpled membrane must function as a capillary breaking layer and inhibit stormwater from penetrating the structure. In favour of the traditional position, one may argue that the dimpled membrane is less exposed to damage and puncturing when it is protected behind the thermal insulation. Furthermore, it may be easier to mount the dimpled membrane directly onto the wall.

5.3. *Uncertainties and limitations related to the experimental setup*

The experimental setup developed in this study enabled the investigation of the drying behaviour of concrete walls under controlled climatic conditions. However, the experimental setup has some limitations. First, the five sides (surfaces) of the concrete segments were sealed with a primer and two layers of epoxy paint. Although the s_d - value was stated to be at least 41 m by the manufacturer, this was not confirmed by additional measurements. Although the amount of moisture that diffused through these surfaces during the measuring period is uncertain, this is not considered to significantly influence the difference between the walls, given that the three walls were treated equally. Second, maintaining a stable exterior and interior climate in the simulator was difficult owing to errors in laboratory equipment. The applied load cells could measure small weight changes on relatively heavy walls (~150 kg) over a period of 6 months; however, they were somewhat sensitive to small temperature variations resulting in large fluctuations in the results. The fluctuation in the measured weights is not considered to affect the overall drying behaviour of the three walls as the walls were subjected to the same temperature and RH variation during the measurement period. Third, creep and drift of the load cells was compensated for by the automatic calibration of the system every 5 min, however, the impact was not measured when the wall segments were unloaded. If creep/drift occurred, the measured weight loss will be higher than the true value. That means that the wall segments would have dried even slower than the measurements show. The potential influence of creep/drift would nevertheless be equal for the three wall segments and thus it is considered not to influence the comparison of the wall segments' performance. Fourth, to reduce the impact of the higher heat loss in the grease-filled gaps, the edges around the weighed wall segments were insulated with 100 mm EPS (edge insulation). The edges of the wall segments were also sealed with a vapour-resistant mortar adhesive. The effect of the edges on the temperature distribution across the walls and thus the overall drying behaviour is uncertain; however, this uncertainty is also equal for all three walls. Fifth, some substances in the grease applied in the gaps around the weighed walls appeared to have diffused into the edge insulation. The effect of this minor deficiency on the weight of the wall segments is unclear; however, it is also presumed to equally influence the three walls. An overview of possible sources of errors is provided in Ref. [38].

6. Conclusion

Based on the results of this experiment, the vapour permeability of the exterior insulation may play a minor role in the drying behaviour of concrete basement walls if the concrete quality is good (low liquid permeability/capillary suction). Moreover, the position of the dimpled membrane may be less important for the overall drying behaviour of high-quality concrete as long as the air gap behind the dimpled membrane is ventilated.

The variation in moisture transfer properties of concrete used in basements should be investigated to better predict the long-term moisture performance and durability of new products and solutions for basement walls. The concrete used in this study resemble the typical concrete used in basements walls nowadays. Older basement structures made of poor concrete quality (high liquid permeability) or other materials might benefit more from using vapour-permeable thermal insulation to increase the outward drying.

The moisture conditions in the air gaps behind the dimpled membrane should be further investigated to gain more knowledge on how different positions of the membrane influence the ventilation rates and outward drying. Data from this experiment may in this concern be used to validate hygrothermal simulations.

CRediT authorship contribution statement

Silje Asphaug: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Conceptualization. **Ingrid Hjermann:** Writing – original draft, Visualization, Project administration, Methodology, Investigation, Conceptualization. **Berit Time:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Tore Kvande:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Sensitivity of the load cells to fluctuations in temperature

The recurring oscillations in the weight-change data are mainly caused by the sensitivity of the load cells to fluctuations in temperature. Fig. A1 shows the temperatures measured on the three load cells, along with the measured weight changes of the three wall segments, including periods with technical errors. Fig. A1 illustrates the correlation between the measured weights and the temperature fluctuations, that is, the weights increases when the temperature increases and decreases when the temperature decreases.

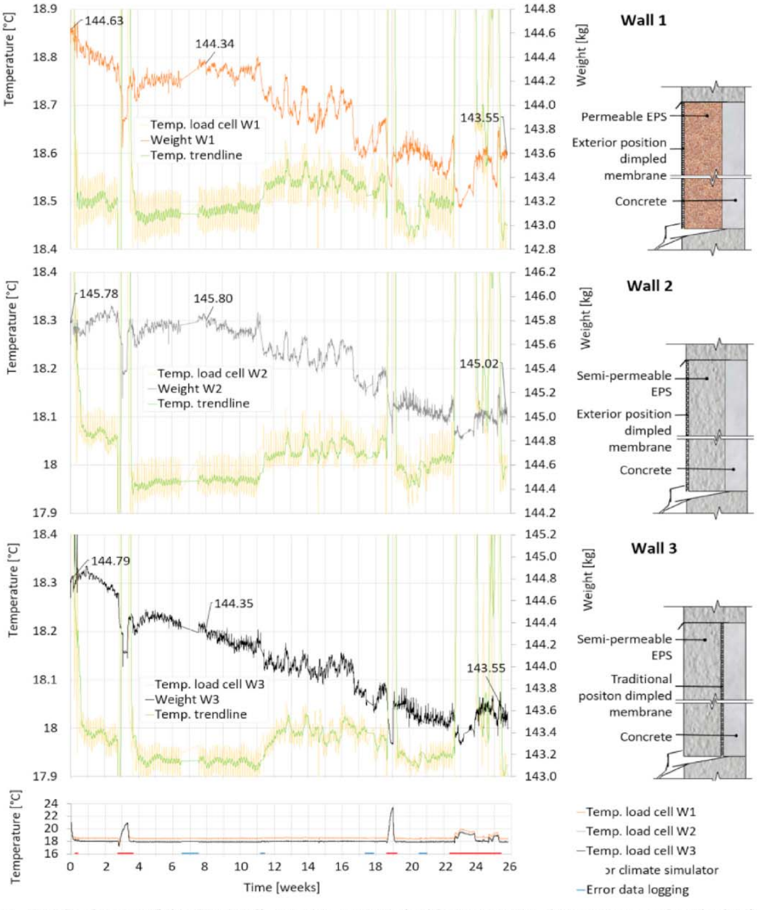

Fig. A1. Weight changes of the three wall segments compared with temperature changes measured at the load cells.

Technical errors

On several occasions, the measured weights of the walls were affected by technical errors in the climate simulator and subsequent large changes in temperature. In these periods, the weights of the wall segments were also affected by opening/closing of the doors and fans being switched on and off in the two climate chambers. The first time the climate simulator stopped, troubleshooting led to an accident affecting the wall segments. Powerful fans related to the solar radiation application were switched on and created an instant (brief) air overpressure in the exterior chamber. The pressure was sufficiently large to cause the bottom side of the hanging walls to swing out of position. More grease had to be applied to the three walls to re-establish the airtightness in the grease-filled gaps. This might have affected the total weight of the walls during that time, but was not likely to affect the weight changes over time. The logging of the weight was also hindered on several occasions by technical errors in the computer system. These periods can be seen as straight lines in the weight-change graphs. Periods with technical errors are marked in Fig. 6 in the main text and in Fig. A1, and are described more thoroughly in Ref. [38].

Factors influencing the weight of the walls during the start-up phase

During the first two months, the weights of the walls varied somewhat differently. Explaining the different behaviours is not straightforward because the weights in this period are influenced by several factors acting simultaneously. First, the load cells were influenced by changes in the temperature, as illustrated in Fig. A1. This had a large impact on the measured weight changes both in the start-up phase and during the periods when the climate simulator was out of order could not maintain a stable climate. During the first period, the simulator was defective, and troubleshooting introduced several factors that influenced the weights: fans were turned ON and OFF, and doors were opened and closed. The air pressure resulting from this action ‘pushed’ the bottom of the hanging walls to swing out of position. To restore the airtightness around the wall segments, more grease was applied. Second, the wall segment configurations and EPS quality may influence the weight changes in the start-up phase. In the traditional wall, moisture in the concrete could start to dry instantly through the air gap behind the dimpled membrane. In the permeable and semi-permeable walls, the moisture in the concrete had to move through the EPS before the weight of the wall segment could be reduced. Therefore, the weight changes in the start-up phase were influenced by both the initial moisture content and the permeability of the EPS. As the initial moisture content of the EPS was not measured, the magnitude of this impact is currently unknown. However, the instant weight decrease imposed by the permeable wall in the first two weeks might be explained by a high moisture content in the EPS combined with its low permeability. The small increase in weight portrayed by the two walls with semi-permeable EPS might be explained by moisture uptake caused by the EPS reaching equilibrium with the high RH in the exterior chamber. Experience from previous laboratory testing of EPS supports the assumption that the initial moisture content in the semi-permeable EPS was low.

Temperature measurements

The temperatures measured in the different layers in the middle of the walls are shown in Fig. A2, for the entire measurement period. Fig. A3 illustrates the temperature variations at different heights for a short period with stable drying (August 16th-18th, end of week 21). As can been seen from Fig. A3, there are differences in temperatures between the warm and cold side of the air gaps behind the dimpled membranes. The average differences are about 0.83 °C at the middle of Wall 1, about 1.1 °C at the middle of Wall 2 and about 0.32, 0.43, and 0.2 °C at the high, middle and low positions in Wall 3 respectively. The differences between the high, middle, and low positions in Wall 3 corresponds to the expected airflow situation, which is conceivable to be turbulent at the top and bottom, and more laminar at the middle.

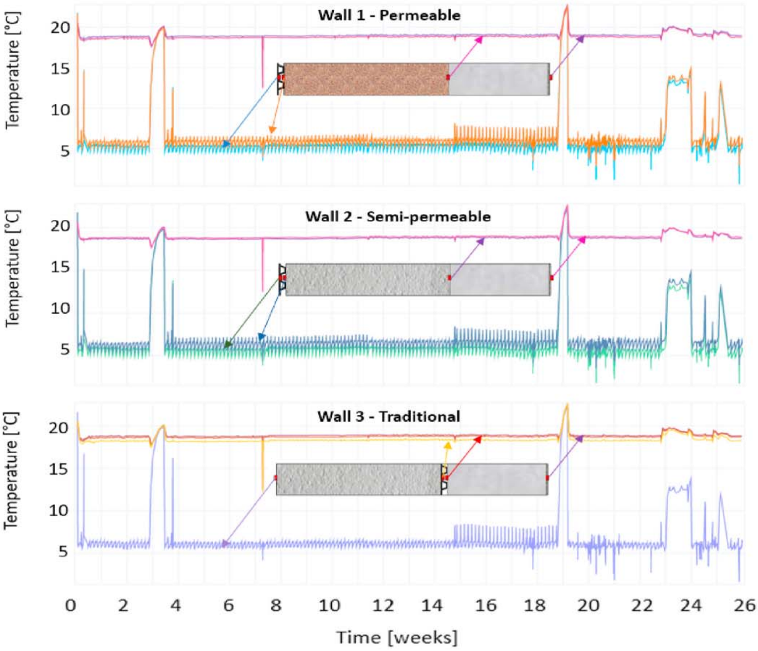

Fig. A2. Temperature variations measured in different layers at the middle of the wall during the entire measurement period. The positions of all the thermocouples are shown in Ref. [38].

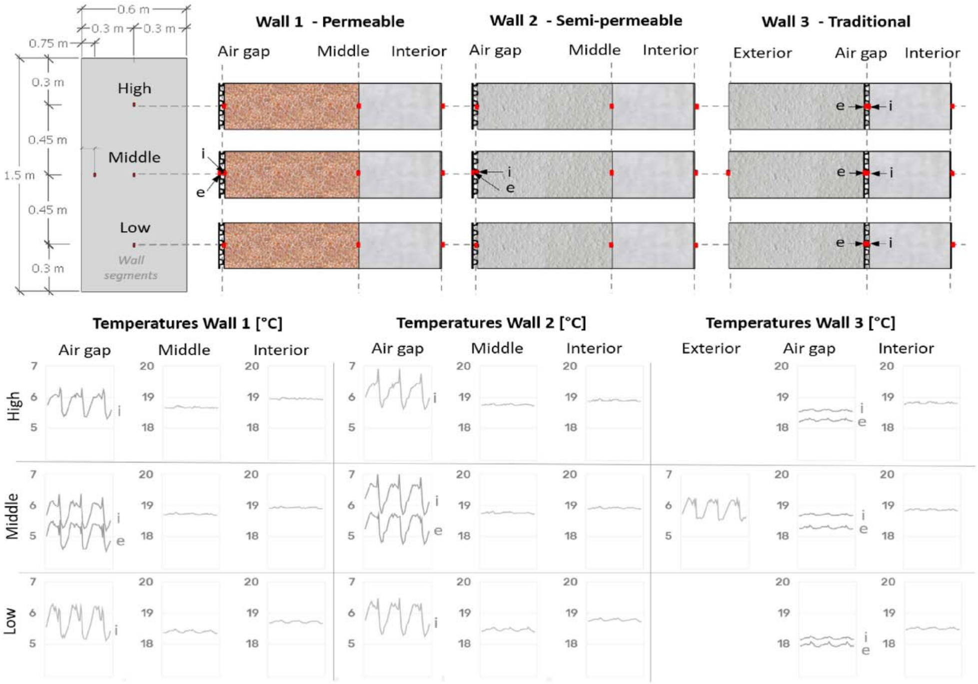

Fig. A3. Temperature variations in different depths and heights in the wall segments during a period with stable climates and drying rates (August 16th-18th, end of week 21). Interior and exterior position of the thermocouples within the air gaps are labelled **i** and **e**.

