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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

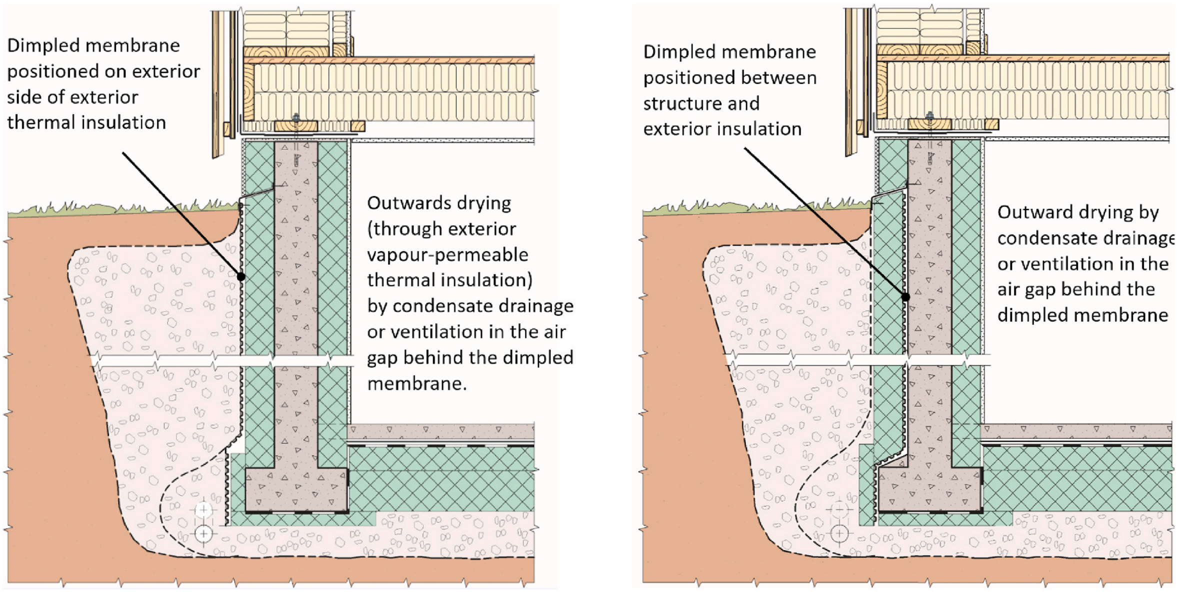

Fig. 1. Dimpled membrane positioned on the exterior side of the vapour-permeable thermal insulation (left). Dimpled membrane positioned directly on the concrete wall (right).