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Paper 4

Moisture resilient performance of concrete basement walls – Numerical simulations of the effect of outward drying

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Moisture-resilient performance of concrete basement walls – Numerical simulations of the effect of outward drying

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ABSTRACT

The moisture safety designs of basements used for habitation have become a topic of concern. Basements are prone to high moisture strain and have a limited outward drying ability compared with above-grade structures. The risk of interior moisture-related damage can be reduced if the basement walls are allowed to dry outward below grade. The use of vapour-permeable thermal insulation and the effect of air gaps behind dimpled membranes on the outward drying of concrete basement walls were investigated in this study. One- and two-dimensional hygrothermal simulations were conducted using WUFI®Pro and COMSOL Multiphysics®. First, the outward drying of concrete wall segments, previously investigated in a laboratory experiment, was simulated. Two EPS types and two dimpled membrane positions were compared, with an emphasis on the airflow through the air gap behind the membrane. Second, the long-term moisture performance of concrete basement walls was simulated. It was observed that when the dimpled membrane was placed between the concrete and exterior EPS, the bottom of the concrete segments dried faster than the top. When the dimpled membrane was placed on the exterior side, the concrete dried more uniformly along the height. Thus, the results indicated that the latter ensured outward drying of the concrete basement walls. However, the overall effect on the interior RH depended on the characteristics of concrete and the amount of interior and exterior insulation. Optimum drying was achieved when the thickness of interior insulation was reduced. The variability of the concrete properties used in basement walls requires further investigation.

1. Introduction

1.1. Habitable basements

In many Nordic countries, basements cover a significant share of the building volume. Traditionally, basements have been used for food storage; however, owing to population growth, rising house prices, and housing shortages, basements are often fitted out to a high standard and used as a living space. In sloped terrains, semi-basements (also referred to as daylight basements, English basements, or walk-out basements) are commonly used for habitation. Bathrooms, living rooms, and bedrooms in these types of basements feature one or more walls which are partly or entirely below the grade. An advantage of habitable basements is that heating and cooling costs may be reduced owing to earth sheltering. However, proper moisture control of habitable basements is essential to reduce the risk of moisture damage; this is because high relative humidity (RH) and moisture content (MC) in structures may lead to the growth of mould and rot fungi, structural decay, and reduced thermal performance of the basement envelope [1–4].

The exterior part of the basement envelope is prone to moisture strain owing to high RH from soil/backfill, precipitation/stormwater, and water from snowmelt [5]. These strains are also expected to increase in the near future because climate change entails frequent and intense heavy rainfall and rain-induced floods [6,7]. The moisture strain on a basement envelope may also increase owing to a stormwater management strategy that involves the infiltration of surface runoff into the ground surrounding the building [8]. Even after renovation, older structures may be prone to moisture uptake from the ground owing to poor drainage underneath the foundations. Bathrooms and laundry rooms are commonly placed in habitable basements; this results in a significant indoor moisture supply and a limited ability for the structure to dry inward. In new buildings, site-casts or concrete-block basement walls contain a significant amount of built-in moisture after construction and require structural drying [9].

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Based on existing literature and recommendations, it is possible to build habitable basements with a relatively low risk of moisture damage; this can be achieved by ensuring optimal drainage of walls and floors, insulation on the outside, and protection against water penetration from the outside by using capillary-breaking layers [5]. Vapour-permeable thermal insulation can also be used to enhance the outward drying of basement walls. However, the effect of outward drying on the moisture performance of interior wall parts requires further investigation [10, 11].

1.2. Design for outward drying

Several products have been designed to ensure the optimal moisture performance of basement walls, such as dimpled membranes, matrix panels, insulation drainage panels, drainage mats, and spray-on waterproofing membranes. Some products are capable of providing several functions on their own, others are used in combination with other products. For example, various products have been designed to eliminate the need for granular backfill, others are designed to enable outward drying [12]. Outward drying may be particularly beneficial in the following cases: 1) poor drainage below foundations that dampens the rehabilitated walls; 2) a bathroom/laundry room that inhibits inward drying; 3) cases in which the use of organic materials, such as wood, need to be increased to reduce the carbon footprint of the building.

In many countries with cold climates, vapour-permeable thermal insulation is applied to the exterior side of basement walls to realise below-grade outward drying; this is widely practised in Sweden [13], Denmark [14] and Norway [15]. The aforementioned insulation method differs from the conventional strategies (e.g. Canada [16,17], Estonia [18], USA [19] and Finland [20]), in which the exterior side of the walls is protected by a waterproofing membrane, treated with sprays or roll-on compounds, or a dimpled membrane is positioned between the wall and exterior thermal insulation.

The principal theory behind the use of below-grade vapour-permeable thermal insulation is that in heated buildings in cold climates, the temperature (T) across the basement wall decreases from the warm interior side to the cold exterior side. Therefore, vapour from the structure may diffuse through the vapour-permeable thermal insulation, owing to the difference in vapour pressure induced by the temperature differences. Subsequently, the vapour is condensed at the exterior cold side of the exterior insulation/exterior membrane/geotextile and drained to the ground below the building [21]. To mitigate the vapour diffusion, mineral wool boards or expanded polystyrene (EPS) of special qualities can be used. Different products are used with or without a draining backfill, protective exterior membrane, or geotextile. The use of vapour-permeable thermal insulation requires efficient stormwater management and on-site drainage because the exterior side of the structure becomes wet quickly when exposed to liquid water [12].

In Norway, the recommendations for below-grade walls prescribe vapour-permeable thermal insulation with a water vapour diffusion resistance factor of less than 10 to increase outward drying [15]. Moreover, it is recommended that a dimpled membrane should be placed on the outer side of the exterior insulation (exterior position). The latter differs from the recommendations in other cold-climate countries, which prescribe a dimpled membrane to be placed between the concrete and exterior insulation (medial position) or the use of a geotextile as the outer layer when the vapour-permeable thermal insulation is primarily used for drying purposes [5,12]. The dimpled membranes/sheets are designed to provide capillary breaks and vertical drainage. As shown in Fig. 1, a dimpled membrane typically consists of polypropylene sheets with a thickness of 1 mm and approximately 7–10 mm dimples extruded on one side to create an air gap.

The position of dimpled membranes is a subject of discussion among Norwegian building researchers. Those in favour of the exterior placement of the dimpled membranes argue that both solutions can realise robust structures. In contrast, some argue that the effect of outward drying is minimal and inadequately documented, and the air gap behind a dimpled membrane positioned directly on the wall (medial position) can ensure sufficient drying if the air gap is slightly ventilated [22].

1.3. Previous literature

Previous studies have investigated the efficacy of outward drying of basement walls using vapour-permeable thermal insulation. The hygrothermal simulations performed by Geving et al. [11] demonstrated that walls fitted with vapour-permeable thermal insulation ($\mu = 4.4$) exhibit faster drying and lower moisture content (MC) at equilibrium compared with standard EPS ($\mu = 50$). However, the simulations did not consider a dimpled membrane on the exterior side of the insulation. Geving et al. [11] also performed field measurements of desiccation of two basement walls rehabilitated with exterior vapour-permeable thermal insulation on the exterior side. The field measurements did not reveal any signs of drying over a period of 19 months. Blom [23] conducted field measurements of the outward drying behaviour of six concrete basement test walls and measured the temperature, RH, and MC of the wall assemblies. The study did not detect any increased drying effect in the walls with exterior vapour-permeable thermal insulation and exterior dimpled membrane compared with the walls with the dimpled membrane positioned directly on them (between the wall and insulation). The use of vapour-permeable thermal insulation combined with landscape fabric (geotextile) instead of a dimpled membrane and backfill of existing soil is a common approach applied in Sweden [12].

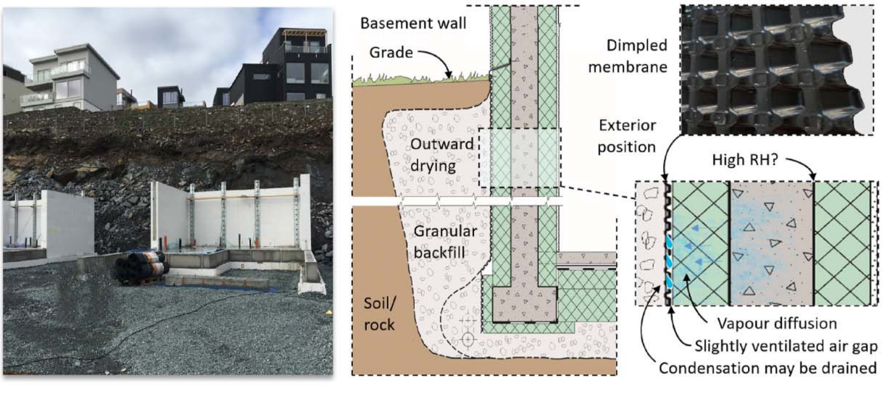

Fig. 1. Basement in dwelling during construction (left). Illustration of basement wall, a dimpled membrane, and a slightly ventilated air gap.

Pallin [12] used hygrothermal simulations to investigate the efficacy of outward drying of concrete basement walls retrofitted with exterior vapour-permeable thermal insulation in the climate of Gothenburg, Sweden. Based on the results, it was reported that the outward drying was slow, and only approximately 6–8 kg/m^2 of the moisture in the wall could be eliminated annually, at maximum. If any of the rain loads that directly hit the ground or drain from the upper wall surfaces accidently penetrate the drainage/insulation board, the expected drying potential can be equalised or reversed. To ensure a positive drying potential, Pallin [12] suggested replacing the landscape fabric with a water vapour barrier.

Few studies have focused on the ventilation and outward drying through the air gap of dimpled membranes used on the exterior side of the basement walls. However, some existing studies have investigated the exterior air gaps in above-grade walls. Although the scope of the following studies is different than that of the present study, their results are nonetheless relevant. Straube [24] performed a laboratory experiment to investigate the role of small gaps in ventilation drying and the optimum gap size required to ensure drainage. According to the results, ventilation drying could play a role in small gaps of approximately 1 mm at a pressure difference of only 1 Pa. Straube and Smegal [25] investigated the role of small gaps in ventilation drying further and used one-dimensional simulation models with source and sink enhancements to simulate the hygrothermal performance of wall systems with drained and ventilated air gaps; this study illustrated the challenges of modelling the real moisture storage of the air in the air gap and the moisture retained on the drainage gap surfaces, highlighting the significance of laboratory investigations and field studies. Finch and Straube [26] investigated the drying of ventilated claddings in above-grade exterior walls. According to Finch and Straube [26], the probable range of ventilation rates depends on the cladding type, cavity dimensions, and venting arrangement and is determined by the thermal and moisture buoyancy and wind pressures. The vent openings are critical details that should be as large as possible and unobstructed. Straube et al. [27] performed field studies on wooden-framed wall systems clad with bricks or vinyl siding. They observed that the drying rates varied significantly under different weather conditions, and the ventilation increased the drying potential of some walls. Furthermore, solar-driven vapour diffusion redistributed the vapour from within the wall to the interior (where it caused damage). Moreover, the ventilation reduced the magnitude of the flow. Rahiminejad and Khovalyg [28] reviewed the ventilation rates in the air gaps behind the cladding of above-grade walls and reported that the stack effect and wind effect are two major mechanisms driving the airflow in ventilated air spaces. Considering basement walls, solar radiation may be more influential on the part of the wall above the grade [12]. Similarly, the wind effect may be more significant on the part above grade than the part below grade; however, the stack effect may be the most significant owing to the temperature difference between the top and bottom of the walls.

Note that various studies have focused on thermally insulated basements. Saber et al. [29] showed that the air gaps in basement walls can be utilised to improve thermal performance. Goldberg and Harmon [30] conducted a comprehensive, large-scale experiment to investigate the moisture durability of interior insulation solutions for basement walls located in cold climates. Straube [9] investigated interior insulation systems by performing both in-situ measurements and hygrothermal simulations. Fedorik et al. [31] investigated various refurbishment strategies for basement walls through hygrothermal simulations, and Blom and Holøs [32] measured the drying behaviour of internally insulated basement walls. However, these studies primarily focused on the performance of the interior insulation systems. They did not address the drying behaviour achieved using exterior vapour-permeable thermal insulation or the positioning of the dimpled membranes. Presently, dimpled membranes are placed at both the exterior and medial positions in practice, as both the configurations can ensure a low risk of moisture failure [15]. However, many basement envelopes still experience extensive failure owing to flawed construction, and knowledge pertaining to robust structures is necessary [30,33]. Further knowledge of the drying ability of basement structures and possible improvements is crucial for the development of more resilient solutions.

1.4. Objective and scope

A laboratory experiment was performed to investigate the drying behaviour of concrete basement walls further and generate data for the validation of hygrothermal simulations [10]. Three concrete wall segments were fitted with different thermal insulations, and different positions of the dimpled membrane were adopted. The wall segments were subjected to steady interior and exterior climates in a climate simulator. The weights of the segments, precipitated condensation, and temperature data were monitored for six months. Although the weights of the walls varied non-uniformly at the beginning, they decreased uniformly during the last four months; they exhibited the same weight loss rate, variations, and total weight change. This indicates that the effect of the thermal insulation and position of the dimpled membrane on outward drying was negligible for the tested concrete quality, even though the MC of the concrete was maximised and the temperature difference across the insulation (driving potential for diffusion) was large (no interior insulation). The results demonstrated the need to further investigate the effect of the concrete quality on the drying behaviour of basement walls and the effect of the air gap behind the dimpled membranes when it is slightly ventilated. The following research questions were raised to address these general inquiries:

1. How do the concrete quality and vapour permeability of exterior thermal insulation affect the outward drying of concrete basement walls?
2. How does the air gap behind a dimpled membrane effect the outward drying of the concrete basement walls?
3. What is the potential of outward drying to improve the moisture performance of thermally insulated concrete basement walls?

Answers to the aforementioned research questions were sought primarily through numerical simulations using the software WUFI®Pro [34] and COMSOL Multiphysics® [35] (henceforth referred to as WUFI and COMSOL). However, this study has the following limitations.

- This study focused on newly built, functionally airtight, and externally drained basement walls above the groundwater table.
- This study focused on walls in basements used for habitation. Unheated or industrial basements were not considered in this study.
- Changes in material properties due to chemical processes, such as curing, were not considered in the simulations.

2. Methodology

2.1. General approach

Simulating the outward drying of thermally insulated basement walls numerically is a complex process requiring at least two dimensions to include the height of the wall [9,36]. In particular, it is challenging to numerically replicate the air exchange in the air gap behind the dimpled membrane and the drainage of condensed moisture. In a coupled heat and moisture transfer model, the dimpled membrane, and the air gap behind it can either be simplified as a homogeneous layer or neglected outright. If a homogeneous layer is included, moisture drying from the concrete accumulates in the thermal insulation and cannot escape through the condensation drainage. In contrast, if the membrane is neglected, moisture diffuses directly to the exterior boundary condition, which may create unrealistically high drying rates.

A better option is to use a coupled heat, air, and moisture model;

however, this approach introduces many complex uncertainties and incurs high computational costs when the full height of the wall (above and below grade) is included. Furthermore, the long-term simulations of basement walls are rendered complex by the below-grade boundary conditions. The boundary conditions vary seasonally and along the depth of the wall, including the possibility of soil freezing during winter. Therefore, a form of simplification is required for comprehensive numerical simulations. This study was conducted in three steps. The purpose of the first two steps was to examine the effect of the dimpled membrane on the outward drying of concrete walls and obtain input and knowledge for the third and final step, which was a full-scale long-term simulation of a basement wall.

The first and second steps were based on the study by Asphaug et al. [10], in which a laboratory experiment was conducted to investigate the outward drying of concrete basement walls and generate data to validate the hygrothermal simulations. Three concrete wall segments with different configurations of thermal insulation and dimpled membranes on the exterior surface were weighed continuously for six months. The wall segments were sealed against moisture transfer by applying epoxy paint on all sides except the exterior surface (which was allowed to dry on the exterior side). In addition, the wall segments were insulated around the perimeter, mounted in a wooden frame, and subjected to a stable cold and humid exterior climate and warm interior climate in a climate simulator, as shown in Fig. 2.

In the first step, the outward drying of the concrete wall segments was investigated using one-dimensional simulation models. In the second step, more advanced two-dimensional airflow models were established to investigate the air exchange in the air gap behind the dimpled membrane further. In the third and final steps, the effect of the outward drying of the concrete on the overall long-term moisture performance of basement walls were investigated. Based on the knowledge gained from the first and second steps, the dimpled membrane was omitted in the third step. The three steps are illustrated in Fig. 3 and described in more detail in Sections 2.2, 2.3, and 2.4.

2.2. Main simulation variables

The main material properties, boundary conditions, and initial conditions used in Steps 1–3 are illustrated in Fig. 3, and a detailed description is provided in Appendix A. Vapour-permeable thermal insulation $\mu > 10$ was adopted in accordance with the Norwegian building design guidelines [15]. To investigate the effect of vapour permeability on outward drying, three types of EPS with different water vapour resistance factors were compared:

- Vapour-permeable EPS $\mu = 4.4$ (applied by Ref. [11]).
- Vapour-permeable EPS $\mu = 8.2$ (measured in the laboratory experiment in question [10]).
- Semi-permeable EPS $\mu = 27.9$ (measured in the laboratory study in question [10]).

Furthermore, three types of concrete obtained from the WUFI software were compared:

- C35/45, high $D_{ww} = 1\text{E-}07$ m^2/s at 100% RH, high vapour resistance ($\mu = 248$).
- Waterproof, medium $D_{ww} = 1.3\text{E-}10$ m^2/s at 100% RH, medium vapour resistance ($\mu = 180$).
- Masea, low $D_{ww} = 5\text{E-}16$ m^2/s at 100% RH, low vapour resistance ($\mu = 76$).

The initial RH of the concrete in the basement wall of Ex. 1 was set to 99% (~100%) because concrete in such systems is cast directly in the formwork of EPS. The concrete in Ex. 2 was simulated using the same initial MC as that in Ex. 1 for comparison.

The size of the air gap openings of the dimpled membrane in Step 2 was difficult to estimate. For comparison, the openings were assumed to be equal at the two positions of the dimpled membrane. As the air gap was assumed to be slightly ventilated, the upper air gap opening was set to 1 mm to enable slight air transfer. The lower air gap opening was varied from 5 mm (the width of the air gap in the simulation model) to a minimum of 1 mm in the simulations.

2.3. Runtime and convergence

Large and complex numerical models require more resources to run efficiently and a well-composed numerical setup to ease convergence. The one-dimensional simulations in Step 1 were performed without convergence failures. However, the two-dimensional air flow simulations in Step 2 were more problematic, especially as the height of the wall increased and the air gap openings reduced. Sufficient convergence and runtime were achieved by removing the several unnecessary details and improving the mesh refinement around the air gap openings. In the long-term simulations in Step 3, implementing the boundary conditions was challenging because the climate varied with the height of the wall, and the climate data consisted of hourly values. Animation was created from the T, RH, and MC plots to analyse the results. An area on the exterior side of the exterior insulation, at the border between above and below grade, was identify as the main cause of errors. Acceptable convergences and runtimes were achieved by 1) reducing the number of data points in the climate files, 2) using an interpolated graph to implement the climate data for one year and repeating it with a mod-function at each boundary, and 3) using a piecewise interpolation of

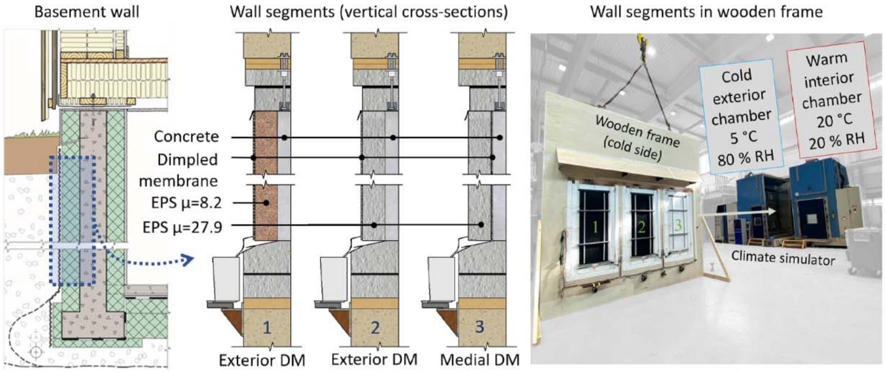

Fig. 2. Concrete wall segments (left) positioned in the wooden frame in the climate simulator (right).

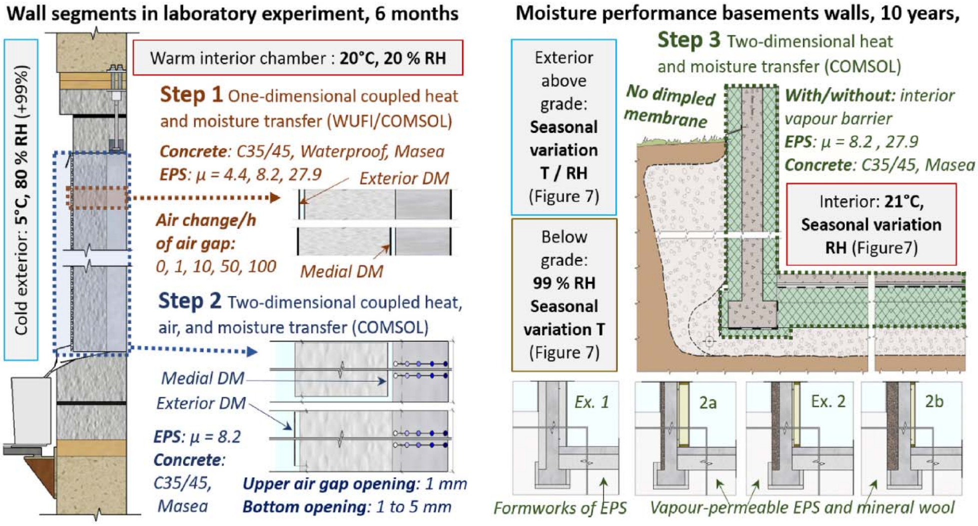

Fig. 3. Main setup, boundary conditions, variable material properties, and model/geometry in Step 1 (upper left), Step 2 (lower left), and Step 3 (right). Detailed descriptions can be found in Section 2.2, 2.3, 2.4, and in Appendix A. Steps 1 and 2 were conducted to investigate the effect of the dimpled membrane on the outward drying in the laboratory experiment. Step 3 was conducted on basement walls without a dimpled membrane, and the effect of outward drying on the moisture performance of interior wall parts was evaluated.

the material data instead of linear interpolation, which reduced the calculation time by half.

2.4. Step 1 - Outward drying of concrete wall segments

The one-dimensional hygrothermal simulations were conducted using WUFI to investigate the influence of vapour permeability of the EPS, concrete characteristics, and position of the dimpled membrane (exterior or medial) on the outward drying of the concrete wall segments.

First, the wall segments were studied by omitting the dimpled membrane from the simulation; it was assumed that the moisture from the concrete could dry directly into the air in the cold and humid climate chamber. Because concrete characteristics may significantly affect the simulated heat and moisture transfer [37] simulations were performed for three concrete types (C35/45, Waterproof, and Masea) and three EPS types (μ = 4.4, 8.33, and 27.9). The simulation period was set to six months in accordance with the laboratory experiment.

Second, the influence of the air exchange behind the dimpled membrane was investigated for both the exterior and medial positions, as illustrated in Fig. 4. Simulations were performed for concrete C35/45, EPS (μ = 8.2), and different air exchanges with exterior air (0, 1,10, 50, and 100). The geometry of the dimpled membrane was simplified, as shown in Fig. 4. Concrete C35/45 was chosen for this investigation because the initial simulations showed that a high liquid permeability would allow for a more rapid initial drying behaviour (faster flattening of the MC graphs). EPS (μ = 8.2) was used to simulate both the exterior and the medial positions. Fig. 4 shows the one-dimensional simulation models, dimensions, boundary conditions, and materials and illustrates the simplification of the dimpled membrane.

2.5. Step 2 - Airflow in air gap behind the dimpled membrane

Step 1 illustrates the need to investigate the effect of the airflow from the exterior into the air gap behind the dimpled membrane on the outward drying of the concrete wall segments.

First, the two-dimensional model of a concrete wall segment was created in COMSOL without an exterior dimpled membrane (one-dimensional layout, concrete, and EPS). The COMSOL model was created according to the procedure described in Ref. [35] and adopted

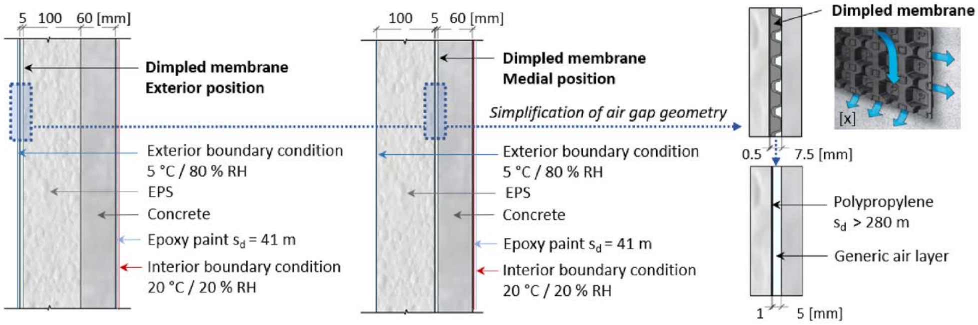

Fig. 4. Step 1 - One-dimensional models of concrete wall segments with exterior and medial position of the dimpled membrane, simplification of air gap geometry, main input data, and dimensions.

the physical principles described in Ref. [38]. The reduction in MC at five depths of the concrete over six months was compared with the MC reduction results obtained using the one-dimensional WUFI model from Step 1 (Appendix B). Neglecting minor deviations, the results can be considered in agreement with each other. Small differences in the liquid transfer coefficient (D_{ww}) in COMSOL and WUFI were identified as the primary causes of the deviation. In COMSOL, D_{ww} was implemented as a function of RH instead of the moisture content. Several points were manually added to the built-in D_{ww} curve of COMSOL to create a more continuous function and achieve a sufficient correlation.