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-

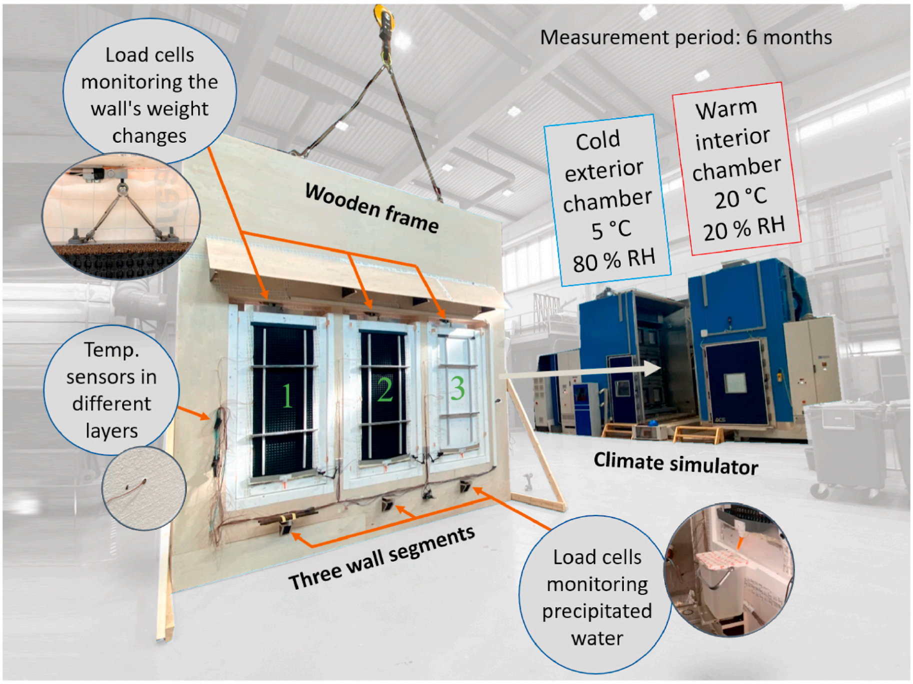

Fig. 2. General overview of the experimental setup. The three wall segments were hung in load cells in an insulated wooden frame and subjected to warm interior and cold exterior climates in a climate simulator for 6 months.

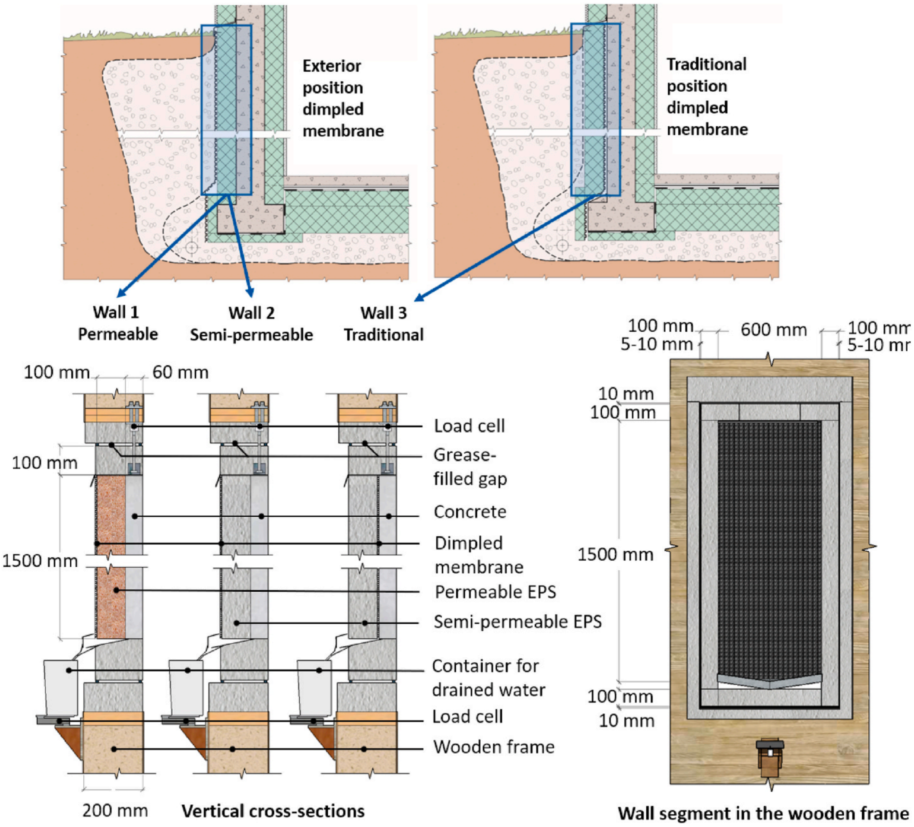

Fig. 3. Diagrams of the wall segments showing dimensions and material configurations (left) and one wall segment positioned in the wooden frame (right).

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

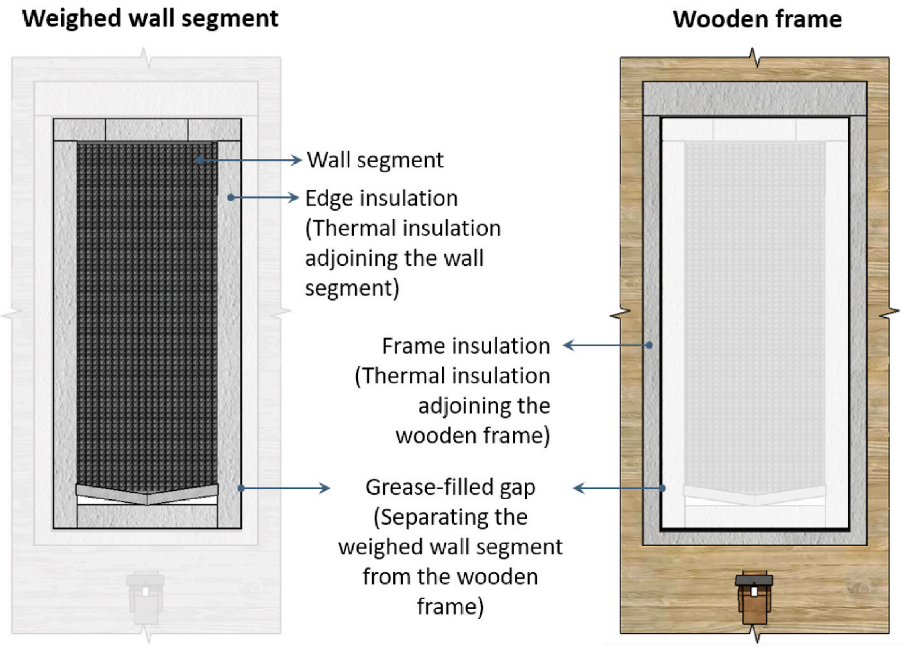

Fig. 4. Diagram of a weighed wall segment consisting of a wall segment and edge insulation (left), wooden frame with frame insulation (right), and a grease-filled gap (left and right). The front view of the weighed wall segment and wooden frame are shown from the exterior side (cold chamber).