Second, the two-dimensional COMSOL model of the concrete wall segment was developed further to include the dimpled membrane, the air in the exterior climate chamber, and the subsequent air flow within the gap of the dimpled membrane, as illustrated in Fig. 5. The exterior and medial positioning of the dimpled membrane were compared. The height of the concrete was set to 1.5 m, and EPS $\mu = 8.2$ was used. Different thicknesses of the air gap openings (2–5 mm) were investigated. The concrete types C35/45 and Masea were compared.

The model was established according to the procedure described previously [39]. An open boundary was set as the left and upper boundary conditions to include air in the cold exterior chamber, the effect of gravity, and pressure differences. The dimpled membrane was modelled as a *line* and not as a layer to reduce the number of mesh elements and ease convergence. In the moisture transport node, the membrane was defined as a *thin moisture barrier* with a vapour diffusion equivalent air layer thickness (s_d) of 280 m. In the air transfer node, the membrane was defined as an *interior wall* (no slip). In the heat transfer node, the membrane was defined as a *thin layer (nonlayered shell)* with thermal resistance (0.0003). Both *laminar flow* and *turbulent flow* were tested; however, *laminar flow* was found to be the most appropriate owing to the low air velocity of the air in the simulations. The air velocity of the air was less than 0.31 m/s within the exterior chamber, less than 0.015 m/s within the air gaps of the medial positioned dimpled membranes and less than 0,025 m/s for the contemporary positioned.

2.6. Step 3 - Long-term moisture performance of basement walls

To investigate the effect of the outward drying of the basement walls on the overall moisture performance of the interior wall parts, long-term simulations of various basement wall-floor transitions were performed. The exterior boundary conditions below the grade included the seasonal variation in temperatures along the height of the below-grade part of the walls. The exterior dimpled membrane was omitted from these assessments to ease convergence, including the air exchange in the air gaps behind the dimpled membrane, which is considered numerically challenging for long-term simulations with varying boundary conditions. Based on the results from Step 2, it can be concluded that the basement walls exhibited a slightly higher drying rate compared to the exterior position owing to the omission of the dimpled membrane.

2.6.1. Numerical model

A two-dimensional model of the basement wall was created using the COMSOL software. The model consisted of a 100 mm thick concrete floor and a 170 mm thick concrete wall. Four configurations with various types of exterior and interior thermal insulation were investigated, as illustrated in Fig. 6. Ex 1. represented a basement wall that is widely used in Nordic countries, with concrete cast directly into formwork of EPS. Ex. 2 represented a basement wall with exterior vapour-permeable thermal insulation and a wooden framework insulated with mineral wool on the interior side. The basement wall in Ex. 2 was also simulated with different thicknesses of the exterior and interior insulation (Ex. 2a and 2b). The two-dimensional models of the concrete basement walls with the main input data, dimensions, and monitoring positions are illustrated in Fig. 6. In normally dry and sufficiently ventilated rooms, omitting the vapour barrier may enable the concrete to dry faster by drying to the interior. In bathrooms, on the other hand, the interior surfaces may have a high vapour resistance, which restricts the ability of the walls to dry inward. The interior surfaces of both basement walls were simulated with and without a vapour barrier.

2.6.2. Exterior boundary conditions above grade

Above the grade, the basement walls were subjected to exterior temperatures and RH variations based on the moisture design reference year (MDRY) of Oslo, Norway (determined by Geving [40] and applied in the WUFI software [34]). The MDRY data were determined based on real measurements; however, the data is composed with higher moisture loads and colder temperatures than in a typical year. The reference year data were based on 3–4 daily measurements, and hourly values were interpolated between them. The original dataset consisted of hourly temperatures and RH values. To reduce the computational costs, a climate file was created using 12-h averages, as shown in Fig. 7. Thus, the number of data points per year was reduced from 8760 to 730. Short- and long-wave radiation and precipitation were neglected.

2.6.3. Interior boundary conditions

The indoor temperature was set at 21 °C. The indoor RH varied with the exterior climate (MDRY Oslo [40]) according to NS ISO 13788:2012 [41] and moisture load according to Humidity Class 3, which is defined in Table 1. The interior boundary conditions are shown in Fig. 7.

2.6.4. Exterior boundary conditions below grade

The below-grade RH was set to 99% according to EN 15026:2007

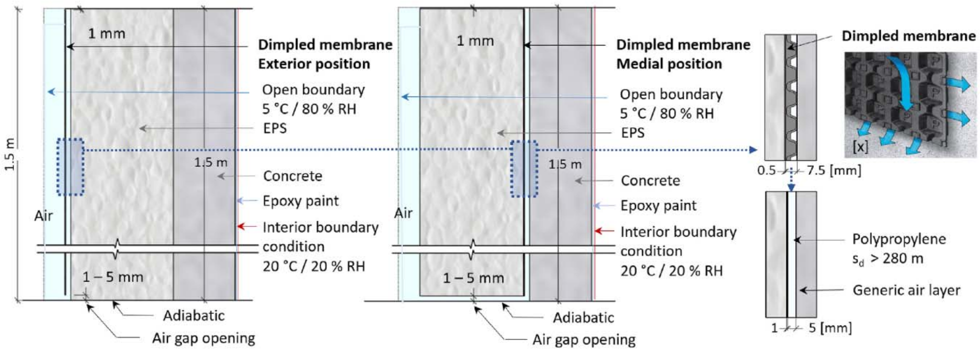

Fig. 5. Step 2 - Two-dimensional models of concrete wall segments with exterior and medial positioning of the dimpled membrane, simplification of the air gap geometry, main input data, and dimensions. Additional simulations were performed to investigate the outward drying changing the RH in the exterior chamber from 80 to 99%, see Fig. C1 Appendix C.

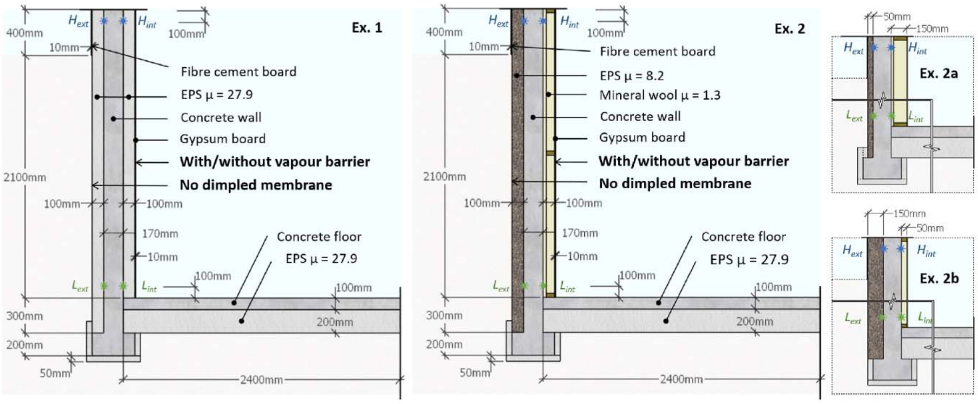

Fig. 6. Step 3 - Two-dimensional models of the concrete basement walls with main input data, dimensions, and monitoring positions. Ex. 1 with formwork of EPS (left) and Ex. 2 with exterior vapour-permeable EPS and interior mineral wool (middle and right). Ex. 1 and Ex. 2 were simulated for two types of concretes without a dimpled membrane on the exterior side and with and without an interior vapour barrier. Simulations were also performed for Ex. 2 for different thicknesses of interior and exterior insulation (left).

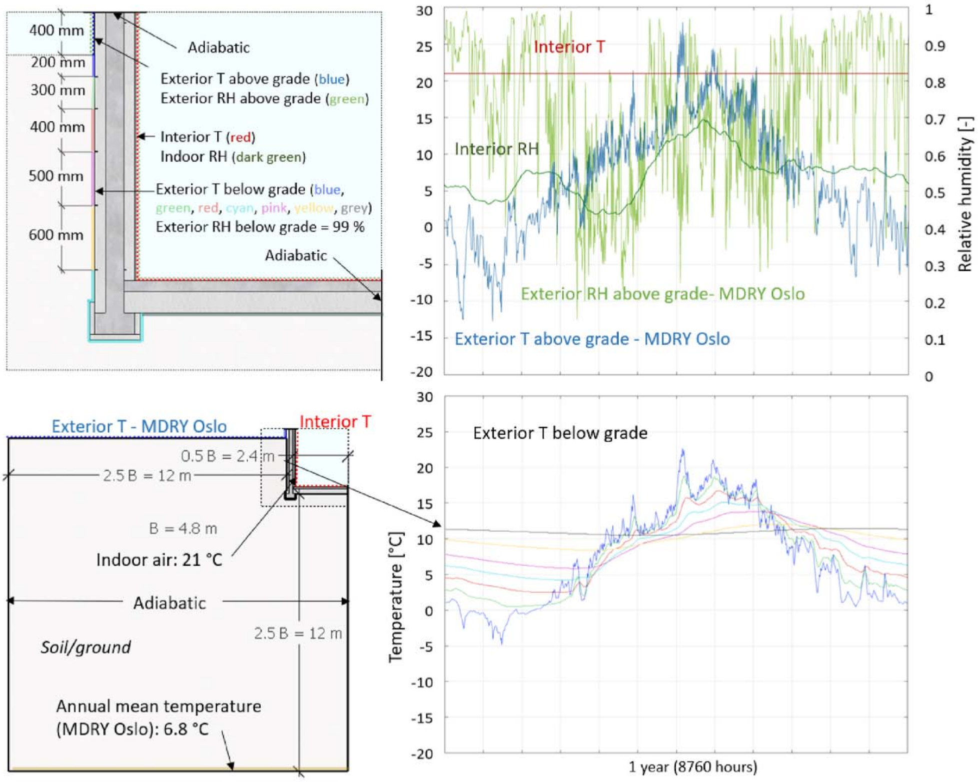

Fig. 7. Main boundary conditions for the basement walls (upper left), temperature and RH variations for the repetitive year (upper right), and varying temperatures below the grade (lower right). Below-grade temperature variations were determined using a separate heat transfer simulation model (lower left). A detailed description of the input parameters is provided in Appendix A.

[42]. The annual temperature variations below the grade were determined using a separate heat transfer simulation of the basement wall-to-floor transition and a large part of the exterior ground. The temperature variations were determined based on the study by Asphaug et al. [36]. Moisture transfer to the soil and evaporation at the soil surface have a significant effect on the heat transfer to the ground [43,

Table 1
Moisture load according to Humidity Class 3.

Outdoor temperature [°C]	−20	0	20	30
Moisture load [g/m^3]	6	6	1	1

44]; however, they were not considered for determining the below-grade boundary conditions. The objective of this study was to compare the moisture performance differences between the different basement walls in a cold climate location. It was assumed that including the additional small variations in the exterior temperature does not significantly affect the relative differences between the walls. The simulation model and main input values are shown in Fig. 7.

The temperature variations on the exterior side of the below-grade basement walls were obtained as integrated averages for each output time at various sections/heights below the grade, as shown in Fig. 7. Initially, the lengths of the sections were equal; however, because the temperature differences between the sections were larger closer to the grade, decreasing the length towards the surface improved the temperature distribution on the basement wall. The indoor air temperature was set to 21 °C, and the lower ground temperature was set to 6.8 °C, which is the annual mean of the MDRY of Oslo. The size of the simulated ground section and soil properties were based on the recommendations of the NS-EN ISO 13793:2001 [45]. A building with dimensions of 12 × 8 m was considered, which resulted in a characteristic width of B = 4.8 m. Freezing was considered by modelling the soil as a phase change material, which changes properties when the temperature approaches −1 °C. The latent heat of fusion of water at 1 atm. was set to 334 kJ/kg, which was the default setting in COMSOL and used by Saaly et al. [46]. The simulation was run for 12 years to stabilise the heat loss. The last year was used for the exterior temperature variations (boundary conditions) below the grade, as shown in Fig. 7. The MDRY of Oslo with 12 h values were used for the exterior air temperature variations. The output times were set to 12 h, which was equal to the dataset used for the wall part above the grade.

3. Results

3.1. Outward drying of concrete wall segments (Step 1)

The one-dimensional coupled heat and moisture transfer simulations of the concrete wall segments were conducted using WUFI. The dimpled membrane was not considered in the initial simulations (Appendix D; Fig. D1). Based on the results, it can be concluded that the concrete characteristics affected the outward drying of the wall segments significantly. The concrete with the highest liquid permeability (C35/45) exhibited the largest weight change. The results elucidated the mechanism of moisture accumulation within the thermal insulation from the C35/45 concrete before the drying of the accumulated moisture by the exterior air. The Masea concrete resulted in little moisture accumulation within the thermal insulation owing to the slow drying of the concrete. Thus, the effect of vapour permeability of the thermal insulation on the outward drying of the concrete may be less for slow-drying concrete.

Subsequently, one-dimensional simulations considering the dimpled membrane were performed using WUFI. The effect of two different positionings of the dimpled membrane (exterior and medial) and that of different air exchange rates at the air gap behind the dimpled membrane were compared (see Appendix D, Fig. D2). The results elucidated the effect of the air exchange with the exterior air on outward drying. When the air exchange with the exterior air was low or absent, the MC of the air in the air gaps increased to 100%; this indicates that condensation would occur within the gaps. When the air exchange was low or absent, the drying of the concrete was larger for the exterior positioning of the dimpled membrane than for the medial positioning. At an air exchange rate of approximately 10, the drying observed for the two positionings was approximately equal.

3.2. Airflow in air gap behind the dimpled membrane (Step 2)

The concrete wall segments with two different positionings of the dimpled membrane (exterior and medial) were compared. For the comparison, different air gap openings at the bottom and different RH of the exterior air were considered (80%, which is according to the laboratory study, and 99%, which is similar to below grade). The results obtained using COMSOL are summarised in Fig. 8 (RH exterior air = 80%). Note that the wall with the medially positioned dimpled membrane enabled the concrete to dry faster at the bottom; however, the wall with an exterior dimpled membrane dried more uniformly along its height. Overall, the walls dried uniformly over six months. However, a difference was observed in the moisture distribution along the height. Note that the MC in the thermal insulation and air gaps increased and decreased during the 6-month period, in accordance with the results from Step 1. Smaller air gap openings increased the RH in the air gaps. Furthermore, it ensured longer periods of condensation. Exterior air with 99% RH resulted in a relatively high MC in the thermal insulation and a slightly slower drying of the concrete segments compared to 80% (Appendix C).

3.3. Long-term moisture performance of basement walls (Step 3)

Long-term simulations of the basement wall-floor transition were performed to investigate the effects of the outward drying of basement walls on the overall moisture performance of the components of the interior wall. Based on the results of Step 2, the exterior dimpled membrane was not considered; thus, the simulations presented slightly higher drying rates than those obtained for the exterior positioning of the dimpled membrane (see Fig. 8). The two basement wall configurations (Ex. 1 and 2) were investigated using the two concrete types (C35/45 and Masea), with and without an interior vapour barrier. The decrease in the RH at the four monitoring points (at the interface between the concrete and insulation) over ten years is shown in Fig. 9.

From the graphs, it can be inferred that the exterior side (dotted lines) of the concrete walls dried faster than the interior side (solid lines) for all the simulated cases. When a vapour barrier was applied to the interior side, the concrete wall in Ex. 2 dried faster than that in Ex. 1 for both types of concrete. The difference was the largest on the exterior side (dotted lines) and the lowest on the interior side (solid green line). At the upper interior side (solid blue line), the RH was affected by the fluctuations in the exterior temperature. Fig. 10 shows the RH and temperature at a cross-section at a high position in the basement walls after 10 years. Ex. 2 was also simulated by varying the thicknesses of the interior and exterior thermal insulation, as shown in Fig. 11. Masea concrete without the interior vapour barrier was selected for the simulations owing to the high interior moisture content portrayed by wall in Ex.2, as shown in Fig. 10.

4. Discussion

4.1. Effect of concrete type and permeability of thermal insulation on outward drying

The outward drying of the concrete wall segments was compared for a period of six months under stable internal (20 °C, 20% RH) and external boundary conditions (5 °C, 80% RH). From the one-dimensional heat and moisture simulations, it was observed that there was a significant difference between the two concrete types, C35/45 and Masea, owing to the differences in material characteristics. As shown in Fig. D1 of Appendix D, C35/45 dried out more than Masea during the six months. The difference between the drying rates decreased as the vapour resistance of the exterior thermal insulation increased. The MC of the cross-sections through the concrete wall segments indicated that the Masea concrete dried the fastest at the surface (owing to the low vapour resistance); however, a slower drying rate was observed deeper

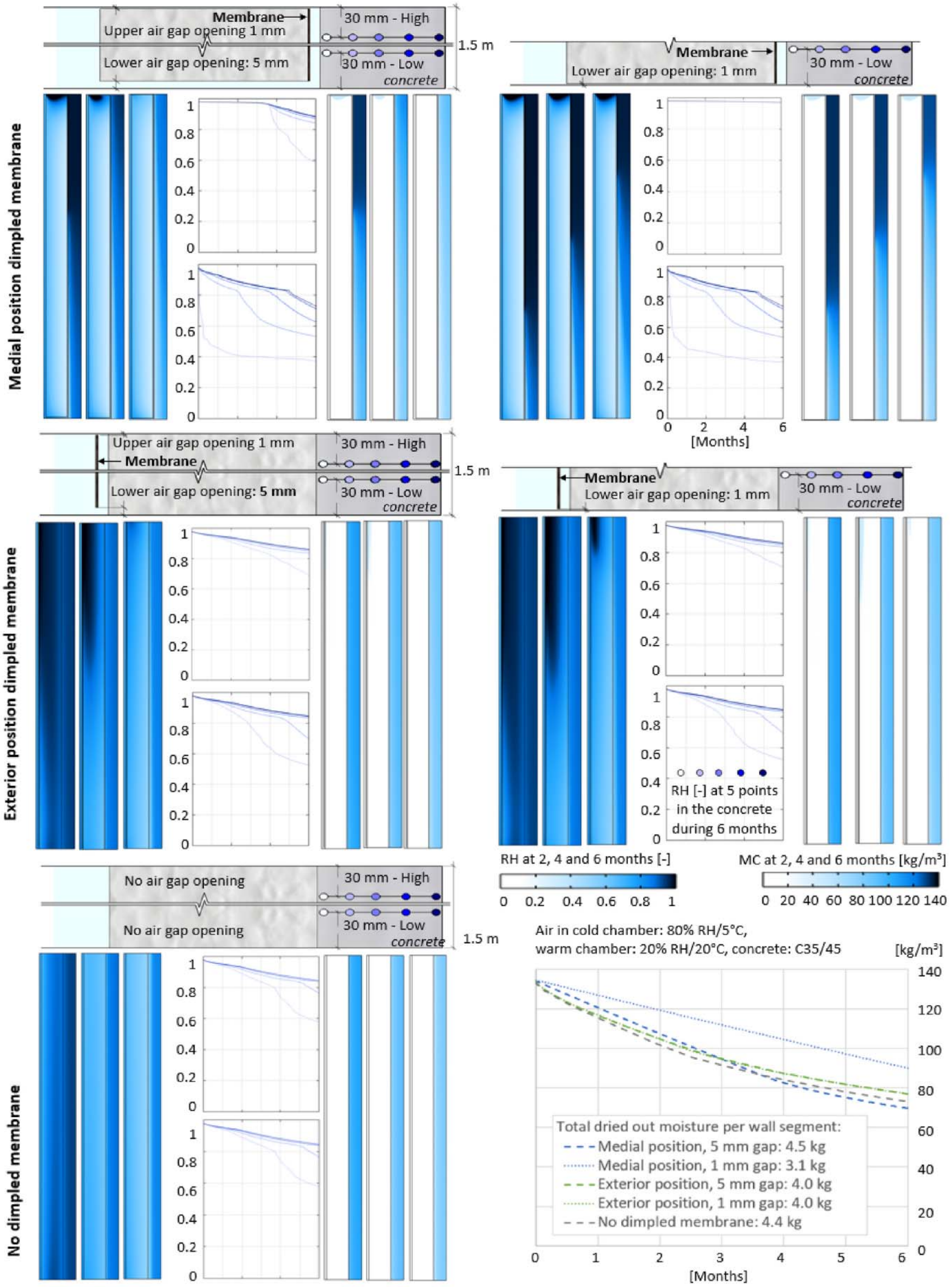

Fig. 8. Concrete wall segments with medial positioning of dimpled membrane and two lower air gap openings (upper left and right), exterior positioning with two air gap openings (middle left and right), and no dimpled membrane (lower left). The upper and lower graphs show the decrease in RH at the five points in the upper and lower part of the concrete, respectively. The left and right plots show the RH and MC for two, four, and six months of drying. The graphs (lower right) show the decrease in average MC of the concrete segments for the five situations considered during six months of drying, and the total amount of dried out moisture per wall segment.

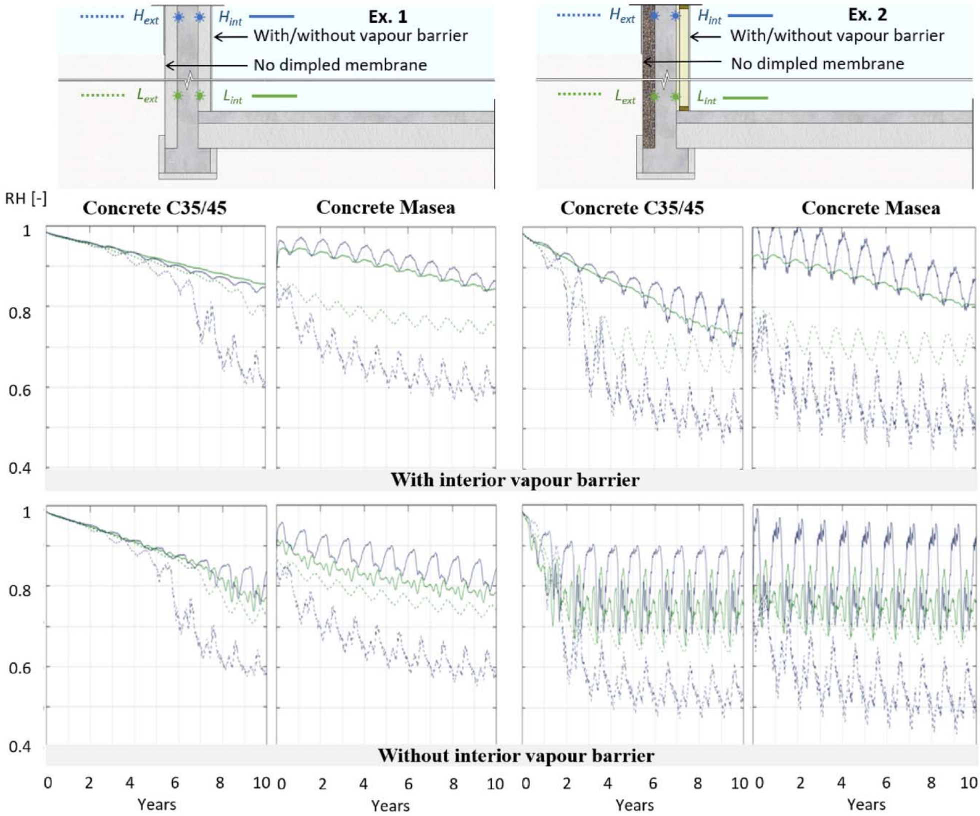

Fig. 9. The ten-years decrease in RH at the four monitoring points located at the interface between the concrete and insulation. Note that the y-axes span from 40% to 100% RH. The positions of the monitoring points are marked in the upper figures.

into the concrete owing to the low liquid conductivity (D_{ww}). The MC at the surface of C35/45 concrete did not decrease as rapidly as that of Masea owing to the high liquid conductivity (D_{ww}) of C35/45; however, the moisture was transferred faster towards the exterior surface from deeper into the concrete. Thus, it can be concluded that C35/45 concrete facilitates more outward drying, at least at high concrete MC. The drying rate of both concretes decreased as the MC decreased because the moisture-dependent liquid transfer coefficient decreased. From Fig. D1 of Appendix D, it can be inferred that the concrete segments insulated with vapour open-thermal insulation ($\mu = 4.4$) dried faster than the uninsulated concrete (which dried directly to the air in the cold and humid climate chamber); this was applicable for all three concrete types; however, the difference was the largest for C35/45 concrete. When the Masea concrete was insulated with the semi-permeable "standard" EPS ($\mu = 27.9$), it dried approximately as quickly as when it was uninsulated.

The drying of the two basement walls over 10 years was investigated, as shown in Figs. 9–11. From the results, it was observed that the Masea concrete dried faster at the surface than deeper into the concrete. C35/45 dried more slowly at the surface compared with the Masea concrete; this is in accordance with the results shown in Fig. D1 in Appendix D. In addition, C35/45 reached a lower MC after 10 years compared with Masea. The fluctuations in the graphs were primarily due to influences from the exterior air temperature. Therefore, the fluctuations were larger in the upper monitoring points than in the lower ones. When it was warmer outside, the moisture was transferred from the exterior to the interior. Note that the oscillations of the RH in the inner monitoring points exhibited a slight delay compared with the oscillations in the outer monitoring points. In addition, the RH in the lower monitoring points fluctuated less than that in the high monitoring points.