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

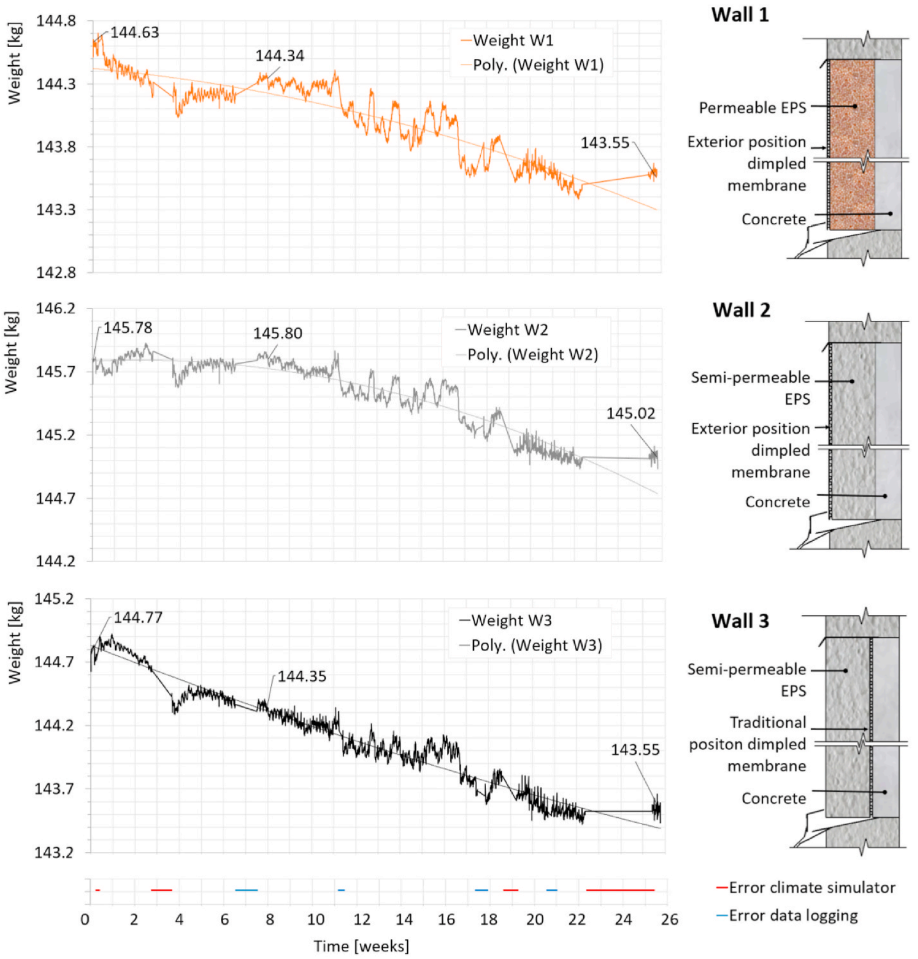

Fig. 6. Weight changes of the three wall segments during the measuring period of 6 months. The flattening portrayed by the three wall segments at the end of the period is due to the difficulties in maintaining the exterior chamber cold (5 °C), see Appendix A.

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

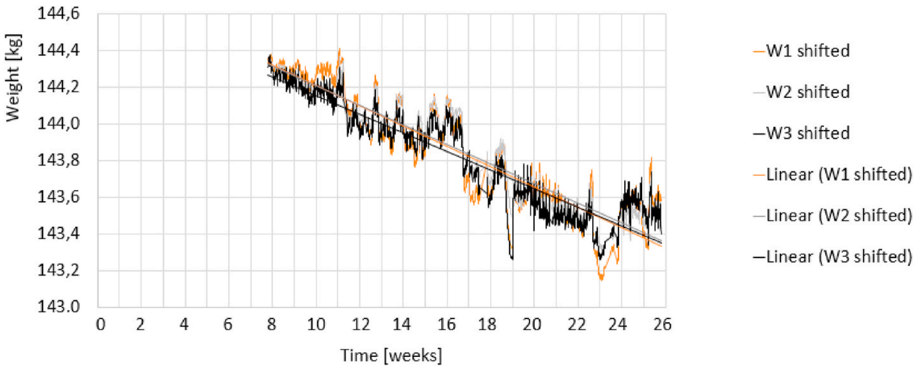

Fig. 7. Weight changes of the three wall segments during the last four months of the measuring period. The graphs have been superimposed for the purpose of comparison.

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.