4.2. Effect of air gap behind the dimpled membrane on outward drying

The effect of the positioning of the dimpled membrane on the outward drying of the concrete wall segments was compared. The comparisons were made using concrete C35/45 for a period of 6 months under stable warm (20 °C, 20% RH) and cold boundary conditions (5 °C, 80% RH). First, the one-dimensional heat and moisture simulations were performed for different air exchange rates in the air gap, as shown in Fig. D2 of Appendix D. For the exterior positioning of the dimpled membrane, the graphs showed that the moisture in the concrete dried at the same rate, regardless of the air exchange rate behind the dimpled membrane. However, the MC of the generic air layer was unrealistically high in the simulations, suggesting that condensation occurred. For the medial positioning of the dimpled membrane, the concrete dried slowly at low air exchange rates. Note that the results for the medial positioning were similar to the results for the exterior positioning for an air exchange rate of approximately 10/h. However, the air exchange rates are difficult to predict for slightly ventilated air gaps. Concrete C35/45 was used for these assessments. Thus, it can be concluded that concretes that dry slowly, such as Masea, would exhibit smaller differences between the drying rates for the two positionings of the dimpled membrane.

The effect of the airflow through the air gap behind the dimpled membrane on the outward drying of the concrete wall segments was investigated further using two-dimensional heat, air, and moisture

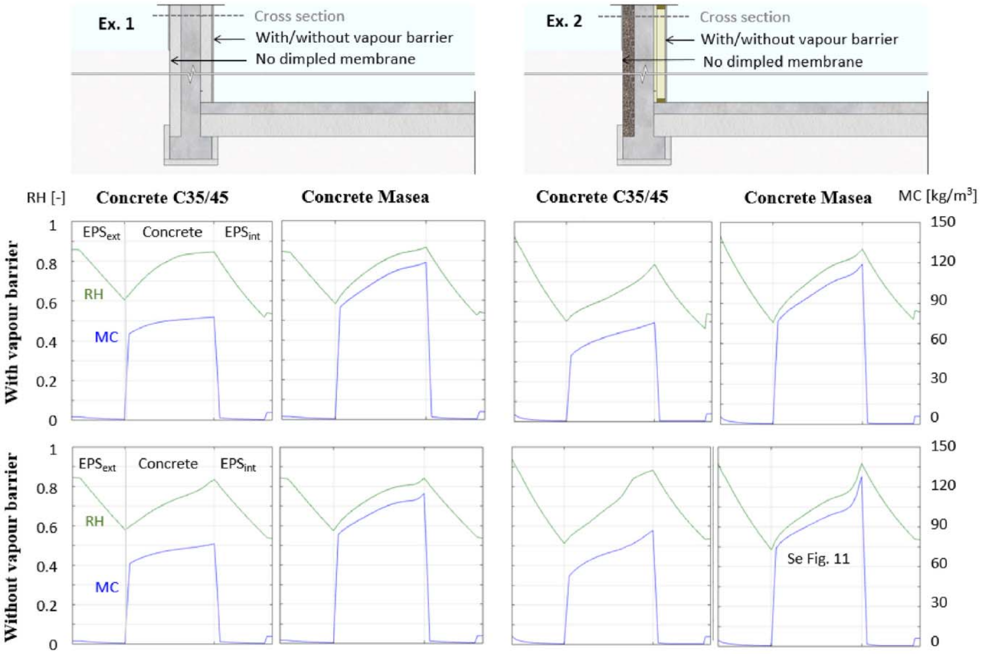

Fig. 10. MC and RH through the cross-section at the high position in the basement walls after 10 years. The position of the cross-section is shown in the upper figures. Ex. 2 with Masea concrete and without an interior vapour barrier is illustrated in Fig. 11 with different thicknesses of the exterior and interior insulation.

simulations, as shown in Fig. 8. From the figures, it can be observed that the concrete wall segments with a medially positioned dimpled membrane dried much faster at the bottom than at the top. However, the segments with an exteriorly positioned dimple membrane dried more uniformly along their height. The concrete wall segments with a medially positioned dimple membrane resulted in relatively slower drying when the bottom air gap opening was reduced from 5 mm to 1 mm. The concrete segments with the exteriorly positioned dimple membranes were less affected by the changes in the opening of the bottom air gap.

The simulations of the wall segments in this study did not consider all the factors that may limit the airflow in and out of the air gaps behind the dimpled membrane in real below-grade basement walls. These factors include the variation in the air gap openings, the density of granular backfilling, wind, and stack effects. Nevertheless, the results obtained are significant as they provide a comparison between the two positionings of the dimpled membrane under similar climate conditions and air gap openings. In addition, the results of the two different positionings of the dimpled membrane were compared with those of the wall segments without a dimpled membrane. The comparison results indicate that applying a dimpled membrane at the exterior positioning, slightly reduced the drying rate, as shown in Fig. 8. For the medial positioning of the dimpled membrane (between the insulation and concrete), it is necessary to ensure that the air gap openings are sufficient to enable drying.

The wall segments in this study were simulated using boundary conditions that reflected the laboratory study. A drawback of the simulation models used in this study is their inability to remove condensed moisture from the air gaps. Instead of being removed, the MC of the air increases to higher levels than the air can realistically hold for a short period. The effect of this uncertainty on the outward drying requires further investigation; however, it was assumed that the outward drying of the concrete segments would be slightly reduced during the condensation period.

4.3. *The effect of outward drying on the moisture performance of basement walls*

The outward drying of concrete basement walls subjected to varying interior and exterior boundary conditions for over 10 years was investigated, as shown in Figs. 9–11. It was presumed that the walls were protected from exterior liquid water intrusion, either by an exterior dimpled membrane or by other measures, both above and below the grade. Thus, the effect of regular wetting by rain or stormwater was not considered. However, the exterior dimpled membrane was not considered in these simulations, owing to difficulties in including the air flow in the air gap in the full-scale simulation of the basement walls. Outward drying of the concrete wall segments with an exterior positioning of a dimpled membrane was compared with that of walls without a dimpled membrane in Step 2, as shown in Fig. 8; a small difference between the outward drying rates was observed for the two configurations.

Fig. 9 shows the variations in RH at high and low interior and exterior monitoring points at the interface between the concrete and EPS. For the basement wall with EPS formwork (Ex 1), the difference between the drying rate of the two concrete types, both with and without an interior vapour barrier, was small. The Masea concrete dried slightly faster at the exterior monitoring points owing to the low vapour resistance ($\mu = 76$); however, after 10 years, the difference between the drying rate of the two concrete types evened out. The RH at the two interior monitoring points decreased at a relatively steady rate for both the concretes, with and without a vapour barrier; however, the Masea concrete was affected more significantly by the external temperature fluctuations. The basement wall with vapour-permeable exterior insulation and interior wooden frame with mineral wool (Ex 2) exhibited a relatively greater difference between the characteristics of the two concrete types, with and without a vapour barrier. Concrete C35/45 with an interior vapour barrier had a lower interior RH after 10 years compared with the wall with more vapour-resistant EPS in Ex 1. The Masea concrete, which is more vapour-permeable, resulted in higher RH

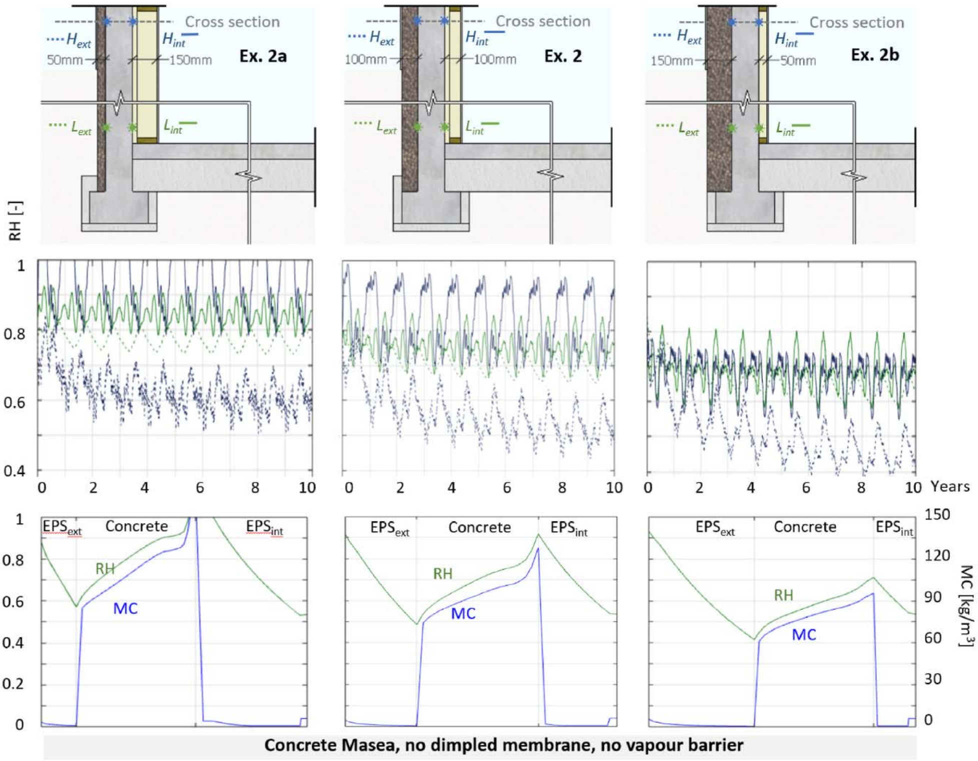

Fig. 11. The 10-year decrease in RH at the four monitoring points (at the interface between the concrete and insulation) (upper). Note that the y-axis spans from 40% to 100% RH. MC and RH through the cross-section at the high position in the basement walls after 10 years (lower). The position of the monitoring points and the cross-section is marked in the upper figures.

on the interior side, even up to 100% in the first years. On the exterior side, however, the RH values were similar. For both the concrete types, the interior vapour barrier resulted in a higher RH on the interior side of the concrete. This indicates that if a vapour barrier is to be used in this type of wall configuration, it should be positioned between the concrete wall and interior insulation.

The basement walls in Exs. 1 and 2 are conventional walls, and they are not considered typical high-risk structures in terms of moisture damage. Note that the objective of investigating the two different types of basement walls was not to determine the wall with the best performance but rather to elucidate the effects of outward drying. Fig. 10 shows that the moisture performance of the basement walls decreased as the thickness of the interior insulation increased. The best performance was achieved when most of the exterior vapour-permeable insulation was positioned on the exterior side.

The primary goal of a moisture-resilient basement wall design is to prevent the walls from being subjected to liquid water from the exterior side. Thus, for externally insulated, well-drained, and airtight basement walls in new buildings with good ventilation, the effect of external drying is considered less significant. For older basement walls, where poor drainage results in moisture absorption via foundations, outward drying may be a suitable method to achieve a drier wall. In this case, the thermal insulation should mainly be positioned on the exterior side of the concrete.

4.4. Uncertainties and limitations

Different concrete characteristics results in different drying rates of the basement walls. The spans of the different properties exhibited by the concrete used in basements requires further investigation.

The initial RH of the concrete in the basement wall of Ex. 1 was set to 99% (~100%) because for this type of basement walls, the concrete is cast in situ in an EPS formwork. For comparison, the concrete in Ex. 2 was simulated using the same initial MC as that in Ex. 1. The concrete used in Ex. 2 might have dried slightly at the surfaces during the time before insulation was added. It was assumed that this drying did not significantly affect the overall results/comparison over 10 years.

In this study, the accuracy of the numerical model in realistically replicating the moisture transfer in the concrete during the drying process was uncertain. The complex coupled heat and moisture transfer models for building components always involve the simplification of real-life factors. Moreover, some materials (e.g. concrete) do not conform to the simplified transport equations, and their material properties are dependent on their present and past moisture content. Therefore, materials with pronounced hysteresis in their moisture storage function (e.g. concrete) may not be accurately described by an averaged moisture storage function [38]. The total moisture transfer resulting from the combination of the liquid and vapour transport processes under varying thermal conditions is also difficult to calculate; this is because the two flows occur simultaneously and cannot be separated for laboratory experiments. The errors caused by these general inaccuracies may be negligible or severe. The results should be compared with measurements to determine the reliability of the calculations.

5. Concluding remarks

The concrete characteristics significantly affected the prediction results of the drying of concrete wall segments. During the six-month period, the concrete with a high liquid transfer coefficient and high vapour resistance (C35/45) dried faster than the concrete with a low liquid transfer coefficient and low vapour permeability (Masea). The Masea concrete dried faster at the exterior surface but exhibited a slow drying rate owing to the low rate of capillary moisture transfer. The concrete with a high liquid transfer coefficient (C35/45) dried slower at the surface but dried faster all the way through the concrete compared with the Masea concrete; thus, it exhibited an overall faster drying rate at high MC. The difference between these two types of concrete also decreased as the vapour resistance of the exterior thermal insulation increased. The concrete insulated exteriorly with vapour-permeable thermal insulation ($\mu = 4.4$) dried faster than the uninsulated concrete, in the laboratory setting (with cold and humid air in the exterior climate chamber, and warm air in the interior climate chamber). This tendency was observed for all three types of concrete; however, the difference was the largest for the concrete with the highest liquid transfer coefficient (C35/45). When the concretes were insulated with the semi-permeable EPS ($\mu = 27.9$), the concrete with the lowest liquid transfer coefficient (Masea) dried approximately as fast as the uninsulated concrete.

The concrete wall segments with a medially positioned dimpled membrane dried much faster at the bottom than at the top, whereas the wall segments with an exteriorly positioned dimple membrane dried uniformly along their height. The concrete wall segments with a medially positioned dimpled membrane exhibited relatively slower drying when the bottom air gap opening was reduced from 5 to 1 mm. The wall segments with exteriorly positioned dimpled membrane was less affected by the changes in the bottom air gap opening; however, more moisture accumulated in the exterior parts of the exterior thermal insulation. The results indicated that the basement walls exhibited a slightly reduced drying rate when the exteriorly positioned dimpled membrane was omitted.

For the basement wall with EPS formwork (Ex. 1), the difference between the drying rate exhibited by the two concretes, with and without an interior vapour barrier, was low. The basement wall with vapour-permeable exterior insulation and an interior wall assembly insulated with mineral wool (Ex. 2) exhibited a relatively greater difference between the characteristics of the two concretes, with and without a vapour barrier. The basement wall with the fastest drying concrete (C35/45) and an interior vapour barrier exhibited a lower interior RH after 10 years compared with the wall with EPS with greater vapour resistance (Ex. 1). In contrast to Ex. 1, the use of Masea concrete resulted in a higher RH on the interior side, even up to 100% in the first year. However, on the exterior side, the RH was similar. For the two types of concrete, the interior vapour barrier resulted in a higher RH on the interior side of the concrete. The results indicate that for optimum performance, the vapour barrier should be positioned between the concrete and interior insulation. However, the span of the moisture properties of conventional concretes used in basement walls needs further investigation.

Therefore, a general conclusion regarding the effects of outward drying on the moisture performance of the insulated basement walls cannot be solely based on the simulations performed in this study. To determine the reliability of the simulations, the results should be compared with measurements of structures subjected to realistic climates. However, the results indicate that placing a dimpled membrane on the exterior side of vapour-permeable thermal insulation can ensure better outward drying. However, the overall effect will depend on the concrete characteristics. If the drying rate of the concrete is low, the effect of vapour-permeable thermal insulation will be less prominent. Positioning the dimpled membrane between the concrete and exterior insulation may be more feasible and can ensure better protection of the concrete and dimpled membrane. In contrast, if the drying rate of the concrete is slow, the aforementioned position of the dimpled membrane may result in sufficient outward drying if the air gap. This position may also increase the drying rate of the lower part of the wall.

CRediT authorship contribution statement

Silje Kathrin Asphaug: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Erlend Andenæs:** Writing – review & editing. **Stig Geving:** Writing – review & editing, Supervision. **Berit Time:** Writing – review & editing, Supervision, Funding acquisition. **Tore Kvande:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Appendix A. Material properties, boundary conditions and initial conditions

The material properties, initial conditions, and boundary conditions applied in the simulation are listed in Tables A1–5.

Table A1

Hygrothermal properties of the wall segments/basement walls in Steps 1, 2, and 3. The properties of mineral wool and wood were based on data from the COMSOL library. The others were based on data from the WUFI Material database [34].

	Dimpled membrane	Air layer (generic)[a]	EPS, 4.4	EPS, 8.2	EPS, 27.9	Concrete C35/45	Concrete Waterproof	Concrete Masea	Epoxy paint[b]	Gypsum	Vapour barrier	Mineral wool	Wood
Step	1	1	1	1, 2, 3	1, 3	1,2,3	1	1,3	1	3	3	3	3

(continued on next page)

Table A1 (*continued*)

	Dimpled membrane	Air layer (generic)[a]	EPS, 4.4	EPS, 8.2	EPS, 27.9	Concrete C35/45	Concrete Waterproof	Concrete Masea	Epoxy paint[b]	Gypsum	Vapour barrier	Mineral wool	Wood
Thickness [mm]		5	100	100	100	60	60	60	1	10	n.a.	100	n.a.
Bulk density [kg/m^3]	130	1.3	26.9	26.9	23.0	2220	2300	2104	130	574	n.a.	73	532
Porosity [m^3/m^3]	0.001	0.999	0.95	0.95	0.95	0.18	0.18	0.22	0.001		n.a.	n.a.	n.a
Thermal conductivity [W/mK]	3	0.047	0.0348	0.0348	0.0348	1.6–2.5	1.6–2.5	1.3–2.2	2.3	Tab. A1	n.a.	0.035	Tab. A2
Specific heat capacity [J/kgK]	1500	1000	1500	1500	1500	850	850	776	2300	1100	n.a.	850	2700
Water vapour diffusion resistance factor [−]	280 000	0.79	4.4	8.33	27.9	248	180	76	41 000	6.9	n.a.	1.4	Tab. A2
s_d-value [m]	280	n.a.	0,44	0.33	2.79	14.88	10.8	4.56	41		10	1e-14	n.a.
Liquid transfer coefficients	n.a.	n.a.	n.a.	n.a.	n.a.	Tab. B6			n.a.	Tab. A2			Tab. A2
Moisture storage function	Tab. A2												

[a] Without additional moisture capacity.

[b] In Step 2, epoxy paint was included in the interior surface transfer coefficient.

Table A2

Moisture storage function of the materials described in Table A1.

DM/Epoxy paint	Air layer	EPS	C35/45	Waterproof	Masea	Gypsum	Mineral wool	Wood
RH:MC	RH:MC	RH:MC 0:0	RH:MC 0:0	RH:MC	RH:MC 0:0	RH:MC	RH:MC	RH: λ
0:0	0:0	0.5:0.461	0.33:37	0:0	0.065:25.5	0:0	0:0	0:0.1
0.5:0.000485	1:0.017	0.6:0.687	0.43:38	0.05:27	0.113:29.6	0.33:5	0.33:0.51	0.97:0.15
0.6:0.000724		0.7:1.06	0.63:65	0.1:32	0.329:46.1	0.75:7	0.75:0.62	1:0.6
0.7:0.00112		0.8:1.79	0.8:75	0.15:34	0.582:80.1	0.97:18	1:4.1	RH:μ
0.8:0.00188		0.85:2.49	0.83:76	0.2:35	0.754:101	1:370		0:200
0.85:0.00262		0.9:3.83	0.93:104	0.3:37	1:144	RH: D_w		0.25:180
0.9:0.00403		0.91:4.26	1:147	0.4:40		0:1.85e-10		0.5:65
0.91:0.00448		0.92:4.78		0.5:48		0.8:1.85e-10		0.6:45
0.92:0.00503		0.93:5.43		0.6:58		1:1.59e-7		0.7:30
0.93:0.00572		0.94:6.27		0.7:72		RH:λ		0.9:20
0.94:0.0066		0.95:7.38		0.8:85		0:0.19		1:10
0.95:0.00777		0.96:8.94		0.9:100		0.97:0.21		RH:WC
0.96:0.00941		0.97:11.3		0.95:118		1:0.6		0:0
0.97:0.0119		0.98:15.1		1:150				0.55:45
0.98:0.0159		0.99:22.7						0.75:80
0.99:0.0239		0.995:30.2						0.97:185
0.995:0.0318		1:44.8						1:870
1:0.0471								RH: D_w
								0: 1.32e-13
								0.65:1.32e-13
								1:8.03e-11

Table A3

Material properties of the soil/ground considered in Step 3. After a comparison between the available sources, the properties provided in NS EN ISO 13793:2001 were used for the simulations.

	NS EN ISO 13793:2001		NS-EN ISO 13370:2017		NS-EN ISO 10456:2007+NA:2010		WUFI
	Homogeneous soil		Clay or silt	Sand or gravel	Clay or silt	Sand or gravel	12 types of soil
	Unfrozen	Frozen					
Bulk density [kg/m^3]	1350	1350	n.a.	n.a.	1200–2200	1700–2200	1267–1579
Thermal conductivity [W/mK]	1.5	2.5	1.5	2	1.5	2.0	Varies with moisture content
Water content [kg/m^3]	450 90% degree of saturation	450 90% degree of saturation	n.a.	n.a.	n.a	n.a	n.a
Heat capacity [J/m^{3}K]	3000000	1900000	3000000	2000000	n.a.	n.a	n.a.
Specific heat capacity [J/kgK]	2222	1407	n.a	n.a.	1670–2500	910–1800	850

Table A4
Boundary conditions used in Steps 1,2, and 3.

Step	Surface	Temperature [°C]	Heat transfer coefficient, α [$W/(m^2 \cdot K)$] (Heat resistance [(m^2K)/W])	RH [%]	Water vapour transfer coefficient[1], β_p [kg/m^2sPa] or [s/m]
1	Interior	20	8 (0.125) [WUFI]	20	2.2e-8[1] (Epoxy paint in separate layer)
	Exterior	5	17 (0.0588) [WUFI]	80	8e-8[1]
2	Interior	20	8 (0.125) [WUFI]	20	4.9e-12 (ink. Epoxy paint)
	Exterior	5	17 (0.0588) [WUFI]	80/100	8e-8[1]
3	Interior	21	Wall: 8.0 (0.125) [EN 15026:2007] Floor: 5.9 (0.17) [EN 15026:2007]	Fig. 6	2.2e-8[1] 4.1e-8[1]
	Exterior, above grade:	Fig. 6	20 (0.05) (incl. 10 mm fibre cement board)	Fig. 6	3e-10 (incl. 10 mm fibre cement board)
	Exterior, below grade:	Fig. 6	n.a.	99% [EN 15026]	n.a.

[1] Derived from the heat transfer coefficient: $\beta_p = 7 \cdot 10^{-9}\alpha$ [38].

Table A5
Initial conditions used in Steps 1,2, and 3.

Step		Dimpled membrane	Air layer	EPS Mineral wool	Concrete C35/45	Concrete Waterproof	Concrete Masea	Epoxy paint	Wood
1	Temperature [°C]	20	20	20	20	20	20	20	20
	Water content[1] [kg/m^3] (RH)	0.002	0.01	(1.79) 0.8	146.39 (0.999), 147 (~1)	149.36 (0.999), 150 (~1)	143.83 (0.999) 144 (~1)	0.002	(0.8)
2	Temperature [°C]	20	20	20	20	20	20	20	20
	Water content[1] [kg/m^3] (RH)	0.002	0.01	(1.79) 0.8	134.71 (0.98)	137.2 (0.98)	140.5 (0.98)	0.002	(0.8)
3	Temperature [°C]	21	21	21	21	21	21	21	21
	Water content[1] [kg/m^3] (RH)	n.a.	n.a.	(1.79) 0.8	134.71 (0.98)	137.2 (0.98)	140.5 (0.98)	n.a.	(0.8)

The liquid transport coefficient is expressed as a function of the water content in the WUFI and converted to a function of RH for use in COMSOL (see Table A6). Only D_{ww} was active in the simulation because of the absence of rain. In WUFI, moisture storage functions are described by linear interpolation; thus, a linear interpolation was also used in COMSOL in the comparison between COMSOL and WUFI an in Step 2. In Step 3, piecewise cubic interpolation was selected, as it is easier to solve numerically.

[1] The concrete in the laboratory experiment had a high initial MC resulting from curing in a water bath for 28 days after casting. At free saturation, the water content in the concrete corresponded to an RH of approximately 1. This was numerically difficult to solve using COMSOL; thus, RH = 0.999 was used for the initial comparison between the WUFI and COMSOL and in Steps 1. RH = 0.98 was used in Step 2 to ease convergence.

Table A6
Liquid transport coefficients of concrete.

	WUFI Material database			Used in the COMSOL model (Step 2 and 3)		
	wc [kg/m^3]	D_{ww} [m^2/s] (redistribution)	D_{ws} (wc)[m^2/s] (suction)	RH [−]	D_{ww} [m^2/s] (redistribution)	D_{ws} (wc)[m^2/s] (suction)
C35/45	0	2.00E-11	1.00E-09	0	2.00E-11	1,00E-09
				0.1	2.70E-11	
	29	4.00E-11	4.00E-09	0,2587	4.00E-11	4,00E-09
	72	6.00E-11	1.00E-08	0,749	6.00E-11	1,00E-08
				0.8	8.00E-11	
				0.87	1.90E-10	
	100	4.00E-10	n.a.	0,916	4.00E-10	n.a.
	116	8.00E-10	2.00E-08	0,9496	8.00E-10	2,00E-08
				0.96	2.50E-9	
	130	8.00E-09	3.00E-08	0,9724	9.00E-9	3,00E-08
				0.985	3.00E-8	
	147	1.00E-07	3.00E-07	1	1.00E-07	3,00E-07
Masea	0	0	0	0	0	0
	101	5E-18	1.44E-8	0.754	5E-18	1.44E-8
				0.82	5.1E-18	
				0.85	1E-17	
				0.9	5E-17	
				0.95	2E-16	
	144	5E-16	2.86E-8	1	5E-16	2.86E-8
Waterproof	0	0	0	n.a		
	72	7.4E-12	7.4E-11			
	85	2.5E-11	2.5E-10			
	100	1E-10	1E-9			
	118	1.3E-10	1.2E-9			

Appendix B. Comparison between COMSOL and WUFI

A two-dimensional model of the concrete wall segment from Ref. [10] was created using one-dimensional heat and moisture transfer physics in COMSOL. The geometry and user-controlled mesh called "Mapped" (rectangular mesh) are shown in Fig. B1. The epoxy paint on the interior side was modelled as a generic layer of 1 mm. A one-dimensional model of the same concrete wall segment was created in the WUFI. The grid was an Automatic (II) Fine 100 grid. In WUFI, the increased accuracy and adapted convergence were selected, and the adaptive time step control was enabled with step and max. stages: 5. The number of convergence failures was controlled; it was 0 for all simulations. The reduction in the MC at five concrete depths over six months was compared. The first comparisons showed large deviations between the results of the two programs. Corrections were made for both models to reduce the differences. Some of the changes were as follows:

- The material data input was improved.
- The transfer coefficients were improved.
- The errors in the input data were corrected.
- The mesh in the COMSOL model was improved.