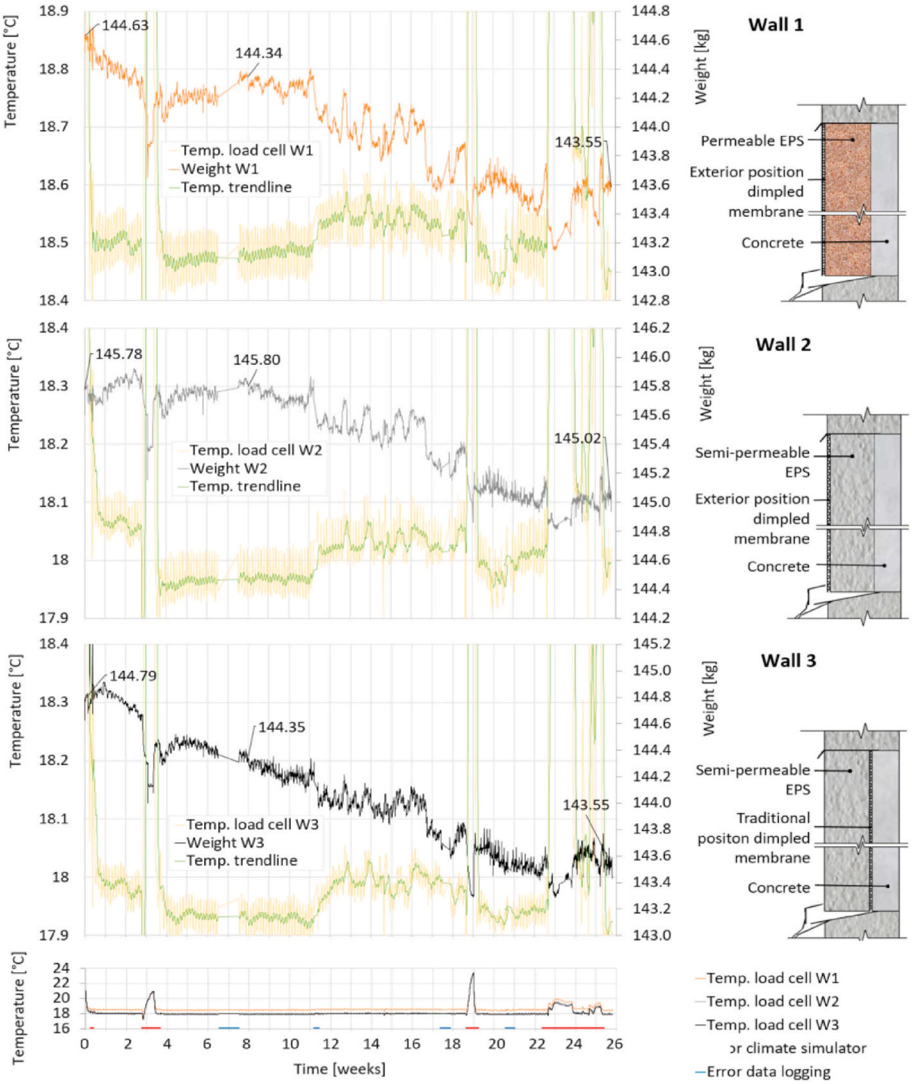

Fig. A1. Weight changes of the three wall segments compared with temperature changes measured at the load cells.

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.

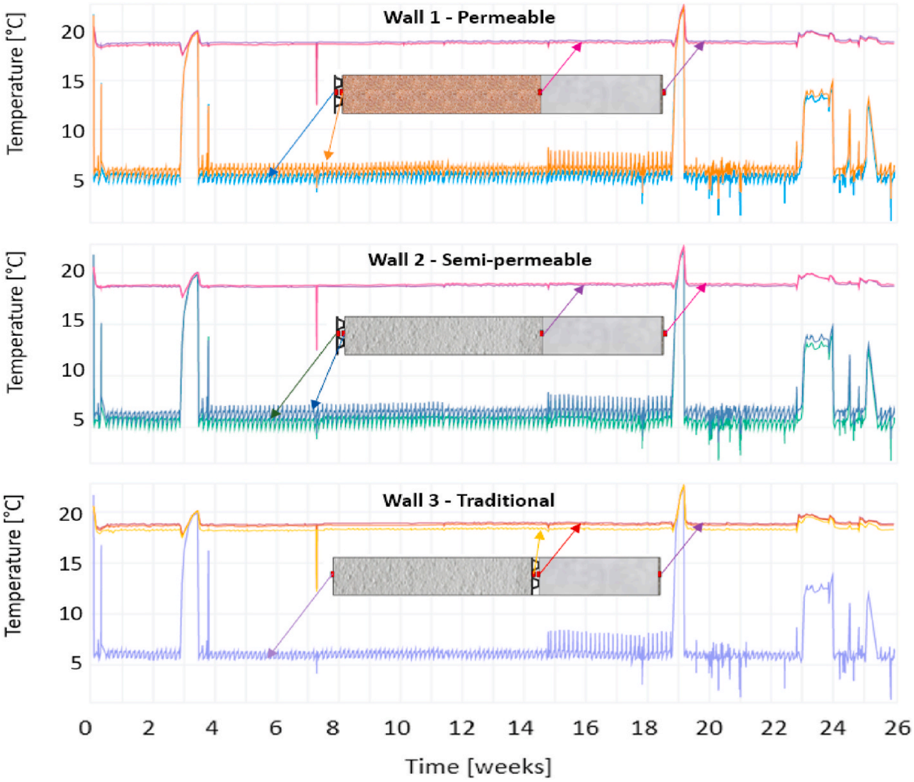

Fig. A2. Temperature variations measured in different layers at the middle of the wall during the entire measurement period. The positions of all the thermocouples are shown in Ref. [38].