Small differences in the liquid transfer coefficient D_w between the two programs were identified as the primary cause of the deviation. The small differences in D_w were attributed to the implementation of the COMSOL as a function of RH instead of MC. Several points were added to "smooth" the D_w -graph until sufficient correlation between the two programs was achieved. The reduction in MC at the five concrete depths over six months is shown in Fig. B1.

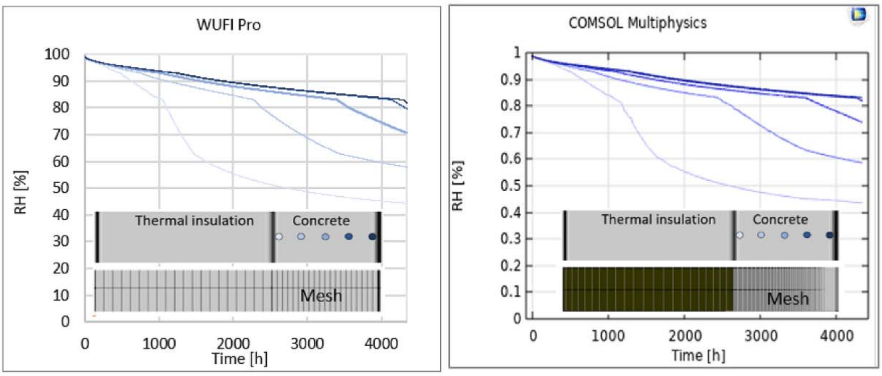

Fig. B1. The simulation models, mesh, and decrease in RH at five points in the concrete during a period of six months obtained using WUFI (left) and COMSOL (right).

Appendix C. Impact of RH in the cold humid climate chamber in Step 2

The RH in the exterior climate chamber in the laboratory experiment was intended to be ~100%; however, owing to the freezing of the cooling pipes, maintaining a low temperature of approximately 5 °C proved to be difficult. Therefore, several tests were conducted, and a temperature of 5 °C and 80% RH was maintained by defreezing for 30 min each day. Figure C1 shows the comparison between the outward drying of the wall segments in the laboratory with 80% RH and outward drying of the wall segments in the exterior climate chamber with 99% RH.

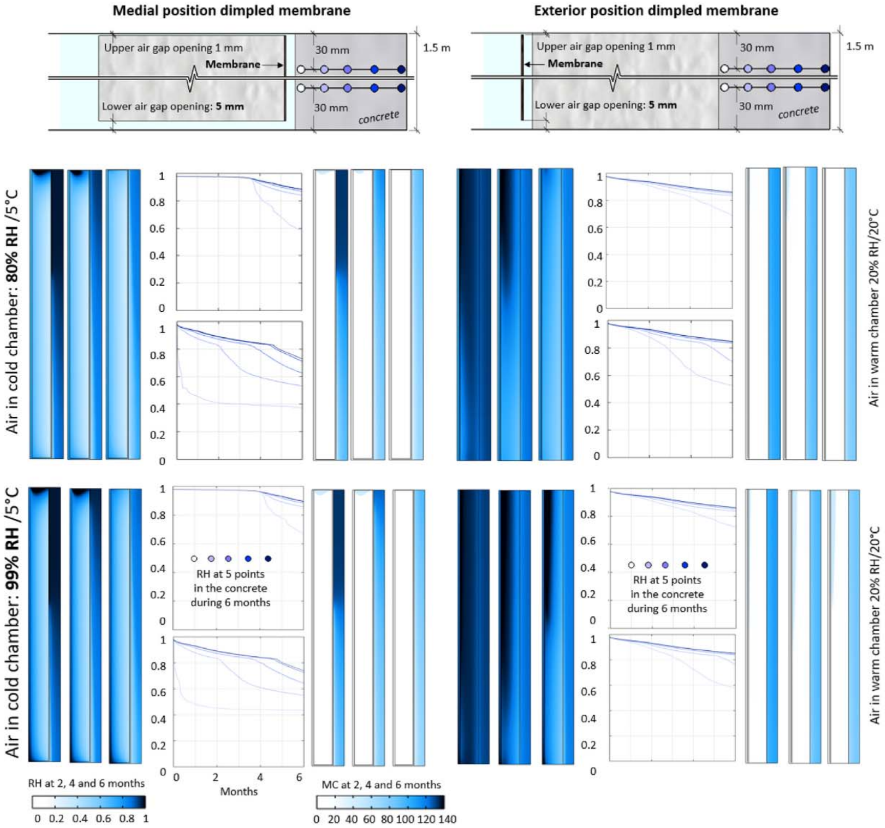

Fig. C1. Drying of the concrete wall segments in the laboratory experiment with 80% RH in the exterior cold and humid climate chamber (upper); drying of the wall segments in the exterior climate chamber with 99% RH (lower). Concrete wall segments with medial positioning (left) and exterior positioning (right) of the dimpled membrane. The upper and lower graphs in each illustration show the decrease in RH during six months of drying at the five points in the upper and lower part of the concrete, respectively. The left and right plots show the RH and MC at two, four, and six months of drying.

Appendix D. Results from one-dimensional simulations in Step 1

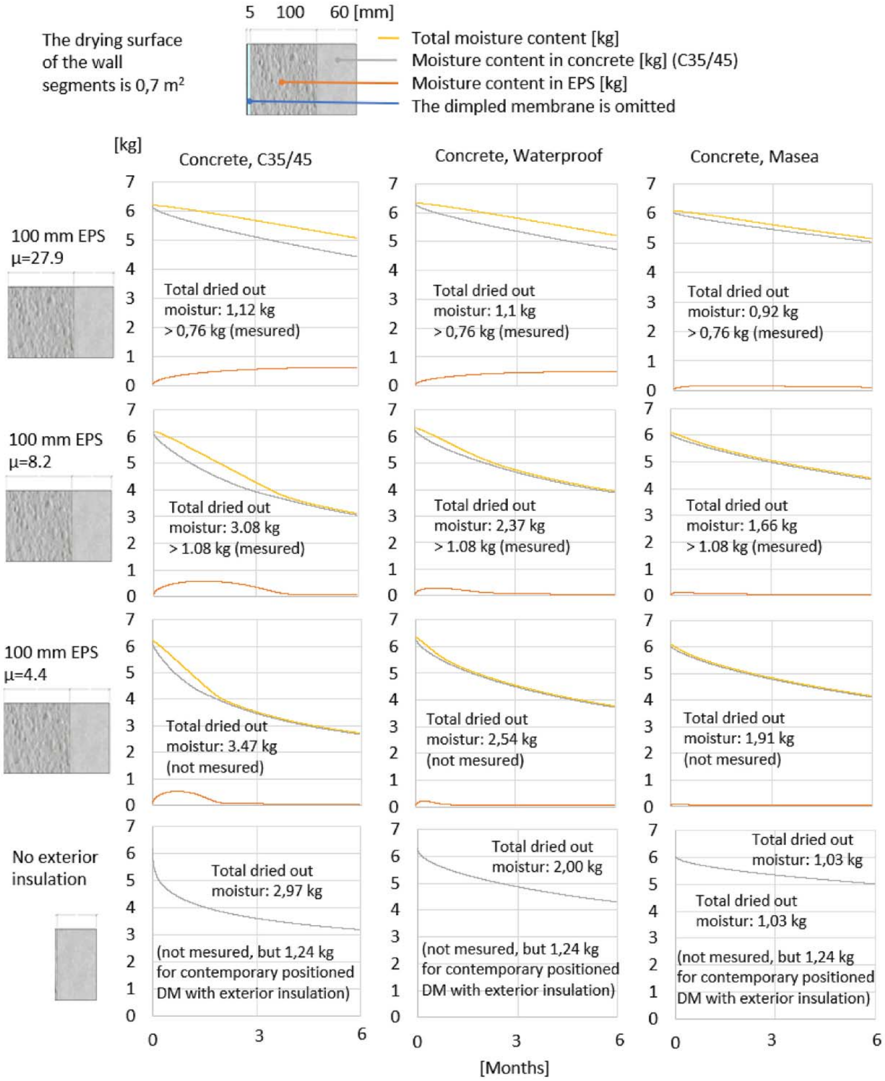

Fig. D1. *Simulated decrease in MC in concrete wall segments over a period of six months for thermal insulations with three different water vapour diffusion resistance factors (μ), and three concrete types. The air in the cold chamber had 80% RH/5°C; the air in the war chamber was 20% RH/20°C. The total amount of dried out moisture is compared to the amount of moisture dried out in the laboratory study* [10].

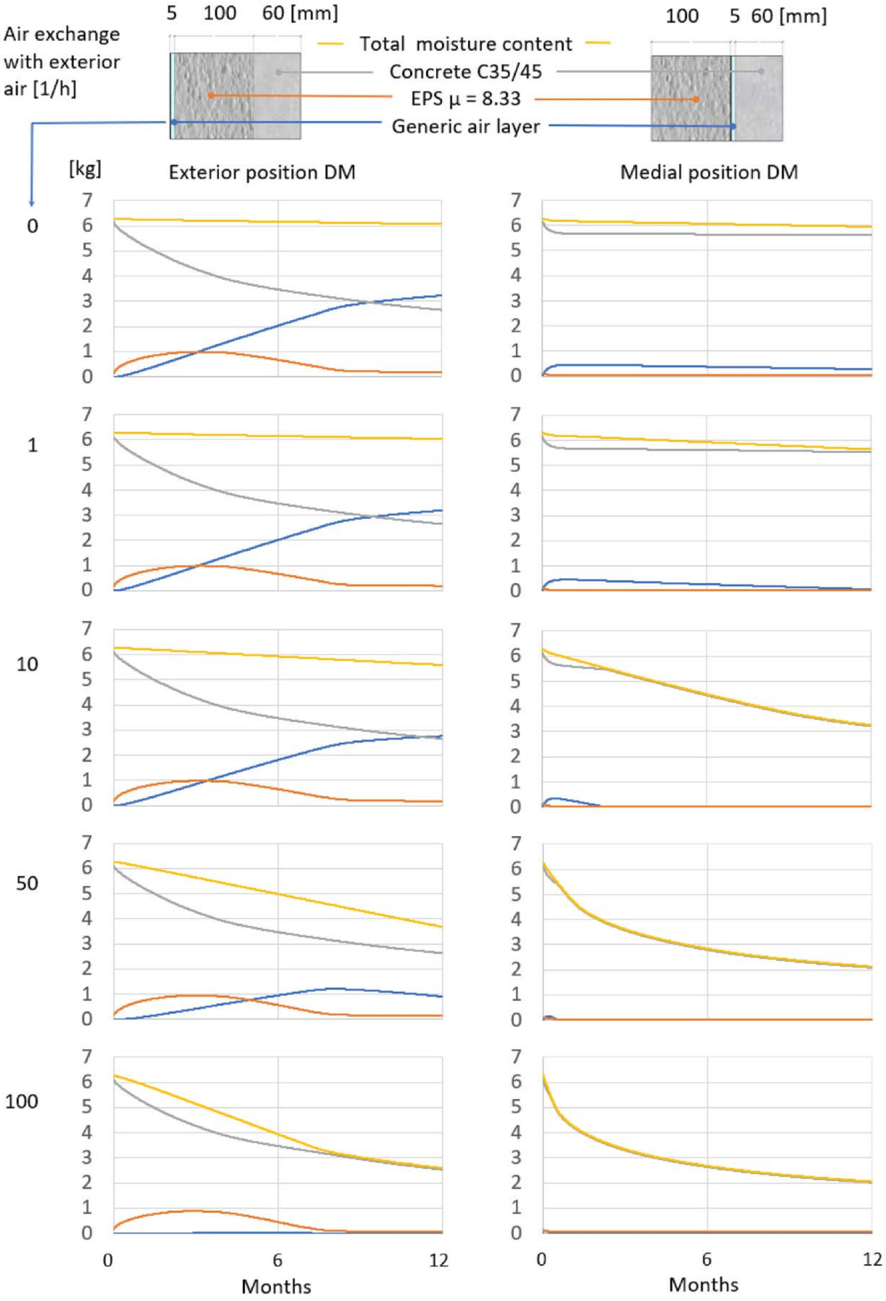

Fig. D2. MC decrease in concrete wall segments for various air exchange rates in the air gap behind the dimpled membrane (DM). The air in the cold chamber was 80% RH/5°C; the air in the war chamber was 20% RH/20°C.

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