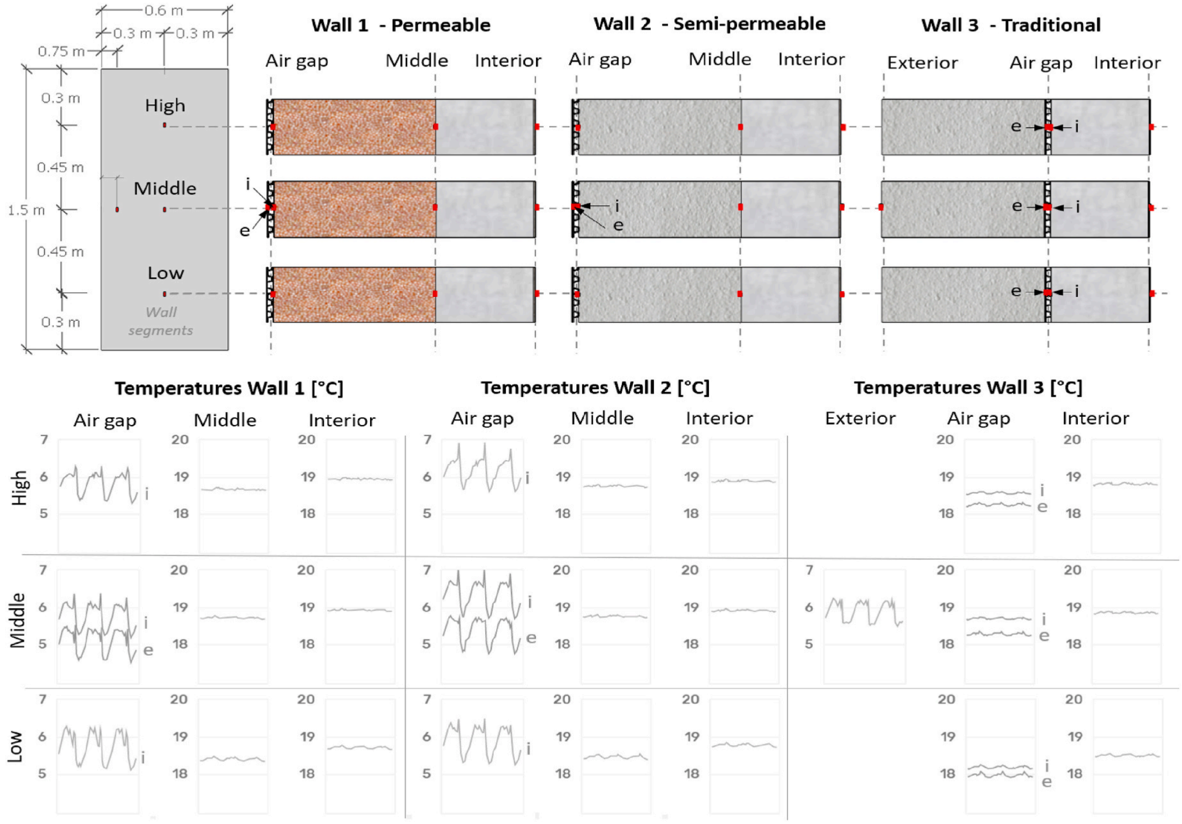

Fig. A3. Temperature variations in different depths and heights in the wall segments during a period with stable climates and drying rates (August 16th-18th, end of week 21). Interior and exterior position of the thermocouples within the air gaps are labelled **i** and **e**.

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